Springer Proceedings in Energy

Krzysztof Mudryk
Sebastian Werle *Editors*

Renewable Energy Sources: Engineering, Technology, Innovation

ICORES 2017

Springer

Springer Proceedings in Energy

More information about this series at http://www.springer.com/series/13370

Krzysztof Mudryk · Sebastian Werle
Editors

Renewable Energy Sources: Engineering, Technology, Innovation

ICORES 2017

Springer

Editors
Krzysztof Mudryk
Faculty of Production and Power Engineering
University of Agriculture in Krakow
Kraków
Poland

Sebastian Werle
Institute of Thermal Technology
Silesian University of Technology
Gliwice
Poland

ISSN 2352-2534 ISSN 2352-2542 (electronic)
Springer Proceedings in Energy
ISBN 978-3-319-72370-9 ISBN 978-3-319-72371-6 (eBook)
https://doi.org/10.1007/978-3-319-72371-6

Library of Congress Control Number: 2017959925

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Study the Physical Properties of the Fruit Pomace for Energy Use

Joanna Pasternak and Paweł Purgał

Abstract The world economy in the production of electricity and heat, is increasingly based on the use of renewable energy sources to replace partially or totally fossil fuels. Biofuels provide an opportunity for energy production in many sectors while maintaining ecological conditions. Having regard to energy security in all regions of the country and the guarantee of sufficient resources for energy production, it must be constantly searched for new and locally available raw materials for the production of environmentally friendly fuel, whose physico-chemical parameters will fully implement efficient combustion or incineration. Fruit processing plants offer post-production waste, which can be used as biomass. At the turn of the last years they developed a number of kilns, whose aim is to get the plant product with a humidity below 15%. Laboratory tests conducted at Kielce University of Technology, demonstrated the possibility of using agro biomass as a component of the mixtures of waste wood for their energy efficiency. Analytical moisture, heat of combustion, calorific value, and ash participation were analyzed. It has shown the difference in the residue of the same mixture at two temperatures of incineration. The possibility of increasing the amount of biomass as a renewable source of energy becomes a reality, both in industry and in private farms. To stop the process of environmental pollution, which has recently been intensified more and more, one should be more broadly interested in the use of post-production waste of plant origin, available on the domestic market.

Keywords Fruit pomace · Calorific value · Ashes

J. Pasternak (✉) · P. Purgał
Katedra Fizyki Budowli I Energii Odnawialnej, Politechnika Świętokrzyska,
Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
e-mail: pass@poczta.onet.pl

P. Purgał
e-mail: ppurgal@tu.kielce.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_1

1 Introduction

Waste other than the dangerous one has a wide application in the combustion process. Industrial plants, community thermal power stations and individual customers are interested in natural fuel, provided that it has sufficing energy properties. Agricultural and food-processing waste was composted or used as fertilizer for years. However, such solutions have often been wearisome for the local environment on account of unchecked effects of fermentations. The implementation of new technologies of initial drying or dryings of biological waste let for acquiring components for producing biofuel, intended for combustion processes or co-burn. During the production of the fruit preserves two types of waste are made. One type is waste stock, generated by long-term storing of raw materials, semi-finished products or final goods. The other type is waste produced during the appropriate food-processing process. In Poland 3 million of tons of different fruit is used annually for the food production [1]. The pomace which until recently were a threat to the local environment, at present constitutes the valuable raw material of the secondary application. These are components with the rich spectrum of carbohydrates, white, fibre, fats and pectins which are a base of the composition of dried fruit in the food, pharmaceutical and cosmetic industry. The poor quality pomace is used as valuable additions to animal fodders. Simultaneously, there is a need for constant monitoring of combustion processes with the contribution of biomass, on account of the productivity of the energy generation process. Findings of fruit pomace physical characteristics in laboratories of the Świętokrzyski Technical University Examinations, conducted in laboratories in the Department of Geomantic Environmental Engineering and Energetic in Kielce have shown, that every kind of biomass is characterized individually by dependent characteristics. Tested samples of the pomace fruit were acquired from the local drying room located in Świętokrzyskie area. Demonstrating is a purpose of research, that the fruit pomace as waste, can constitute the component to the biomass, intended for the combustion process. Literature data, concerning the research on physical parameters of the fruit pomace, show that results of the dried fruit heating value are developing on the level 23.29 MJ/kg [2]. Examinations, conducted in the laboratory of the Świętokrzyski Technical University, are diversifying the checked values of fruit biomass—from 22.55 MJ/kg for the pomace of pears to 26.53 MJ/kg for the raspberry pomace. Publications containing the research widest spectrum, are giving calorific values of the chosen fruit pomace: apples 15.94 MJ/kg and the blackcurrant 20.86 MJ/kg [3].

2 Analytical Damp

The test material is a mixture of fruit pomace and sawdust in the proportion of 50–50% of the test sample. Sawdust from the sawmill contained 30% of deciduous and 70% coniferous wood. Examinations of the pomace were carried out for samples about 1 g mass and the fraction below 0.16 mm. The initial moisture content of the samples did not exceed 15%. All pellet samples were analyzed subjected to a drying process at 105 °C to stabilize the mass. The level of the analytical damp was established, using the drying method for 1 g mass samples of biomass with the accuracy to ±0.001 g. Every kind of biomass was being dried simultaneously in three melting pots. M_{ad} did calculations according to the model [4] (Fig. 1).

Findings show that no kind of the examined pomace exceeded the 5.5–6.8% of the analytical damp. Adding sawdust slightly picked up level of the damp of individual blends by about 0.5% with the exception of the raspberry pomace, which demonstrated the fall in the checked parameter in comparison to the other blends.

3 The Heating Value and the Calorific Value of Fruit Biomass

Marking heating value of the chosen fruit pomace and their blends with sawdust, was conducted in Laboratory of Environmental Biology and the Microclimate in the Department of Geomantic Environmental Engineering and PŚK Energetic. 1 g mass samples were burnt in the KL-12 bomb calorimeter. For calculating average heating values, quantities were chosen, which didn't differ between themselves

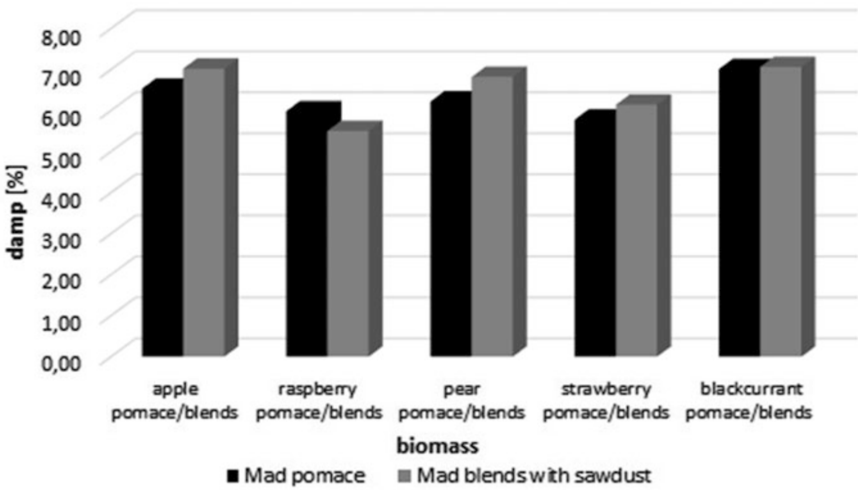


Fig. 1 Analytical damp in pomace and blends with the participation of the 50% sawdust

more than about 120 J/g according to standard guidelines [5]. The KL-12 calorimeter automatically converted the heating value of the tested sample into its calorific value. Complete burn of the fruit pomace in the environment of clean oxygen was characterized by a lack of remains after burning them, and average values were counted for relative results of the heating value of samples of the acceptable difference according to the norm in question. According to the definition, the calorific value is a quantity of heating given off at the complete and total burn of the unit of fuel, taking into account that after the completion of the burn, water stays in the form of steam, it is the parameter significant for the that kind of target audience of biomass [6] (Fig. 2).

The heating value of the blackcurrants pomace and their blends is developing relatively on the comparable level. In case of strawberries and raspberries, their blends are characterized by lower values to 1 MJ/kg. Only adding sawdust to the apples and pears pomace caused an increase in the heating value of blends.

Taking into consideration the fact, that there is lack of ability of some pomace pelleting on account of their looseness at low humidity level, blends with the participation of the 50% sawdust were subjected to attempts using sawdust resin of a tree as binder of the natural origin. Examinations conducted on the samples of blends have shown the same high level of the calorific value the in comparison to achieved results for very pomace (Fig. 3).

The calorific value resulting from the experimentally measured heating value is proportionally lower for every sample. The examined pomace has a calorific value in the scope from 21 to 25 MJ/kg. Demonstrated calorific values of blends exceed the value 21.5 MJ/kg but the standing out raspberries pomace with sawdust combination exceeds even 24 MJ/kg.

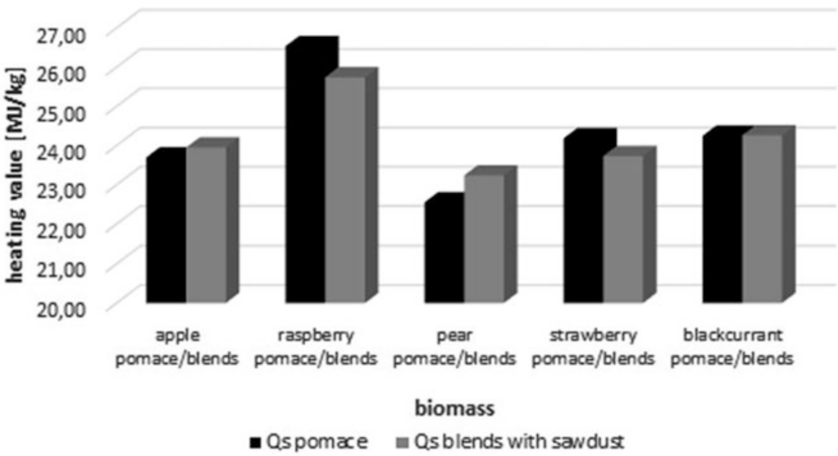


Fig. 2 Heating value of fruit pomace and their blends with sawdust

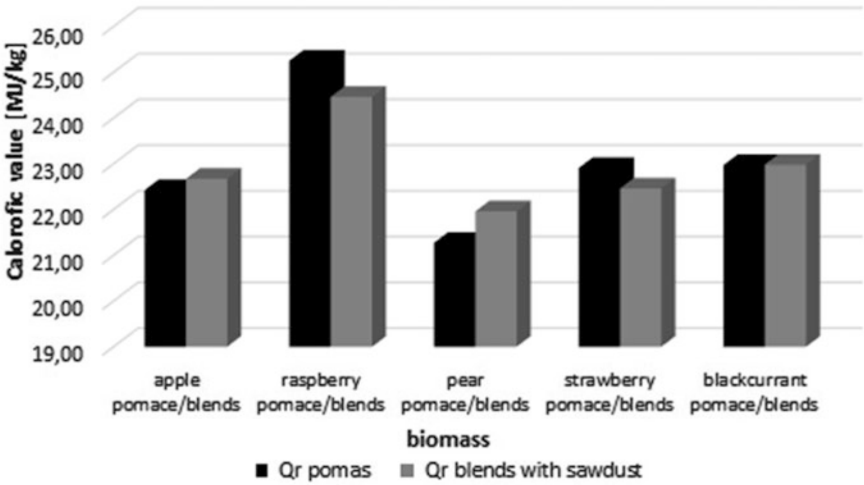


Fig. 3 Calorific value of fruit pomace and their blends with sawdust

4 Examining the Content of Ashes

Reducing samples of the pomace to ashes was conducted in temperature 550 °C [7] and in temperature 815 °C [8] or the technology of the co-burn of biomass with coal, according to guidelines of norms, concerning solid fuels and biomass. Norm PN-EN ISO 18122:2016, "Solid biofuels. Marking of the content of ash", make the low temperature of reducing biomass samples to ashes towards guidelines of the PN-ISO 1171 Norm: 2002, "Solid fuels. Marking of ash", where the hard bituminous or lignite coal is described fuel. Biomass was treated methodically as fuel parametric close to the lignite coal, and therefore individual test procedures developed by laboratories gave the temperature of reducing to ashes 600 °C, examining ashes for biomass consumed in hot water boilers. Temperature 800 °C was allowed, when examinations were conducted paying special attention to the co-burn with coal [9]. The gradation of measuring temperatures in thematic norms results from differences of the chemical composition of fossil fuels and biomass.

Examining the amount of ashes after burning the sample in 550 °C was carried out according to the following methodology

- 1 g biomass amount every was put in the stove in the room temperature.
- the stove was evenly being heated to 250 °C within 30–50 min.
- samples were left in temperature 250 °C through 60 min.
- after this time heating was being continued to temperature 550 °C for 30 min. raising temperature evenly 10 °C/min.
- the sample was left in temperature 550 °C for 120 min.
- melting pots were weighed on the laboratory scale after reducing biomass to ashes with the accuracy 0.1 mg.

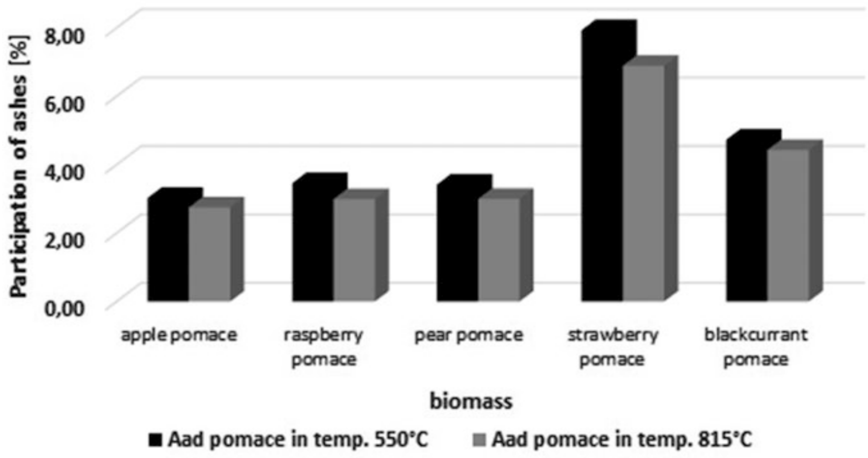


Fig. 4 Participation of ashes in the fruit pomace in the process of reducing to ashes in temperature 550 and 815 °C

- every time finishing off the sample was conducted by 1 h and repeat weighing.

Examining the amount of ashes after burning the sample in pace. 815 °C was carried out according to the following methodology

- 1 g of biomass every was put in the stove in the room temperature.
- the stove was evenly was being heated to 500 °C within 60 min.
- samples were left in temperature 500 °C for 60 min.
- after this time heating was being continued to temperature 815 ± 10 °C.
- a sample was left in temperature 815 °C for 60 min.
- melting pots were weighed on the laboratory scales after reducing biomass to ashes with the accuracy 0.1 mg (Fig. 4).

In case of biomass burning an amount of ashes is essential. The process of reducing the fruit pomace to ashes was conducted comparatively in two temperatures. Amount of ashes, at applying the standard procedure in temperature 550 °C, proved to be higher than the amount in temperature 815 °C. The biggest amount of ashes remained from the strawberries pomace, because almost a 8% after applying the methodology of reducing to ashes for biomass, while for remaining samples developed in the scope 2.8–4.5%. Increasing the temperature of the combustion process of the fruit pomace resulted in lowering remains of samples from 0.5 up to the 1.0% (Fig. 5).

Putting remains together after the process of reducing pomace to ashes and their blends with sawdust in the participation of the 50%, shows a significant reduction of ashes amount in case of blends. The larger difference was observed for the strawberries pomace and their blends with sawdust, where the difference of

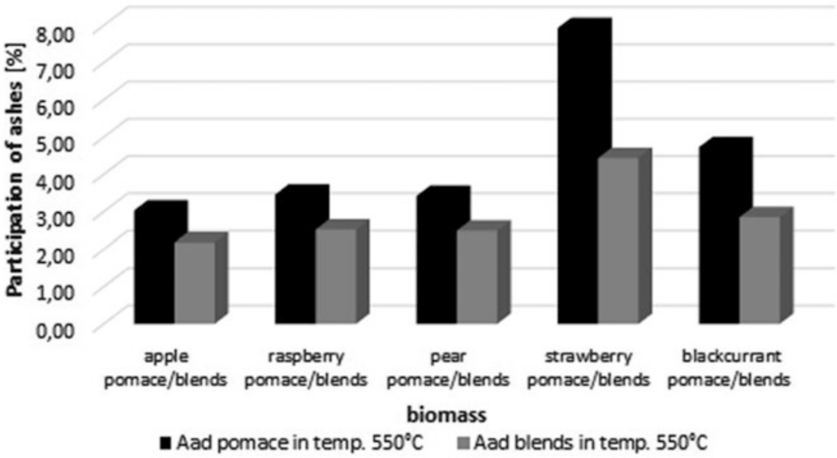


Fig. 5 Participation of ashes in fruit pomace and blends in temperature 550 °C

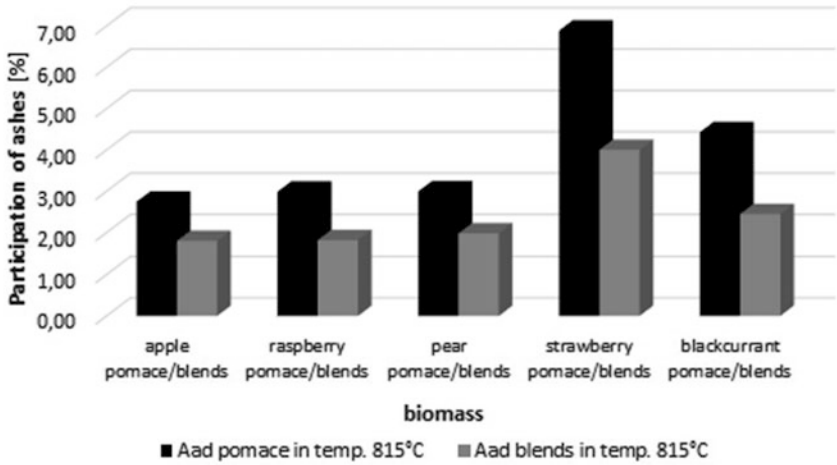


Fig. 6 Participation of ashes in fruit pomace and blends in temperature 815 °C

achieved remains amounted for 2%. In case of remaining samples the gradation was between 0.5 and 1.0% (Fig. 6).

Increasing the temperature of reducing to ashes to 815 °C caused lowering the amount of ashes, left after blends burning, in comparison to very pomace, subjected to the same process. The mixture with the strawberry pomace was different around 3%, while remaining blends were characterized by lower remains of ashes in comparison to the remains from the pomace in the scope from 1.0 up to the 2.0%.

Temperature differences about 265 °C of described processes, determine the remains in the form of ashes, whose amount is decreasing in the diversified way depending on the sample type. In both cases, a lot of ash remains from the strawberry pomace, in spite of their low level for the analytical damp.

The least amount of ashes were found in melting pots, where the apple pomace was tested. Attempts to reduce to ashes were conducted with checking for gaining the difference of results not larger than the 0.1%—in compliance with the requirements norm [7]. Comparatively, according to literature data, the content of ashes in biomass exceeds the 7% at the combustion temperature above 700 °C [9].

5 Fractions of Samples of Biomass Subjected to Burning to Ashes

Every examination of the biomass samples subjected to high temperature of reducing to ashes should be preceded by the measurement of the analytical moisture content. It is quantity which participates in calculations of the amount of ash, remaining after given fuel burning. The norm concerning the drying method, shows the fraction of the research material below 0.2 mm [4]. Grinders for biomass grinding often have the smallest mesh sieve size of 0.425 mm, therefore there is a need to use additional sieve to adapt the fraction to standard methodology exists. However, preparing the fruit pomace samples, it can be noticed, that on the sieve remain stones which don't participate neither in the process of the drying or reducing to ashes. It concerns the currants, strawberries, or raspberries pomace. The publications, concerning the process of preparation of biofuels samples, are pointing out to impediments of different kind, often connected with the structure of the research material, where differences in findings result derive from [10]. "It is not possible to get the analytical modicum of 0.2 mm. And so a compromise attempt is necessary between the size of the grain of the sample and the repetitiveness of results" [11]. The latest norm concerning reducing biomass to ashes already shows other fraction of analytical-material, "1 mm or smaller" [6]. However, reducing to ashes the same sample, for which the percentage share of the dampness was determined, we are still dealing with the fraction shown for the drying method. The research cycle which was carried out in laboratories of the Świętokrzyski Technical University, was done for uniform fraction—below 0.16 mm.

6 The Summary and Conclusions

The research on physical characteristics of the fruit pomace shows that after the process of the drying from 15 to 7% for pomace, they are possible to use as solid biofuel. Preliminary attempts, determining the energy efficiency of food-processing waste, confirm the thesis, that they can constitute a product ready to burn or can be used as the high-energy addition. Willingness of applying the fruit pomace to the burn including sawdust without using other binder than resin is being shown to be authoritative, when the participation of the pomace will be smaller than the 50% in relation to the permanence pelet whether of briquette. This is a way to utilize post-production waste, characterized by exaggerated combustion heating value from 22 to 26 MJ/kg, due to the sugar content of the fruit pomace. When analyzing the amount of ash of the selected blends, the temp 550 °C is in the range of 2.18–4.44%. In co-combustion with coal at 815 °C the amount of ash is in the range of 1.80–4.00%. Innovative technological solutions of the structure of biomass stoves enable the maximum use of that kind of fuel to energy purposes. Selection of the kind of biomass for composing fuel about parameters of the burn maximizing the energy efficiency of the process, at limited emission of exhaust fumes as well as including the economic calculation, is becoming a task for further deliberations in this respect.

References

1. Łaba S.: Proekologiczne działania w zakresie zagospodarowania odpadów w przemyśle owocowo-warzywnym, Stowarzyszenie Ekonomistów Rolnictwa i Agrobiznesu, Roczniki Naukowe tom XIV, zeszyt 5
2. Lasek J., Głód K., Kazalski K., Janusz M., Wilk B.: Ocena modeli do określania właściwości kalorycznych paliw stałych pod kątem ich zastosowania w bilansowaniu obiektów energetyki zawodowej—cz. I modelowanie oraz analiza procedur wyznaczania wartości opałowej biomasy, Rynek Energii pp. 100 (2013)
3. Borycka B.: Walory ekologiczne spalania biomasy z odpadów owocowo—warzywnych, Energetyka i Ekologia pp. 848 (2009)
4. PN-EN ISO 18134-3:2015-11: Biopaliwa stałe. Oznaczanie zawartości wilgoci. Metoda suszarkowa
5. PN-EN ISO 1928:2002: Paliwa stałe. Oznaczanie ciepła spalania metodą spalania w bombie kalorymetrycznej i obliczanie wartości opałowej
6. http://www.sigma-not.pl/publikacja-79270-możliwości-zagospodarowywania-wytłoków-i-innych-odpadów-przemysłu-owocowo-warzywnego-przemysl-fermentacyjny-2013-9
7. PN-EN ISO 18122:2016 Biopaliwa stałe. Oznaczanie zawartości popiołu
8. PN-ISO 1171: 2002 Paliwa stałe. Oznaczanie popiołu
9. Wielgoński G., Łechtańska P.: Emisja Zanieczyszczeń z procesu spalania biomasy, Politechnika Łódzka, Wydział Inżynierii Procesowej i Ochrony Środowiska pp. 391–400 (2010)
10. Koruba D., Piotrowski J.Z., Latosińska J.: Biomass—alternative renewable energy source to the fossil fuels. In: E3S Web of Conferences 14, Energy and Fuels pp. 1–10 (2017)
11. Wisz J., Matwiejew A.: Biomasa-badania w laboratorium w aspekcie przydatności do energetycznego spalania, Energetyka pp. 631 (2005)

Tests of a Steam Piston Engine Under Supercritical Conditions

Janusz Wełnowski, Damian Wełnowski, Tomasz Topoliński, Józef Flizikowski and Adam Mroziński

Abstract The purpose of the tests is smart growth of a micro combined heat and power plant, intended to be fed with biogas, biomass or any other type of fuel (an aspect to be taken into account in the developmental stage of a prototype) with an impulse piston steam engine, power generator or a water brake (modelling, simulating, substituting workloads). The research system included the following units: an inductive supercritical steam generator (eventually replaced with a steam boiler fed with biogas, biomass or any other solid or liquid fuel), a piston steam engine fed with steam of supercritical parameters with a patented steam-supply system including an impulse injection valve, a power generator (interchangeably with water brake), a steam generation system.

Keywords Steam engine · Supercritical steam
Micro combined heat and power plants

1 Research Equipment

At present, technologies using ultra supercritical steam (at high pressure and high temperature—Fig. 1) are developed [1–31, 34–36].

The objective of this study is a research methodology for a steam engine under supercritical steam conditions. Another purpose is identification of mechanical engineering variables for preparation of fuel, combustion and conversion of obtained energy to the end usable form.

Considering the above, one can notice that using a compression-ignition engine with direct injection and a combustion chamber over a piston is a very good solution. A head of such an engine from the combustion chamber side is flat.

J. Wełnowski (✉) · D. Wełnowski
Prosperitos sp. z o.o., Białe Błota, Poland
e-mail: jwelnowski.itp@gmail.com

T. Topoliński · J. Flizikowski · A. Mroziński
University of Science and Technology in Bydgoszcz, Bydgoszcz, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_2

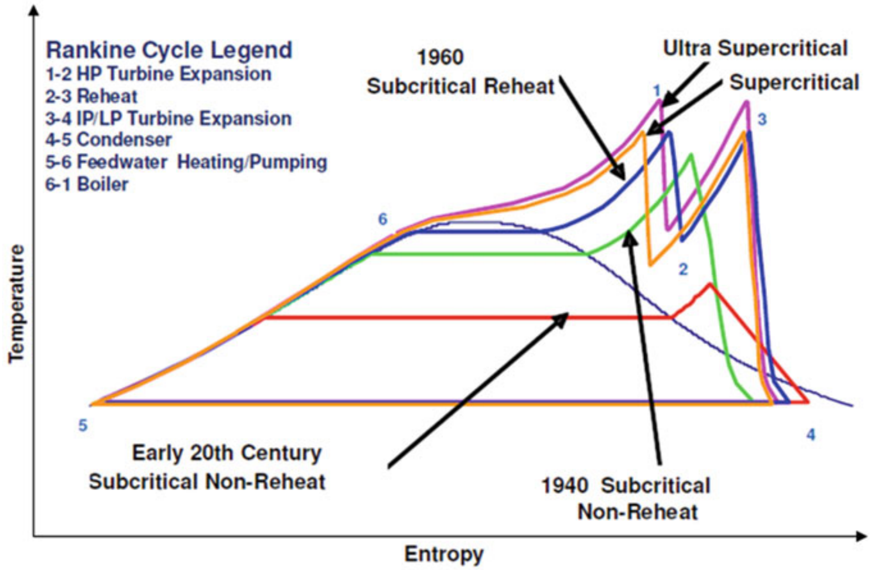


Fig. 1 Rankine cycle—overheated, supercritical, ultra-supercritical steam [6, 50]

Therefore, when using a piston with flat bottom (without a combustion chamber), it is possible to obtain a minimum clearance volume which relates, above all, to the maintenance of technological clearance between the piston in the top return point and the head.

A fuel injector hole is then adapted for steam delivery, whereas a glow plug hole can be used to indicate the engine or measure temperature—which is particularly important for a prototype engine.

The engine cylinder responsible for steam machine circulation operated in a two-stroke cycle. It was fed with steam of relatively low pressure values, i.e. up to 7 MPa (a limit related to the amount of heat possible to collect from the exhaust system and a large demand for steam consumption), therefore the project authors decided to inject steam through the inlet valves of the engine, and to release decompressed steam through the outlet valves. Use of the original (yet modified—a transmission and cam profile change) timing gear system is advantageous as it allows for regulation of the inlet valve opening angle to a certain extent by using variable valve timing, which in turn ensures an optimal—for given conditions—decompression coefficient [38–41] (Fig. 2).

This coefficient is determined by the following relation:

$$\varepsilon = \frac{V_2}{V_1} = \frac{V_{SZ} + V_S}{V_1} \tag{1}$$

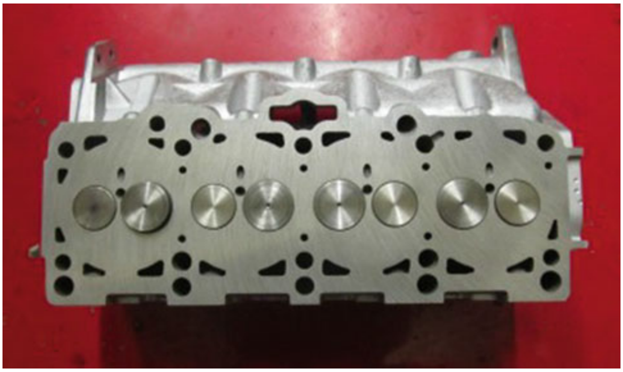


Fig. 2 Head of a 1.9 TDI engine installed in Volkswagen AG vehicles [9]

where:

V_1 volume of supplied steam, i.e. of the cylinder when closing the (inlet) valves delivering the steam,
V_2 total volume above the piston in the bottom return point V_{sz},
V_{SZ} clearance volume,
V_S displacement.

A decompression coefficient should be selected in such a way to make sure that pressure in the cylinder equals atmospheric pressure at specific pressure of supplied steam at the bottom return point (Fig. 3). In such a situation, thermal energy of the steam will be completely converted into work [32–37].

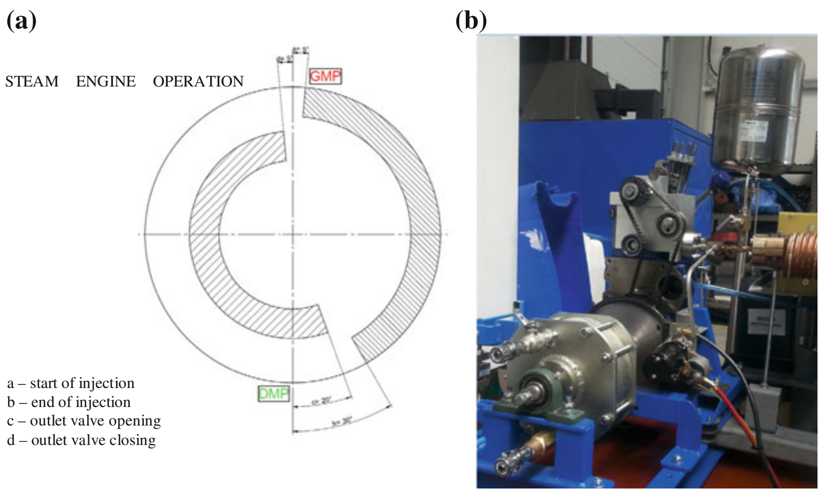


Fig. 3 An operation diagram (**a**) of the tested engine (**b**)

When designing the test stand, particular attention was paid to the opportunity to test performance of a steam engine as a truly innovative components of a micro combined heat and power plant [42–49]. For the research purposes, the following configuration of the test stand was planned:

- An inductive steam generator for precise generation and distribution of steam of ultra-supercritical parameters.
- A single-cylinder test engine of a two-stroke cycle and a steam injection valve.
- A water brake for testing torque generated at the output shaft with an option of alternative installation of a power generator.
- A system of steam regeneration for supplying the engine in a closed circuit.
- A system for controlling, collecting and recording measurement data with conversion of measured values to electric signals.

Research objectives on a such stand (Fig. 3) are as follows:

(a) Measurements with real-time recording of physical values of processes occurring in the steam generator, engine, water brake and the steam regeneration system, which allow for analyses on:
   - engine indicating,
   - external characteristics determination,
   - engine thermal balance,
   - steam regeneration thermal balance,
   - engine efficiency,
   - efficiency of a micro combined heat and power plant while using steam regeneration heat.

(b) Verification of structural assumptions of the steam engine and steam injection system in the context of operation.
(c) Verification of materials and components available in the technique, capable of operation at temperatures up to 650 °C and pressure up to 35 MPa.

2 Test Methodology

Models useful in analytical optimisation tests of the conversion of steam energy to a rotary motion (ABO):

1. Structural and functional models **($\mathbf{M_{k-f}}$)** of a set of devices for converting steam energy to a rotary motion.
2. Models of the efficiency and structural features of the effects **($\mathbf{M_{s-e}}$)** of a set of configured devices for converting steam energy to a rotary motion.

Structural and functional models ($\mathbf{M_{k-f}}$). Conversion of heat to work on the test stand takes place in a system specified in Fig. 4.

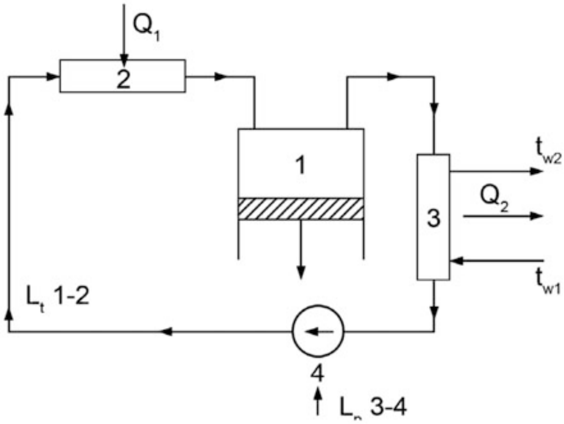


Fig. 4 Test stand layout, 1—piston engine, 2—ultra supercritical steam generator, 3—cooler (condenser), 4—high-pressure pump

The thermal cycle provided on the test stand is shown in the ‘i-s’ coordinate system in Fig. 5. It consists of the following processes:

1–2: isentropic (adiabatic) decompression of supercritical steam s = const, q = 0 in the engine (1—Fig. 4),
2–3: isobaric condensation of steam decompressed to p_2, p = const in the condenser (3—Fig. 4),
3–4: isochoric, v = const, pumping of the condensate (4—Fig. 4),
4–1: isobaric supply of heat in the heater (2—Fig. 4).

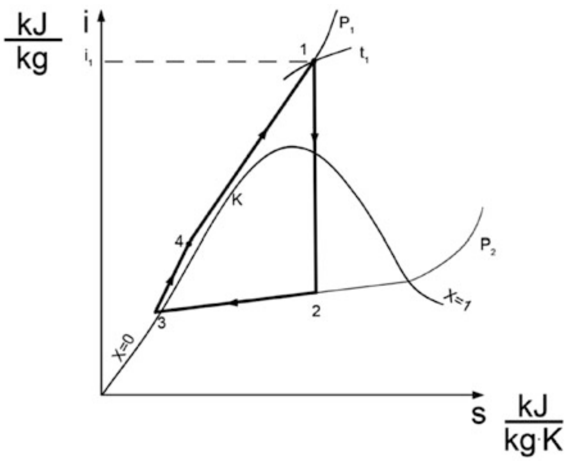


Fig. 5 Thermal cycle

The energy flow balance in the thermal cycle provided on the test stand was described by the following relations:

– the value of the $L_{t\ 1-2}$ work flux (N power) obtained in the process (1) equals:

$$L_{t\,1-2} = N = m\,(i_1 - i_2) \quad kW, \tag{2}$$

where:

m mass flux of steam in kg s^{-1}
i_1 specific enthalpy of steam in the 1st state (supercritical), in kJ kg^{-1}
i_2 specific enthalpy of steam decompressed to p_2, in kJ kg^{-1}

– the value of the Q_2 flux discharged in the process (2–3) of isobaric condensation equals:

$$Q_2 = m \cdot (i_2 - i'_3) \quad kW, \tag{3}$$

where:i'_3—enthalpy of condensate at p_2 and x = 0
This heat is discharged by water cooling the condenser according to the below equation:

$$Q_2 = m_w \cdot c_w \cdot (tw_2 - tw_1) \quad kW, \tag{4}$$

where:

m_w mass flux of condenser cooling water in kg/s,
tw_2, tw_1 inlet and outlet cooling water temperatures.

– the value of the *Lp* pumping work flux of the isochoric process (3–4) equals:

$$Lp = m \cdot (u_4 - u_3) = m \cdot [(i_4 - i_3) - v \cdot (p_4 - p_3)] \quad kW, \tag{5}$$

where:

u_4 internal energy of condensate in the 4th state, in kJ kg^{-1},
u_3 internal energy of condensate in the 3rd state, in kJ kg^{-1},
v specific volume of condensate in $m^3\ kg^{-1}$
p_4 pressure of condensate in the 4th state in bar,
p_3 pressure of condensate in the 3rd state in bar (p_3 = 5 bar).

Since $Lp \ll L_{t\,1-2}$ is ignored in the cycle balance (3).

– the value of the Q_1 heat flux supplied to the cycle in the process (4–1) of isobaric heating, p = const (p = 350 bar) equals:

$$Q_1 = m \cdot (i_1 - i_4) \quad kW, \tag{6}$$

where:
i_4—enthalpy of condensate in the 4th state at p_4 = 350 bar in kJ kg^{-1}.

The thermal balance of the cycle was described with the following equation:

$$Q_1 + Lp = Q_2 + L_{t\,1-2}, \quad (7)$$

Ignoring the value of the pumping work flux in the balance equation, it can be express with the following formula:

$$Q_1 = Q_2 + L_{t\,1-2}, \quad (8)$$

$$L_{t\,1-2} = Q_1 - Q_2, \quad (9)$$

Models of the efficiency and structural features of the effects ($M_{s\text{–}e}$). A fundamental assumption in the projects was to test the effectiveness of a new generation engine used to supply an automatic micro combined heat and power plant. The purpose of the said tests resulted from innovative presumptions of an analysis of a prior art analysis which can be expressed as follows:

- Theoretical, obtainable steam engine efficiency at around 45%.
- Possible use of a steam generator for any type of fuel—solid, liquid or gas—including all biorenewable fuels, depending on local resources.
- Autonomy of a power plant with electric energy and useful heat distribution.

A compensation model is developed similarly as in the case for regulation characteristics, however with compensation of interferences alone, for required work conditions, efficiency and performance. The compensation characteristics defines basic engine operation and process parameters with compensation of interferences and deformation of flow sections in order to obtain a defined power objective λ = const and $\lambda \neq 1$, and $Q_c \Rightarrow Q_{cmax}$ = const. The unit power demand is determined by the (2) and (8) relation. Each state and process of a characterised working motion occurs as a result of other motion properties of the engine, energetic material (steam), process, thus it requires special calculations, simulations, tests, analyses and assessments of the phenomena and processes (Table 1).

Software in the LabView environment, after running the application, initiates the process of recording signals measured by analogue converters and saves their values in dtms files. Such files contain a lot of data:

- Digital inputs—information on the value of input digital signals used in the control and diagnostics system. There is a description of a given signal next to the X0..15 input description. The ‘1’ logic—a high level at the input is indicated by a LED flashing green.
- Digital outputs—information on the value of output digital signals used in the control and diagnostics system. There is a description of a given signal next to the Y0..15 output description. The ‘1’ logic—a high level at the output is

Table 1 Target variable of steam engine motion characteristics

Characteristics	Shaft speed n	Operating power at shaft N, P_R	Steam dosing q	Conversion degree λ	Mass performance Q_m	Target performance Q_c
Idle speed	$n \neq const$	$P_R = f(n)$	q(0;1)	$\lambda = 1$	$Q_m = 0$ lub $Q_m = dm/dt$,	$Q_c = 0$
Load	$n \neq const$	$P_R = f(n)$	q(0;1)	$\lambda = f(n)$	$Q_m = f(n) = dm/dt$	$Q_c \neq 0$
External	$n \neq const$	$P_R = f(n)$	q(0;1)	$\lambda = f(n)$	$Q_m = f(n) = dm/dt$	$Q_c \neq Q_m$
Control	$\Delta n \neq const$	$P_R = f(\Delta n)$	q(0;1)	$\lambda = f(\Delta n)$	$Q_m = f(\Delta n) = dm/dt$	$Q_c \leq Q_m$
Regulation	$\Delta n \neq const$	$P_R = P_{Rmin}$	q(1)	$\lambda = const$	$Q_m = Q_{mmax} = const$	$Q_c \approx Q_m$
Compensation	$\Delta n \neq const$	$P_R = P_{Rmin}$	q(0;1)	$\lambda = const$	$Q_m = Q_{mmax} = const$,	$Q_c \approx Q_m$

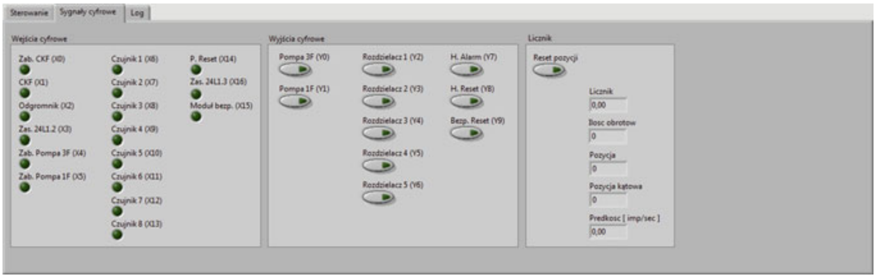


Fig. 6 View of the Front Panel window—digital signals (input, output, counter)

indicated by a LED flashing green. Press and hold the button to excite a high signal at the output for as long as the button is pressed (Fig. 6).

– Counter—information from the counter module on the shaft position. After running the application and setting the shaft in the 0 position, press the 'Reset pozycji' (position reset) button in order to reset counter values. This box contains the following information on the engine shaft position or motion:

- Licznik (counter)—recorded impulses,
- Ilość obrotów (number of rotations)—number of shaft rotations,
- Pozycja (position)—current position of the shaft in impulses,
- Pozycja kątowa (angle position)—current shaft angle position,
- Prędkość (speed)—number of impulses recorded in 1 s during shaft motions.

Assessment of thermal cycle energy performance

Measurements during the tests were carried out on the basis of engineering parameters at points selected in accordance with presented simulation calculations. The test results indicate an optimal structure of the device at maximisation of the performance, optimal energy generation efficiency and maximum durability of the structural components. For thermal cycle energy performance assessment on the test stand.

External characteristics of the engine—Fig. 7—was prepared on the basis of power records in the engine rotation functions, using strain gauges of the water brake and the impulse counter connected to the engine elements.

Its technical order was calculated, taking into account the values of parameters defining subsequent states according to the 'i-s' chart indications (Fig. 5).

– state 1—inlet steam to the engine

$$\text{Pressure}\,(p_1) = 350\,\text{bar}$$
$$\text{Temperature}\,(t_1) = 650\,^\circ\text{C}$$
$$\text{Specific enthalpy}\,(i_1) = 3556\ \text{kJ kg}^{-1}$$

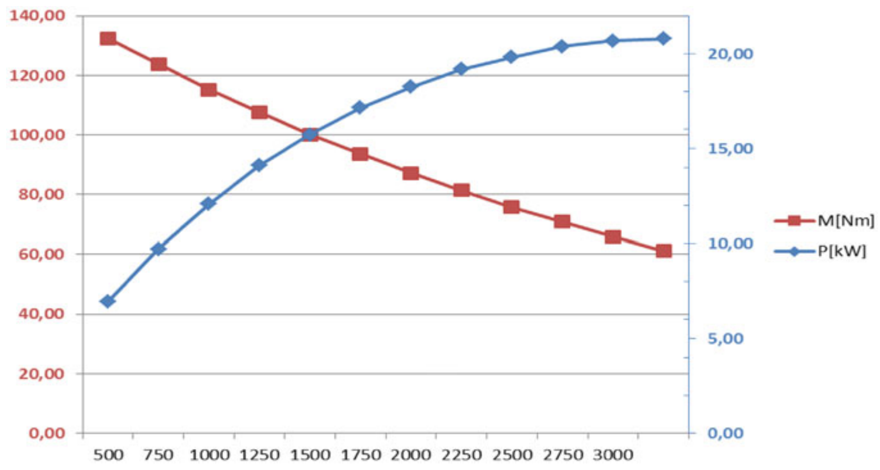


Fig. 7 External characteristics

– state 2—steam after decompression in the engine:

$$\begin{aligned}&\text{Pressure }(p_2) = 0.2\,\text{bar}\\&\text{Temperature }(t_2) = 70^\circ\text{C}\\&\text{Specific enthalpy }(i_2) = 2120\ \text{kJ kg}^{-1}\end{aligned}$$

– state 4—steam condensate:

$$\begin{aligned}&\text{Pressure }(p_3) = 350\,\text{bar}\\&\text{Temperature }(t_3) = 700^\circ\text{C}\\&\text{Specific enthalpy }(i_3) = 2514\ \text{kJ kg}^{-1}\end{aligned}$$

The η technical order of the cycle was determined using the below formula:

$$\eta = \frac{i1 - i2}{\text{i1} - \text{i4}} = \frac{3556 - 2120}{3556 - 251.4} = 0.434, \tag{10}$$

The efficiency value should be considered high. It is higher than the Diesel engine efficiency. The efficiency grows to 0.452 is pressure in the condenser is further reduced. An essential components in the cycle thermal balance is the discharged Q_2 heat which equals:

$$\begin{aligned}&Q_2 = i_2 - i_3,\\&Q_2 = 2292 - 421.2 = 1870.8\ \text{kJ kg}^{-1}\end{aligned} \tag{11}$$

Assuming that 86% of the discharged heat is recovered, the general efficiency of the cogeneration system will be:

$$\eta_o = \frac{\text{Lt}\,1 - 2 + 0.86\text{Q2}}{\text{Q1}}, \tag{12}$$

$$\eta_o = \frac{(i_1 - i_2) + 0.86\text{Q2}}{\text{i}_1 - \text{i}_3}, \tag{13}$$

$$\eta_o = \frac{(3556 - 2292) + 0.861870.8}{3556 - 421.2} = 0.92, \tag{14}$$

3 Summary and Conclusions

Following the tests, the design team carried out an overall analysis of the same, in which the presented technology was compared with other technologies [1–6, 34–36, 39–49], taking into consideration economic and performance parameters. The results of the tests conducted allowed for improvement of the structural assumptions.

With the research performed, it was possible to obtain a micro combined heat and power system and a structure of an injection valve which fulfils the desirable functions and ensures proper engine operation as demonstrated by the developed engine characteristics. The average engine shaft power above 20 kW was obtained, which—at 45 kW of power taken from the mains by the steam generator—guarantees the expected general efficiency at 44%. According to the estimates, 45% of heat generated by exhaust steam coming from the engine can be recovered with the steam regeneration system. This increases the general efficiency of the micro combined heat and power system to 89%.

Scientific and practical objectives have been achieved by solving defined research (study) problems within the following aspects: original and effective test method for a steam piston engine under supercritical steam conditions; identification of mechanical engineering variables for preparation of fuel, combustion and conversion of obtained energy to the end usable form. The test plan covered optimisation of energy cogeneration technology process variables (highly-efficient, low-emission combustion, effective heat and electric power cogeneration), on the basis of the model applied (relations between the phenomena and processes), finding such design conditions to ensure the expected quality of a product (q_R), e.g. in incineration of primary and post-consumer biomaterials, post-consumer polymer and fibrous plastics (BNE) of proper performance (W_R) and minimum unit power consumption necessary to prepare a charge (E_R) in the conversion process.

References

1. Dowkontt, J.: Teoria silników cieplnych. WKiŁ, Warszawa (1973)
2. Zagórski, J.: Zarys techniki cieplnej. WNT, Warszawa (1971)
3. Ochęduszko, S.: Termodynamika stosowana. WNT, Warszawa (1970)
4. Szargut, J.: Termodynamika techniczna. PWN, Warszawa (1991)
5. Staniszewski, B.: Termodynamika. PWN, Warszawa (1982)
6. Knizia, K.: Die thermodynamik des Dampkraftprozesses. Springer Verlag, Berlin (2010)
7. Golec, T., Rakowski, J., Świrski, J.: Perspektywy postępu technicznego w wytwarzaniu energii elektrycznej przy wykorzystaniu węgla kamiennego, węgla brunatnego oraz gazu ziemnego z uwzględnieniem efektu środowiskowego. Instytut Energetyki, Warszawa (2003)
8. Li, X., Kininmont, D., Le Pierres, R., Dewson, S.J.: Alloy 617 for the high temperature diffusion—bonded compact heat exchangers. Proceedings of ICAPP 2008, Anaheim, CA USA, June 8–12 (2008)
9. Flizikowski, J., Mroziński, A., Tomporowski, A.: Active monitoring as cognitive control of grinders design. AIP Conf. Proc. **1822**, 020006 (2017)
10. Flizikowski, J, Topoliński, T, Opielak, M, Tomporowski, A, Mroziński, A.: Research and analysis of operating characteristics of energetic biomass micronizer. Eksploatacja i Niezawodność—Maintenance and Reliability, vol. 17, no 1, str. 19–26 (2015)
11. Rataj, Z.L., Walewski, A.W., Wojnar, W.B.: Badania oraz wariantowa analiza techniczna rozwiązań koncepcyjnych kotłów pyłowych na parametry nadkrytyczne z paleniskiem niskoemisyjnym—wybór technologii odsiarczania i odazotowania spalin, oraz utylizacji odpadów paleniskowych. Politechnika Śląska, IMUE, Gliwice (1998)
12. Kotlicki, T., Pawlik, M.: Innowacyjne technologie węglowe dla ograniczenia emisji CO_2. Rynek Energii nr 3 (2011)
13. Kacejko, P.: Inżynieria elektryczna i informatyczna w nowych technologiach elektroenergetycznych. Nowoczesna Edukacja, Lublin (2011)
14. Skorek, J., Kalina, J.: Gazowe układy kogeneracyjne. WNT, Warszawa (2005)
15. Piętak, A.: Studium możliwości wykorzystania silników o obiegu Stirlinga do kogeneracyjnych agregatów zasilanych biopaliwami. IMP PAN, tom 33 Gdańsk (2013)
16. Fu, J., Liu, J., Ren, C., Wang, L., Deng, B., Xu, Z.: An open steam power cycle used for IC engine exhaust gas energy recovery. Energy **44**, 544–554 (2012)
17. Fu, J., Liu, J., Ren, C., Xu, Z., Ren, C., Deng, B.: A combined thermodynamic cycle based on methanol dissociation for IC (internal combustion) engine exhaust heat recovery. Energy **55**, 778–786 (2013)
18. Ayhan, V.: Theoretical and experimental investigation of diesel engine with steam injection system on performance and emission parameters. Appl. Therm. Eng. **54**, 161–170 (2013)
19. Hassan, M.H.: Technologies to recover exhaust heat from internal combustion engines. Renew. Sustain. Energy Rev. **16**, 5649–559 (2012)
20. Parlak, A.: Investigation of the effects of steam injection on performance and emissions of a diesel engine fuelled with tobacco seed oil methyl ester. Fuel Process. Technol. **116**, 101–109 (2013)
21. Wang, T., Zhang, Y., Shu, C.: A review of researches on thermal exhaust heat recovery with Rankine cycle. Renew. Sustain. Energy Rev. **15**, 2862–2871 (2011)
22. Franco, A., Diaz, A.R.: The future challenges for clean coal technologies: joining efficiency increase and pollutant emission control. Energy **34**, 348–354 (2008)
23. Garcia, R.F.: Efficiency enhancement of combined cycles by suitable working fluids and operating conditions. Appl. Therm. Eng. **42**, 25–33 (2012)
24. Wenzhi, G., Junmeng, Z., Guanghua, B., Liming, F.: Performance evaluation and experiment system for waste heat recovery of diesel engine. Energy **55**, 226–235 (2013)
25. Vaja, I., Gambarotta, A.: Internal Combustion Engine (ICE) bottoming with Organic Rankine Cycles (ORCs). Energy **35**, 1084–1093 (2010)

26. Schuster, A., Karellas, S., Aumann, R.: Efficiency optimization potential in supercritical Organic Rankine Cycles. Energy **35**, 1033–1039 (2010)
27. Lewandowski, M.: Proekologiczne źródła energii odnawialnej. WNT, Warszawa (2002)
28. Pikoń, K., Stelmach, S.: Współczesne problemy energetyki. Archiwum Gospodarki Odpadami i Ochrony Środowiska, Gliwice (2013)
29. Rataj, Z.L., Walewski, A.W., Wojnar, W.B.: Badania oraz wariantowa analiza techniczna rozwiązań koncepcyjnych kotłów pyłowych na parametry nadkrytyczne z paleniskiem niskoemisyjnym—wybór technologii odsiarczania i odazotowania spalin, oraz utylizacji odpadów paleniskowych. Politechnika Śląska, IMUE, Gliwice (1998)
30. Chochowski, A.: Energia. Difin, pp. 86–87 (2012)
31. Wiser, W.H.: Energy Resources. Springer-Verlag, New York (2000)
32. Paska, J.: Wytwarzanie energii elektrycznej. Oficyna Wydawnicza PW, Warszawa (2005)
33. Zandian, A., Ashjaee, M.: The thermal efficiency improvement of a steam Rankine cycle by innovative design of a hybrid cooling tower and a solar chimney concept. Renew. Energy **51**, 465–473 (2013)
34. Shipley, A., Hampson, A., Hedman, B., Garland, P., Bautista, P.: Combined heat and power effective energy solutions for a sustainable future. Elsevier, Energy Efficiency and Renewable Energy (2008)
35. San Martín, J.I., Zamora, I., San Martín, J.J., Aperribay, V., Eguía, P.: Trigeneration Systems with Fuel Cells. Power **40**, 65–85 (2008)
36. Babus'Haq, R.F., Pearson, J.P., Probert, S.D., O'Callaghan, P.W.: Economics of mini-combined heat-and-power packages for use in hotels. Heat Recovery Syst. CHP **10** (3), 269–75 (1990)
37. Evans, R.D.: Environmental and economic implications of small-scale CHP. Energy Policy **21**, 79–91 (1990)
38. Orchard, W.: CHP demonstration scheme reduces CO2 emissions by 73 percent. Energy Manag. 20–21 (1990)
39. Badr, O., Naik, S., O'Callaghan, P.W., Probert, S.D.: Expansion machine for a low power-output steam Rankine-Cycle Engine. Appl. Energy **39**, 93–116 (1991)
40. Badr, O., O'Callaghan, P.W., Hussein, M., Probert, S.D.: Multi-vane expanders as prime movers for low-grade energy organic Rankine-cycle engines. Appl. Energy **16**(2), 129–146 (1984)
41. Bahadori, M.N.: Solar water-pumping. Solar Energy **21**(4), 307–316 (1978)
42. Suri, R., Chandra, S., Kreshinamorthy, M.V., Srinivasamurthy, S., Berndorfer, K., Hopmann, H., Wolf, D.: Development of small power-plants in rural areas in India. Proc. ISES Congress, pp. 1722–1727 (1978), New Delhi
43. Lorenz, J., Fuestel, J., Kraft, M.: New developments for future solar-power plants. In: Proceedings of International Syrup: Workshop on Solar Energy, pp. 1318–1328, Cairo (1978)
44. O'Callaghan, P.W., Wood, R.J., Bell, M.A., Hussein, M., Patel, R.M., Buick, T.R., Probert S. D.: Optimization of a multi-vane expander as the prime mover in an organic Rankine cycle. Final report of Contract No. EEB/1/121/80/UK/H, Commission of European Communities (1983)
45. O'Callaghan, P.W., Bell, M.A., Wood, R.J.: The development of heat-engine driven heat-pumps. Final Report of Contract No. GR/B/75334, SERC, UK (1984)
46. O'Neill, P.: Development of the screw compressor and its application in the petrochemical and related industries. In: Proceedings of the Fluid Machinery for the Oil, Petrochemical and Related Industries Conference Paper, No. C48/81, 24–26 March 1981, The Hague, Netherlands. Mechanical Engineering Publications, London, pp. 1–13 (1981)
47. Badr, O., Naik, S., O'Callaghan, P.W., Probert, S.D.: Wankel engines as steam expanders: design considerations. Appl. Energy **40**, 157–170 (1991)

48. Badr, O., Naik, S., O'Callaghan, P.W., Probert, S.D.: Rotary Wankel engines as expansion devices in steam Rankine-cycle engines. Appl. Energy **39**(1), 59–76 (1991)
49. Antonelli, M., Martorano, L.: A study on the rotary steam engine for distributed generation in small size power plants. Appl. Energy **97**, 642–647 (2012)
50. http://www.asiapacificpartnership.org/pdf/PGTTF/events-october-06/24%20-%20New%20Gen%20Strategy%20Ultra-Supercritical%20Technlgy.pdf

The Visualization of Combustion Air Flow that Flows into the Dendromass Combustion Process Using CFD Simulations

Alexander Čaja, Štefan Papučík, Marek Patsch and Nikola Kantová

Abstract The air quality significantly affects the state of the environment, human health as well as individual ecosystems, and biomass burning contributes significantly it. The European Union is pushing on regulations of boiler manufacturers in order to reduce the emission concentration. Due to this, manufacturers improve, modify and innovate their products, reduce emissions and also increase the efficiency of the boilers. This research focuses on a particular type of wood-blowing boiler. Many factors directly or indirectly affect the burning quality, which enter the process of incinerating solid dendromass. The distribution of combustion air is one of the factors affecting efficiency and emissions in a small heat sources [1]. The experimental boiler has a supply of primary air to the chamber with wood and the supply of secondary air to the combustion chamber for combustion of the formed wood gas. During the operation of the boiler, uneven wood burning-of and the solid residue were found. Therefore, combustion in such a boiler is less efficient and produces higher emissions. Therefore, it is necessary to analyze the air flow in a particular combustion plant [2]. The actual distribution of combustion air to the dendromass incineration process is impossible to detect by real-time measurement and therefore a suitable alternative of his detection is CFD simulation, which used to optimize the distribution of combustion air in a small heat source [3]. In the first stage, the analyses of the combustion air distribution were performed under various input conditions and consequently the optimization measures of the combustion air distribution were solved. The CFD simulation data will be analyzed using non-invasive visualization measurements using the PIV method in further research.

A. Čaja (✉) · Š. Papučík · M. Patsch · N. Kantová
Department of Power Engineering, Faculty of Mechanical Engineering,
University of Žilina, Univerzitna 1, 010 26 Žilina, Slovakia
e-mail: alexander.caja@fstroj.uniza.sk

Š. Papučík
e-mail: stefan.papucik@fstroj.uniza.sk

M. Patsch
e-mail: marek.patsch@fstroj.uniza.sk

N. Kantová
e-mail: nikola.kantova@fstroj.uniza.sk

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_3

Keywords Combustion · Dendromass · CFD simulation · Mathematical simulation

1 Introduction

Biomass is increasingly used as a renewable source in industrial and domestic heat production facilities. The European Union is pushing on producers of small heat sources to reduce the formation of emissions and increase the efficiency during biomass combustion. The development is needed in this field in order to achieve the required emission and heat power parameters [4]. There are many aspects, which influence the biomass combustion. One of the most important aspects is the distribution of combustion air in a gasification boiler. The numerical simulation is effective tool to analyze combustion air distribution, since production and experimental measurement are financial and time-consuming [5].

2 Numerical Simulation

Analysis was carried out in the Ansys program on 12 areas in gasification and also combustion space of the heat source with various inlet air settings into a heat source in the range from 10 to 150 $m^3 h^{-1}$.

The analysis of the combustion air distribution in the investigated heat source was realized on a 3D model (see Fig. 1), where the mesh of approximately 7,000,000

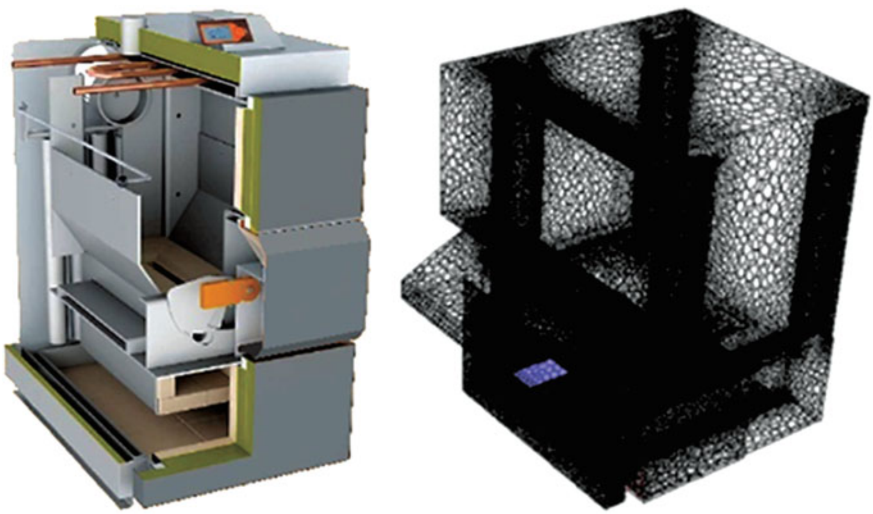


Fig. 1 3D and mathematical model of small heat source

elements was generated and then optimized. The object was simulated by the k-ε model, in which standard wall functions and basic lifting effects were set [6].

3 Results

Initial data analyses already show an asymmetrical and unequal distribution of the speed profile. In Fig. 2 is shown the overall course of the airflow distribution in the 3D model and it is easy to identify areas with the higher airflow velocity [7].

Figure 3 shows the cross-sections, which have a vertical direction through the center of the heat source with various inlet airflow settings. When the fan was set on a flow rate of 10 $m^3 h^{-1}$, the combustion air velocity was up to 0.9 $m s^{-1}$ in the combustion chamber space and in the air distribution section. It can be observed that a larger change of velocity occurred with a flow rate of 40 $m^3 h^{-1}$, where the air velocity in the mentioned areas increased in the range from 2.8 to 4.6 $m s^{-1}$. The largest change of combustion air velocity was with the volume flow rate of 90 $m^3 h^{-1}$, where the velocity in the air distribution area and the combustion chamber reached a maximum value of 6 $m s^{-1}$. In the area of redistribution, the air is affected by Coanda effect, is kept on the wall, where the highest velocity is also reached. With an increasing velocity, the airflow is carried from the back part of the boiler to the center in the gasification space, and then is pulled into the nozzle in the front part.

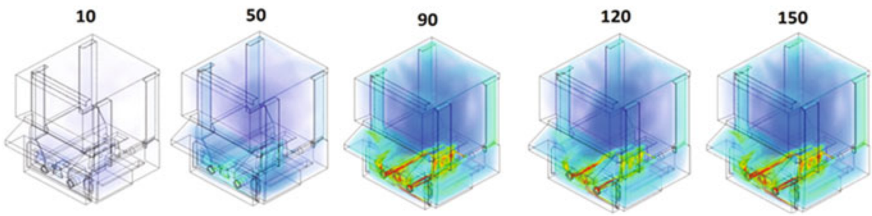


Fig. 2 Distribution of combustion air

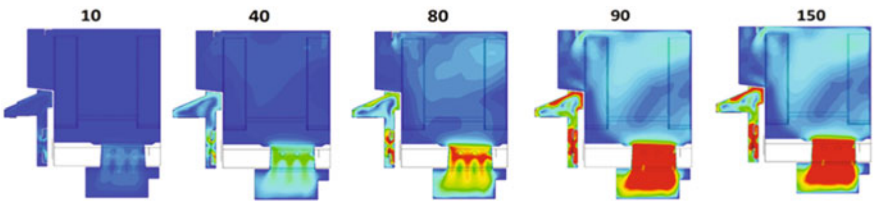


Fig. 3 Vertical cuts through the center of the 3D model

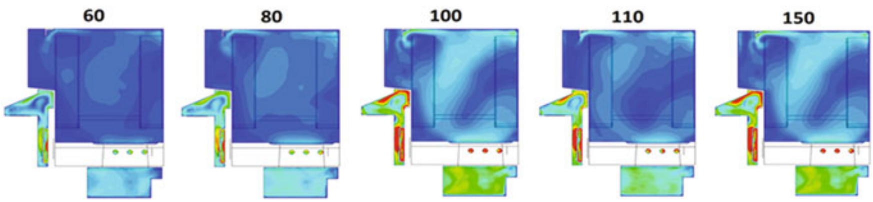


Fig. 4 Vertical cuts in the left part of the 3D model

In the following vertical sections, it is possible to see a change during the setting of the fan on a flow rate of 80 m^3 h^{-1} in the area of the air distribution and at the entrance of the secondary air into the space. It is noticeable that the air flows faster along the wall, about 5 m s^{-1} and rises to a value from 9 to 11 m s^{-1} in the lower part. In the area of secondary air inlet, there is stream velocity from 4 to 5 m s^{-1}. It can be seen that in the back inlet of the secondary air into the nozzle, the stream is carried at the highest speed (see Fig. 4). In the gasification chamber can observed that air distribution is again directed from the back to the center part and enters into the combustion chamber in the front part, in the case of flow rate 100 m^3 h^{-1}. In the combustion chamber, the airflow is uniform with a velocity about 4 m s^{-1}.

In the vertical cuts on the right part of the numerical model is observed larger change in flow velocity with a flow rate of 60 m^3 h^{-1} and again in the air distribution area, where the value is from 4 to 5.5 m s^{-1}. In the area of the combustion chamber is velocity around 1.5 m s^{-1}. The distribution is carried along the wall due to Coanda effect. Other significant changes in velocity is recorded in the fan setting with a flow rate of 100 m^3 h^{-1}. In the area of the gasification chamber, the air is distributed from the back part of the boiler forward and it is twisted down into the combustion chamber. There is increased stream velocity to 6 m s^{-1} in the area of secondary air inlet by increasing the flow rate.

In the horizontal cut of the heat source combustion chamber, a significant change in velocity occurred in the fan setting on a volume flow rate of 90 m^3 h^{-1}. The air velocity reached maximum at the center of the chamber and the value was from 2 to 8 m s^{-1}. It is noticeable that the air is equally distributed and flows into the center of the chamber and farther is reflected from the bottom part to the sides.

The change of velocity in the four primary air nozzles, which distribute the air into the gasification chamber, can be seen on the horizontal cut in the lower part of the gasification chamber. A significant change in velocity can be recorded with a flow rate of 90 m^3 h^{-1} in the nozzle of primary air. The value of flow air velocity is in the range from 4 to 5.5 m s^{-1}. It can be seen that the largest amount of air is in the right front nozzle.

In the horizontal cuts (see Fig. 5), which are located in the central part of the gasifying chamber, was observed the air distribution in the center of the gasification chamber and the velocity up to 2.3 m s^{-1}. In the case of flow rate of 130 m^3 h^{-1}, it can be seen that the largest air distribution is again in the right front nozzle of primary air and the velocity is about 6 m s^{-1}. In the area of air distribution, there is

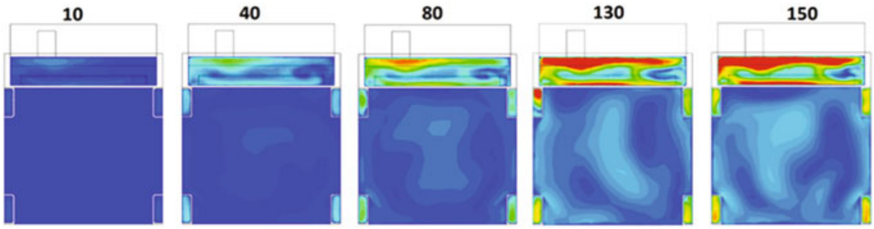


Fig. 5 Horizontal cuts in bottom part of gasification chamber

air flow oriented on the right side. The significant changes in fan velocity setting on a flow rate of 90 m^3 h^{-1} were recorded in vertical cuts that are oriented through the left horseshoe through the primary air inlet. The air distribution is again carried along the wall. The gasification chamber shows that the air flows from the back side of the boiler to the center gradually decreases. In the middle, it deflects back into the back of the chamber. In the area of primary air inlet to the nozzle, there is no significant deviation and flow is uniform there. The air velocity ranges from 1.8 to 4.2 m s^{-1}.

In vertical cuts, which are located over the right horseshoe, was observed the highest change of combustion air flow velocity with a flow rate of 90 m^3 h^{-1} in the air distribution area. The air distribution is again carried along the wall and gradually enters the nozzles. In the gasification chamber, the air is centered on the center and is evenly distributed. Gradually, it decreases lower and slightly deviates on the back side of the boiler. Air velocity in the air distribution area is 6 m s^{-1}. It is possible to see how the velocity decreases during transition to the chamber.

Figure 6 shows a vertical cut, which is directed in the back part of the heat source that passes through the back part of secondary air inlet to the bottom nozzle and also through bottom nozzles, where the primary air flows. The most noticeable change in air velocity is observed in fan setting for flow rate of 90 m^3 h^{-1}. The highest velocity is recorded in the bottom nozzle with the velocity of 6 m s^{-1}. In the gasification chamber, there is seen air deviation on the right side. In nozzles of secondary air, the stream is evenly distributed. Bottom air nozzle shows the highest

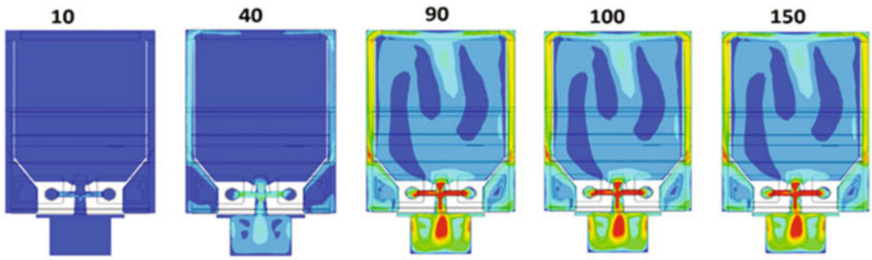


Fig. 6 Vertical cuts in bottom part of heat source

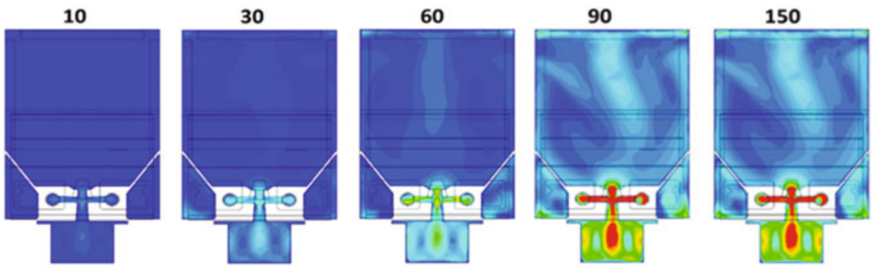


Fig. 7 Vertical cuts in bottom part of heat source made central secondary air intake

air velocity, but the distribution is slightly deviated on the right side. In the combustion chamber, the air flow is centered on the center and it deviates evenly into the sides in the lower part.

On the vertical cuts (see Fig. 7) in the back part of the heat source done by the central inlet of secondary air to the lower nozzle, during the setting for flow rate on 90 m^3 h^{-1}, the highest change of velocity is observed in the lower nozzle area and the combustion chamber. It can be seen that a larger amount of flowing air is located in the right part of the nozzle. In the gasification chamber, the distribution of air is slightly deflected from the center to the right. In the combustion chamber, it is again seen that more air is flowing to the right. The velocity in the nozzle and center of the chamber is 6 m s^{-1}. The vertical sections which are oriented in the back part of the heat source done by the front inlet of the secondary air into the lower nozzle have a similar course like the previous cross sections. Air deflection is realized on the right side. In the combustion chamber, the flow of the stream is more uniform than in the middle or back part of the nozzle inlet. In the case of fan setting for flow rate of 90 m^3 h^{-1}, the highest change of velocity is again reached and a value of this is up to 6 m s^{-1} in the lower nozzle and mid-section of the combustion chamber. In the area of gasification, there is no significant change in velocity, but the deviation of the distribution is again led slightly to the right. In vertical cuts in the front part of the heat source, which are made through the secondary air inlet, during already of a 50 m^3 h^{-1}, there is recorded a slight change of velocity in secondary air inlets, where the value is from 2.3 to 3.7 m s^{-1}. The distribution of airflow is relatively uniform. The dramatic change of velocity is occurred again during a volume flow rate of 90 m^3 h^{-1}, where the velocity reached a maximum value of 6.0 m s^{-1}. In the gasification chamber, it can be seen that the air is deviated from the center to the right side. In the area of secondary air inlet into the nozzle, there is no large displacement, and the distribution of the combustion air equilibrium is almost optimal [8].

4 Conclusion

Introductory numerical simulations of a 3D combustion air distribution model in an experimental boiler showed lack of combustion air distributions that can cause defects during combustion of dendromass by the gasification. For instance, the incomplete combustion of fuel in the corners of the gasification chamber lead to unequal distribution of the flowing air therein, or in the poor distribution of the secondary and primary air into the gasification nozzle [9]. These imperfections in the combustion air distribution degrade the quality of the combustion of dendromass by the gasification process in the investigated boiler. In the next stage, verification measurements will be realized on the designed and constructed experimental device using the noninvasive visualization method PIV—particle image velocimetry. Based on numerical simulations and verification measurements, optimization of the combustion air distribution will be carried out on the considered small heat source.

Acknowledgements This work has been supported by the project VEGA 1/0864/16/7 "Analysis and optimization of the factors entering into the process of burning dendromass in small heat sources".

References

1. Holubčík, M., Nosek, R., Jandačka, J., Palacka, M.: Using of local heat sources with warm-water heat exchanger for combustion of wood biomass in low temperature heating systems, Key Eng. Mater. **688,** s. 59–64 (2016). ISSN 1013-9826
2. Nosek, R., Holubčík, M., Jandačka, J., Vician, P.: Formation of emission from combustion of biomass in small heat source. Key Eng. Mater. **688**, s. 65–73 (2016). ISSN 1013-9826
3. Mičieta, J., Vondál, J., Jandačka, J., Lenhard, R.: Optimization principle of operating parameters of heat exchanger by using CFD simulation. In: EPJ Web of Conference, vol. 114, art. no. 02074 (2016)
4. Vantúch, M., Kaduchová, K., Lenhard, R.: The impact of municipal waste combustion in small heat sources. In: The Application of Experimental and Numerical Methods in Fluid Mechanics and Energy 2016. American Institute of Physics Publishing (2016)
5. Ďurčanský, P., Lenhard, R., Jandačka, J.: Comparison of mathematical models for heat exchangers of unconventional CHP units. Acta Polytech. J. Adv. Eng. **55**(4), s. 223–228 (2015)
6. Lenhard, R., Mičieta, J., Jandačka, J., Gavlas, S.: Specifics of phytomass combustion in small experimental device, In: EPJ Web of Conference, vol. 92, art. no. 02047 (2015)
7. Lenhard, R., Kaduchová, K., Jandačka, J.: Numerical simulation of indirectly heated hot water heater. Adv. Mater. Res. **857–877**, s. 1693–1697. (2014). ISSN 1022-6680
8. Galletti, Ch., Parente A., Tognotti, L.: Numerical and experimental investigation of a mild combustion burner [online]. Combust. Flame **151,** 649–664 (2007)
9. Fan, J.R., Liang, X.H., Xu, Q.S., Zhang, X.Y., Cen, K.F.: Numerical simulation of the flow and combustion processes in a three-dimensional, w-shaped boiler furnace [online]. Energy **22**(8), 847–857 (1997)

Possibility of Using Energy Crops for Phytoremediation of Heavy Metals Contaminated Land—A Three-Year Experience

Marta Pogrzeba, Jacek Krzyżak, Szymon Rusinowski, Anja Hebner, Kathrin Kopielski, Sebastian Werle and Izabela Ratman-Kłosińska

Abstract Heavy metal soil contamination is a worldwide problem. The affected sites could be either sites of a former industrial activity or arable land located in their vicinity. The presence of heavy metals in excessive quantities renders these sites idle or underused due to contamination and lack of efficient ways to remediate. Phytoremediation driven energy crops production may be a promising alternative for the management of these sites. A four year field experiment has been established on heavy metal (HM) contaminated sites located in Bytom, Upper Silesia Industrial Region, Southern Poland (arable land) and Leipzig, Germany (post-industrial site). The objective for this experiment was to distinguished energy crop species optimal with respect to both: energy crop yield and phytoremediation potential. The testing involves the following pre-selected plant species: miscanthus (*Miscanthus* x *giganteus*), virginia mallow (*Sida hermaphrodita*), cordgrass (*Spartina pectinata*), and switchgrass (*Panicum virgatum*). The experimental trials were established in May 2014. Both sites were treated as follows: (i) K—Control, no treatment;

M. Pogrzeba (✉) · J. Krzyżak · S. Rusinowski · I. Ratman-Kłosińska
Institute for Ecology of Industrial Areas, 6 Kossutha St, 40-844 Katowice, Poland
e-mail: m.pogrzeba@ietu.pl

J. Krzyżak
e-mail: j.krzyzak@ietu.pl

S. Rusinowski
e-mail: s.rusinowski@ietu.pl

I. Ratman-Kłosińska
e-mail: i.ratman-klosinska@ietu.pl

A. Hebner · K. Kopielski
Business Unit BioPlanta, Vita 34 AG, Deutscher Platz 5, 04103 Leipzig, Germany
e-mail: anja.hebner@vita34.de

K. Kopielski
e-mail: kathrin.kopielski@vita34.de

S. Werle
Institute of Thermal Technology, The Silesian University of Technology,
22 Konarskiego St, 44-100 Gliwice, Poland
e-mail: Sebastian.Werle@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_4

(ii) NPK—NPK standard fertilization, applied to the soil before the experiment; (iii) INC—Commercial microbial inoculum Emfarma Plus®, ProBiotics Poland. The presented data were collected after the third growing season; heavy metal uptake for each of the species and experimental options were determined. Levels of the bioavailable content of heavy metals in the soil seem to be the main factor responsible for the differences in the metal uptake by the plants. Plant species cultivated at the German site were characterized by low metal concentration in shoots, except *P. virgatum* which accumulated a high amount of zinc, even if the bioavailability of this metal in soil was low. The highest lead uptake was observed for *M.* x *giganteus* and *P. virgatum*, while the highest cadmium content was found for *S. hermaphrodita* grown on a contaminated arable soil in Bytom. Cultivation of energy crops on HM contaminated areas could be a solution for remediating these sites while increasing their economic value.

Keywords Phytoremediation · Energy crops · Heavy metals

1 Introduction

Due to the poor sustainability of heavy industries and overexploitation of resources in the second half of the 20th century, a significant proportion of arable land in Poland (~0.9 Mha) is considered contaminated with heavy metals and thus unsuitable for food and feed production [1]. According to the Institute of Soil Science and Plant Cultivation (IUNG) in Poland, it was found that slightly more than ca 2% of the agricultural land in the provinces of the Upper Silesia, Lower Silesia and Lesser Poland are contaminated with heavy metals to a degree greater than 1 (scale 0–5) [2]. The presence of elevated, and sometimes high content of heavy metals in soils [3] has been also observed in the areas where land are used for other purposes than agriculture.

The European Environmental Agency [4] draws attention to “new reclamation techniques” based on plants strongly accumulating metals, which may lead to a reduction of heavy metal content in soils and at the same time help reduce the costs of remediation. However, as indicated in the report, the possibility of applying these methods and their effectiveness are rather limited due to long time of land reclamation by such techniques. Therefore they will rather not deliver a rapid and radical reduction of the surface of the historically contaminated areas. However the attractiveness of phytoremediation can be significantly enhanced if combined for example with energy crops production.

One of the key criteria for success when planning site remediation with the use of plants is the choice of appropriate plants and the goal of the remediation *i.e.* phytoextraction or phytostabilisation. For the soil clean up purpose the species should be characterised by the ability to accumulate high amounts of heavy metals in the above-ground parts. On the contrary, for the phytostabilisation plants with limited ability to extract and accumulate heavy metals from soil should be considered. In both cases however the production of a satisfactory biomass yield is important.

Energy crops seem to demonstrate features making them useful for both phytoextraction and/or phytstabilisation pruposes. Studies on polluted and unpolluted soils conducted by Institute for Ecology of Industrial Areas (IETU) over the last ten years, have revealed that the uptake of metals by energy crops (*e.g. Miscanthus* x *giganteu*s, *Panicum virgatum* and *Sida hermaphrodita*) is dependent on the level of HM bioavailable forms in soil [5, 6]. For example, *M.* x *giganteus* and *S. hermaphrodita* grown on contaminated soils can accumulate up to 150 and 4 mg Pb kg^{-1}, 14 mg and 5.2 Cd kg^{-1}, 700 and 1200 mg Zn kg^{-1} respectively [5, 6].

A four year field experiment has been carried out on heavy metal contaminated sites located in Poland (arable land) and in Germany (former sewage sludge dewatering site). It involves testing of 4 preselected plant species: miscanthus (*M.* x *giganteus*), virginia mallow (*S. hermaphrodita*), cordgrass (*Spartina pectinata*), and switchgrass (*P. virgatum*) to find the optimum one with respect to both energy crop yield and phytoremediation capacity. Differences between the test sites as well as the differences between heavy metal concentration in shoots of investigated plant species after the third year of the experiments are presented.

2 Materials and Methods

2.1 Site Description

The Polish test site is located in the Upper Silesian Industrial Region, on the outskirts of Bytom (50° 20′ 43.0″N 18° 57′ 19.6″E)—an industrial city about 15 km from Katowice, in the proximity of a large closed down lead and zinc works, consisting of the ore mining, enriching and smelting facilities. This metallurgical complex was in operation for more than 100 years and contributed significantly to the contamination of the local soils. During the last 30 years the area was used for agricultural purposes. Recently the land has been used for cultivation of grain crops, especially for wheat production. Soil contamination with lead, cadmium and zinc in this area exceeds permissible limits for agricultural soil in Poland.

The German site is a former sewage sludge dewatering site, located in the north of Leipzig (51° 25′ 23.7″N 12° 21′ 56.2″E). The history of this site is directly related to the main sewage plant of the city. The sewage sludge dewatering site and the sewage plant are located in the distance of about 9 km from each other, operated as one unit from 1952 to 1990. During this time the sewage sludge resulting from municipal and industrial wastewater treatment was pumped to the dewatering site. In 1990 the operation of the dewatering site was abandoned and up to this time about 800,000 tons of sewage sludge remained in several basins.

2.2 Experiment Design

Based on the experience of IETU gained from previous investigations with energy crop species, four plant species were selected for the field trials: miscanthus (*M.* x *giganteus*), virginia mallow (*S. hermaphrodita*), cordgrass (*S. pectinata*), and switchgrass (*P. virgatum*). Experimental plots (16 m^2 each) were established in spring 2014 at each of the test sites. Between the plots a 4 m buffer zone was left to avoid interconnection between experimental variants. Due to apprehension of uncontrolled fertilizer application pseudo-replications were performed. On each plot four sections were distinguished: edge plants excluded from further analysis and three sections (pseudo-replication within one plot) from which samples were taken. Plots were treated in a different way as described in Table 1.

2.3 Chemical Analyses of Soil and Plant Samples

Data on soil characteristics were collected before the start of the experiment. For site characterization three composite soil samples per plot (from the depth of 0–20 cm) were collected and analysed. Physical and chemical soil properties such as: soil texture, pH, EC, content of organic matter, total metal concentration (*aqua regia* extraction) and bioavailable fractions of heavy metals ($CaCl_2$ extraction) were analysed.

Table 1 Experimental variants/soil treatments

Variant	Code	Treatment	Description
1	C	No additives	Control plot
2	NPK	NPK standard fertilization	Ammonium sulphate and Polifoska—4% N, 22% P_2O_5, 32% K_2O—calculation based on specific plant requirements, applied once before plant establishment: – *M.* x *giganteus*—nitrogen 70 kg ha^{-1}, phosphorus 30 kg ha^{-1} as P_2O_5 and potassium 45 kg ha^{-1} as K_2O; – *S. hermaphrodita*—nitrogen 100 kg ha^{-1}, phosphorus 80 kg ha^{-1} as P_2O_5 and potassium 120 kg ha^{-1} as K_2O; – *S. pectinata* and *P. virgatum*—nitrogen 80 kg ha^{-1}, phosphorus 50 kg ha^{-1} as P_2O_5 and potassium 75 kg ha^{-1} as K_2O
3	INC	Inoculum addition	Commercial microbial inoculum (EmFarma Plus™, ProBiotics Polska Magdalena Górska, Poland). Microbial inoculum consisting of: Lactic Acid Bacteria >3.0 × 105 CFU ml^{-1}, Yeast <1.0 × 106 CFU ml^{-1}, and Purple Non-Sulfur Bacteria >1.0 × 104 CFU ml^{-1} in molasses suspension. It was applied on seedlings roots before plantation establishment and on the leaves as aerosol in the middle of every month during the growing seasons (from May to September 2014, 2015, 2016)

Soil pH was measured in H_2O (1:2.5 m/v) with a glass/calomel electrode (OSH 10-10, METRON, Poland) and a pH-meter (CPC-551, Elmetron, Poland) at 20 °C. The conductivity was determined by an ESP 2ZM electrode (EUROSENSOR, Poland) according to the Polish standard [7].

Soil texture was evaluated using a hydrometric method, according to the Polish standard [8]. The content of bioavailable forms of metals was obtained using extraction with 0.01 M $CaCl_2$. Extraction was conducted with 3 g of air-dried and sieved soil and 30 ml 0.01 M $CaCl_2$ for 2 h.

Plant samples for HM concentration in shoots were collected from three randomly selected plants on each plot which was not exposed to the edge effect. Plant samples were washed, cut and oven-dried at 70 °C, milled and digested using concentrated nitric acid in a microwave system (MDS 2000, CEM, USA). Concentrations of metals both in soil and plants were measured with flame atomic absorption spectrophotometry (Varian Spectra AA300).

2.4 Data Analysis

Data reported in this paper were analyzed using a three-way and one-way ANOVA, followed by a post hoc comparison using the Fisher LSD test ($P < 0.05$). Statistical analyses were performed using Statistica 12 (Statsoft, USA). Spider charts were constructed using Excel MS Office (Microsoft, USA) on standardized data. Standardization of HM concentration in shoots was performed using Statistica 12 Software (Statsoft, USA).

3 Results and Discussion

3.1 Soil Characteristics at the Experimental Sites

Soil characteristics at the experimental sites are presented in Table 2. Soil texture on the experimental field at Polish site was classified as silty loam. The pH-value was almost neutral, followed by a moderate content of organic matter and low electric conductivity. Lead and cadmium contamination levels in soil from the Polish site ranged from 362.3 to 639.1 and 13.69 to 26.29 mg kg^{-1} d.w., respectively. For zinc the range was about 1300—2498 mg kg^{-1} d.w. The results showed that the HM content in soil exceeded the limits defined by the government regulation [9]. Total lead and cadmium concentration exceeded the limits set in the regulation 4 to 6-fold, whereas the total zinc concentration exceeded the limits 4 to 7-fold [9]. The level of bioavailable forms of cadmium and zinc were relatively high (about 5 and 2.5% respectively), whereas bioavailability of lead was below the detection limit.

Table 2 Soil characteristics from experimental site

Parameter	Polish site	German site
pH (1: 2.5 soil/KCl ratio)	5.94–6.55	6.19–6.50
Electrical conductivity (μS/cm)	77–117	484–1495
Organic matter content (%)	4.0–7.08	28.3–39.7
Sand (1–0.05 mm) (%)	28	58
Silt (0.05–0.002 mm) (%)	56	19
Clay (< 0.002 mm) (%)	16	23
Total heavy metal concentration (extraction with aqua regia*)*		
Pb (mg kg^{-1})	362.3–639.1	474.0–686.0
Cd (mg kg^{-1})	13.69–26.29	25.70–36.39
Zn (mg kg^{-1})	1300–2498	2974–4044
$CaCl_2$ extractable metal fraction[a]		
Pb (mg kg^{-1})	BDL	BDL
Cd (mg kg^{-1})	0.349–1.928	0.220–0.460
Zn (mg kg^{-1})	9.26–112.47	3.45–25.60

[a]—extraction with 0.01 M $CaCl_2$
BDL—below detection limit

For the German site, the soil is classified as sandy loam, the pH-value is neutral, followed by high (33%) level of organic matter and electric conductivity, due to upper layer of soil build up by dewatered and decomposed sewage sludge. For the German site lead and cadmium levels in soil ranged from 474.0 to 686.0 and 25.70 to 36.39 mg kg^{-1} d.w., respectively. In case of zinc, the range was between 2974 and 4044 mg kg^{-1}. The bioavailability of metals in soil was very low, mainly due to high level of organic matter (Pb below detection limit, Cd 0.25 mg kg^{-1} d.w. and Zn 16 mg kg^{-1} d.w.). Sewage sludge at the former sludge dewatering site was remediated using phytoremediation. One of the best monitored full-scale phytoremediation projects in Europe. Today the heavy metal content is below limits in terms of use as demonstration site with limited access (not open to the public). The total concentration of investigated HM on German site are at the similar level when compare to Polish site and also exceed the limits prescribe in the Polish regulation [9].

With regards to the contents of heavy metals and their bioavailability both Polish and German site should be classified as marginal. Moreover the agricultural production at Polish and German site should be abandoned [10].

3.2 Heavy Metals in Biomass After the Third Growing Season

Heavy metal accumulation in plant organs depends on different factors *e.g.* HM content in soil (site factor), ability of plants to accumulate HM (plant factor), and plant growth which can be improved by the application of soil amendments (treatment factor) [11–13]. As the obtained results showed, beside the mentioned factors, each of the tested plants has a different natural ability to selectively uptake of Pb, Cd and Zn (Table 3). Moreover HM concentration in the soil, especially the level of bioavailable HM has also a high impact on the HM concentration (particularly Pb and Zn) in plant shoots. Fertilization influenced only Zn uptake in plant shoots. In addition, the combined effect of site and treatments did not influence the HM concentrations in the shoots. It had also no influence on Pb concentration in shoots similarly as the combined effect of factors such as site, species and treatment.

Spider charts (Fig. 1) were used as a tool to assess the values pattern changes of the measured parameters in the above ground organs of the tested plant species among different treatments after third growing season for each site separately. The charts can be divided into three representative sections: Pb concentration in shoots of each tested species (*M.* x *giganteus*, *S. hermaphrodita*, *P. virgatum* and *S. pectinata*) (1), Cd concentration in shoots of each tested species (2) and Zn concentration in shoots of each tested species (3). Significant differences in HM concentration in shoots of the tested species and the applied treatment for each site are presented in Tables 4 and 5, respectively.

It was found that for plants grown on the control plot (C) at the Bytom site *P. virgatum* had the highest Pb concentration in shoots. Significantly lower and equal values were found for *S. pectinata* and *M.* x *giganteus* while the lowest value was found for *S. hermaphrodita*. The Pb accumulation in the fertilized experimental variants at the Bytom site showed the same tendencies as in control. The results obtained for the Leipzig site showed no significant differences of Pb concentration in shoots between species, additionally the same tendency was observed for the fertilized plants. In the case of Cd concentration in the shoots of the control plants cultivated at the Bytom site, the highest values were found for *S. hermaphrodita*, other investigated species had lower Cd concentration in shoots and there were no significant differences in those values between them. The same pattern was observed for the inoculum treated plants, however for the NPK fertilized plants *S. pectinata* had lower Cd concentration in shoots when compared to *M.* x *giganteus* and *P. virgatum*. Variations between the Cd concentration in plant shoots cultivated at the Leipzig site were different when compared to those observed in the plants grown at the Bytom site. The highest value of Cd accumulation on control plots was found for *M.* x *giganteus*, while the rest of the plants accumulated comparable amounts of Cd. Fertilization significantly affected the differences between Cd concentration in shoots of the tested species. Chemical fertilization resulted in the same range of Cd accumulation in *M.* x *giganteus*, *S. hermaphrodita* and *P. virgatum* plants, however *S. pecitnata* showed significantly lower values of Cd

Table 3 Significance of the factor and/or a combination of factors influencing HM uptake to above-ground plant parts of energy crops

	Site	Species	Treatment	Site × Species	Site × Treatment	Species × Treatment	Site × Species × Treatment
Pb	0.0000*	0.0000*	0.3047	0.0000*	0.9156	0.7966	0.2205
Cd	0.3673	0.0000*	0.0552	0.000*	0.0795	0.0357*	0.0080*
Zn	0.0000*	0.0000*	0.0003*	0.0000*	0.1294	0.0000*	0.0000*

Values are probabilities that investigated factor or factors combination had significant effect on heavy metals concentration in plants shoots. Probabilities were obtained using two-way ANOVA at $P \leq 0.05$

* Significant differences among factors

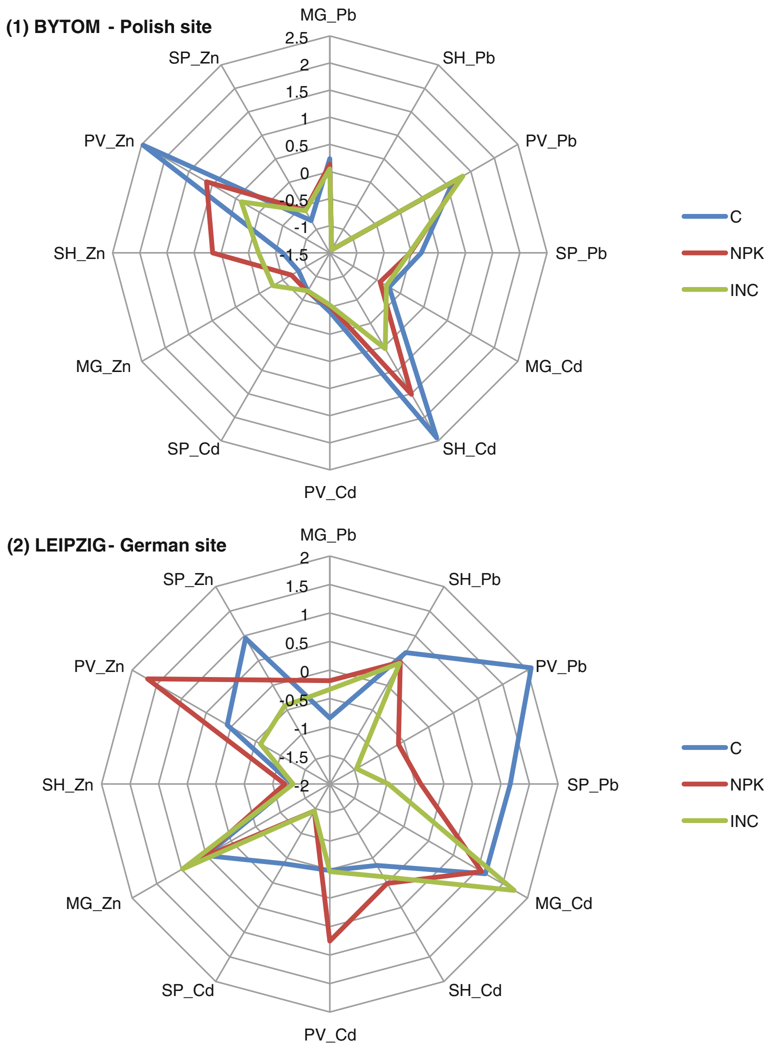


Fig. 1 Spider charts constructed on heavy metals concentrations in shoots show patterns of differences between tested species (MG—*Miscanthus* x *giganteus*; SH—*Sida hermaphrodita*; PV—*Panicum virgatum* and SP—*Spartina pectinata*) and treatments (C—control, NPK—NPK fertilizer treated plant, INC—microbial inoculum treated plant) on Bytom (1) and Leipzig (2) site after third growing season (2016). Pb, Cd, Zn—heavy metal concentration in above ground plant organs. For better data visualization all presented values were standardized. Each measurement was performed in 3 replicates (n = 3)

concentration in shoots compared to the other experimental variants. Microbial inoculation of plants cultivated at the Leipzig site showed similar pattern to this obtained for control plants with the exception of *S. pectinata* which had lower Cd concentration in shoot compared to *S. hermaphrodita* and *P. virgatum*.

Table 4 Matrix of statistical significant differences among analyzed parameters presented on spider charts: differences between tested plant species (Fig. 1)

		Bytom site				Leipzig site			
		MG	SH	PV	SP	MG	SH	PV	SP
C	Pb	b	c	a	b	a	a	a	a
	Cd	b	a	b	b	a	b	b	b
	Zn	b	b	a	b	ab	c	b	a
NPK	Pb	b	c	a	b	a	a	a	a
	Cd	b	a	bc	c	a	a	a	b
	Zn	b	a	a	b	b	c	a	b
INC	Pb	b	c	a	b	a	a	a	a
	Cd	b	a	b	b	a	b	b	c
	Zn	b	b	a	b	a	c	b	b

MG—*Miscanthus* x *giganteus*; SH—*Sida hermaphrodita*; PV—*Panicum virgatum*; SP—*Spartina pectinata*
C—control; NPK—NPK fertilized plants, INC—microbial inoculated plants
A lower case letter (a, b, c—where “a” corresponds to the highest value and “c” to the lowest) denotes significant differences among heavy metals concentration in plant shoots taken from different plots at $P \leq 0.05$ according to Fisher LSD test. Each measurement was performed in 3 replicate (n = 3)

Table 5 Matrix of statistical significant differences among analyzed parameters presented on spider charts: differences between applied treatments (Fig. 1)

		Bytom site			Leipzig site		
		C	NPK	INC	C	NPK	INC
MG	Pb	a	a	a	a	a	a
	Cd	a	a	a	a	a	a
	Zn	b	ab	a	a	a	a
SH	Pb	a	a	a	a	a	a
	Cd	a	a	a	a	a	a
	Zn	b	a	b	a	a	a
PV	Pb	a	a	a	a	b	b
	Cd	a	a	a	a	a	a
	Zn	a	ab	b	b	a	a
SP	Pb	a	a	a	a	a	a
	Cd	a	a	a	a	b	b
	Zn	a	a	a	a	b	b

MG—*Miscanthus* x *giganteus*; SH—*Sida hermaphrodita*; PV—*Panicum virgatum*; SP—*Spartina pectinata*
C—control; NPK—NPK fertilized plants, INC—microbial inoculated plants
A lower case letter (a, b,—where “a” corresponds to the highest value and “b” to the lowest) denotes significant differences among heavy metals concentrations in plant shoots taken from different plots at $P \leq 0.05$ according to Fisher LSD test. Each measurement was performed in 3 replicate (n = 3)

Concentration of Zn in shoots for control plants cultivated at the Bytom site was the highest for *P. virgatum*. The values of this parameter obtained for other tested species were not significant. Similar results were found for the inoculated plants cultivated at the Bytom site. Plant exposed to the fertilizer showed the highest values for *P. virgatum* as in control and for *S. hermaphrodita*. Other tested species had equal and significantly lower values of Zn concentration in shoots. Data obtained for the Leipzig site concerning Zn concentration in shoots showed different effects for each of the treatments. For control plots, the highest Zn concentration in shoots was found for *S. pectinata* and *M.* x *giganteus*, in addition it was found that there were no significant differences between the accumulation of Zn in *M.* x *giganteus* and *P. virgatum*. The lowest values on control plots were found for *S. hermaphrodita*. In the case of fertilization, the highest Zn accumulation was found for *P. virgatum* shoots. The values obtained for *M.* x *giganteus* and *S. pectinata* were equal and lower compared to *P. virgatum*. The lowest Zn concentration in shoots was found for *S. hermaphrodita*. Microbial inoculation caused the highest Zn concentration in shoots of *M.* x *giganteus* while the lowest was found for *S. hermaphrodita*. Accumulation of Zn in *P. virgatum* and *S. pectinata* shoots was significantly higher compared to *S. hermaphrodita* and much lower compared to *M.* x *giganteus*. In addition, the results presented on the spider chart constructed for plants cultivated at the Leipzig site (Fig. 1) show that the changes between the accumulation of Zn in shoots of *P. virgatum* and *S. pectinata* were mostly driven by the applied fertilizer and the response of those plants to the treatment considering the fact that the Zn concentration in shoots was species-specific.

The applied treatment had no influence on Pb concentration in shoot of *M.* x *giganteus*, *S. hermaphrodita* and *S. pectinata* at both investigated sites. However, data on *P. virgatum* plants cultivated at the Leipzig site show that both fertilizers caused lower Pb concentration in shoots compared to control. There were no differences in the Cd accumulation in shots between control and the plants treated with the fertilizers observed for each of the tested species cultivated at the Bytom site. Application of the fertilizers resulted in lower Cd concentration in *S. pectinata* shoots when cultivated on Leipzig site. All the tested species with exception of *S. pectinata* cultivated on Bytom site showed differences in Zn concentration in shoots under different fertilization treatment. *M.* x *giganteus* demonstrated the highest Zn concentrations in shoots when treated with the microbial inoculum, in addition the lowest Cd accumulation was found for control plants. There were no differences between Cd concentrations in shoots of the fertilized plants. In the case of *S. hermaphrodita* NPK fertilizer caused higher Zn concentration in shoots compared to the other experimental variants. Lower values of Zn concentration in *P. virgatum* shoots were found when plants were treated with fertilizers. In the case of plants cultivated at the Leipzig site fertilization did not affect Zn accumulation in *M.* x *giganteus* and *S. hermaphrodita*, however significantly lower and significantly higher values of this parameter were found for *S. pectinata* and *P. virgatum* treated with fertilizers, respectively. There is a dearth of information comparing those four energy crop species on HM contaminated sites, especially under field conditions. Korzeniowska and Stanisławska-Głubiak [14] performed plot experiment where

HM were introduced artificially. They compared accumulation of Cu, Ni and Zn in *M.* x *giganteus* and *S. pectinata* after the first and second growing season in above and below ground plant organs. *S. pectinata* showed higher suitability for phytoextraction of Zn compared to *M.* x *giganteus*. Our results indicate that after the third growing season *S. pectinata* accumulated more Zn than *M.* x *giganteus,* however in comparison to other plant species those differences are insignificant.

4 Conclusions

Among the tested plant species the highest Cd concentration in shoots was found for *S. hermaphrodita* and *M.* x *giganteus* grown at the Bytom and Leipzig site, respectively. The highest Pb concentration in shoots was found for *P. virgatum* originating from the Bytom site, while there were no differences in Pb accumulation among the investigated species grown at the Leipzig site. The highest Zn concentration in shoots was found for *P. virgatum* from the Bytom site, while for Leipzig site the highest values were found for *S. pectinata* and *M.* x *giganteus*. Treatments turned out to have no significant influence on Pb and Cd concentration in the shoots of the tested species. The Zn concentration in shoots of the tested species was differently affected by the treatments. *P. virgatum* and *S. pectinata* showed to be species which were the most sensitive to treatments, while considering HM concentration in shoots. The presented evaluations allow to identify the most suitable species, among investigated, for phytoextraction purposes, simultaneously indicating that the choice of proper species for phytoextraction or phytostabilisation is strongly site specific. When properly planned remediation approach on HM contaminated land using energy crops can be an effective solution for the environmental and economic restoration of such areas.

Acknowledgements Research financed by the PHYTO2ENERGY project—7FP EU, Grant Agreement No. 610797 and IETU statutory funds by Polish Ministry of Science and Higher Education.

References

1. Kucharski, R., Marchwińska, E., Gzyl, J.: Agricultural policy in polluted areas. Ecol. Eng. **3**, 299–312 (1994)
2. Maliszewska-Kordybach, B., Smreczak, B., Klimkowicz-Pawlas, A.: Threats of chemical pollution of soils in agricultural areas in Poland in the light of IUNG-PIB Puławy studies. Studia i Raporty IUNG-PIB Zeszyt **35**(9), 97–118 (2013). (in Polish)
3. Karczewska, A., Kabał, A.C.: The soils polluted with heavy metals and arsenic in Lower Silesia—the need and methods of reclamations. Zesz. Nauk. UP Wroc. Rol. XCVI, Nr **576**, 59–80, (2010). (in Polish)
4. European Environment Agency EEA.: The European environment—state and outlook, Copenhagen (2005)

5. Pogrzeba, M., Rusinowski, S., Sitko, K., Krzyżak, J., Cieślińska, K., Małkowski, E., Ciszek, D., Werle, S., McCalmont, J.P., Mos, M., Kalaji, H.M.: Relationships between soil and selected physiological parameters of *Miscanthus* x *giganteus* cultivated on arable land contaminated with heavy metals under different fertilization. Env. Poll. **225**, 163–174 (2017)
6. Pogrzeba, M., Krzyżak, J., Rusinowski, S., Werle, S., Hebner, A., Milandru, A.: Case study on phytoremediation driven energy crop production using *Sida hermaphrodita*. Int. J. P| hytoremediat. (2017). (in press)
7. PN-ISO 11265:1997 Soil quality—determination of electrical conductivity. (in Polish)
8. PN-R-04032:1998—Soil and mineral pieces—soil sampling and texture assessment (in Polish)
9. D.2002. nr.165 poz.1369—Regulation of the Polish Ministry of Environment on Soil and Ground Standards. (in Polish)
10. Gopalakrishnan, G., Cristina, N.M., Snyder, S.W.: A novel framework to classify marginal land for sustainable biomass feedstock production. J. Environ. Qual. **40**, 1593–1600 (2011)
11. Meers, E., Van Slycken, S., Adriaensen, K., Ruttens, A., Vangronsveld, J., Du Laing, G., Witters, N., Thewys, T., Tack, F.M.G.: The use of bio-energy crops (Zea mays) for 'phytoattenuation' of heavy metals on moderately contaminated soils: a field experiment. Chemosphere **78**, 35–41 (2010). https://doi.org/10.1016/j.chemosphere.2009.08.015
12. Mench, M., Lepp, N., Bert, V., Schwitzguébel, J.P., Gawronski, S.W., Schröder, P., Vangronsveld, J.: Successes and limitations of phytotechnologies at field scale: outcomes, assessment and outlook from COST Action 859. J. Soils Sediments **10**, 1039–1070 (2010)
13. Quintela-Sabarísa, C., Marchand, L., Kidd, P.S., Friesl-Hanl, W., Puschenreiter, M., Kumpiene, J., Müller, I., Neu, S., Janssen, J., Vangronsveld, J., Dimitriouh, I., Siebielec, G., Gałązka, R., Bert, V., Herzig, R., Cundy, A.B., Oustrière, N., Kolbasa, A., Galland, W., Mench, M.: Assessing phytotoxicity of trace element-contaminated soils phytomanaged with gentle remediation options at ten European field trials. Sci. Total Environ. **599–600**, 1388–1398 (2017)
14. Korzeniowska, J., Stanisławska Głubiak, E.: Phytoremediation potential of *Miscanthus* X *giganteus* and *Spartina pectinata* in soil contaminated with heavy metals. **22**(15), 11648–11657 (2015)

The Formation of Particulate Matter During the Combustion of Different Fuels and Air Temperatures

Nikola Kantová, Radovan Nosek, Michal Holubčík and Jozef Jandačka

Abstract Particulate matter (PM) belongs to significant pollutants threatening human health. Therefore, it is important to pay attention on these solid emissions. Several factors, such as type of fuel, quantity and temperature of the combustion air, operation conditions and design of heat source etc., influence on their formation. The aim of this work is investigation of fuel type and various inlet air temperatures on PM formation. The above mentioned parameters were measured in wood stove. In the first stage of the research, there were measured following fuels: beech, spruce wood, birch with bark and birch without bark. The results show that higher PM concentrations were measured during the combustion of birch with bark. The outcome of these analyses is the negative effect of bark on PM formation. In the second stage, there was investigated the effect of different combustion air temperatures on PM formation. Based on the measured results, it can be concluded, that temperature of combustion air has not influence on PM concentration, but it has influence on heat power.

Keywords Particulate matter · Fuels · Combustion · Air temperature

N. Kantová (✉) · R. Nosek · M. Holubčík · J. Jandačka
Faculty of Mechanical Engineering, Department of Power Engineering,
University of Žilina, Univerzitna 1, 010 26 Žilina, Slovakia
e-mail: nikola.kantova@fstroj.uniza.sk

R. Nosek
e-mail: radovan.nosek@fstroj.uniza.sk

M. Holubčík
e-mail: michal.holubcik@fstroj.uniza.sk

J. Jandačka
e-mail: jozef.jandacka@fstroj.uniza.sk

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_5

1 Introduction

Epidemiology studies have shown a clear correlation between the particle concentration in the air and severe health effects on human being [1]. Particles less than 2.5 μm, also named respirable particles, can penetrate deep into human lungs, deposit in the alveolus, and may be transported to systemic apparatus or tissue leading to various health problems [2]. Due to PM health effects, there is a need to decrease the particle from combustion. Because the mechanisms of the health effects are not yet known exactly, studying PM properties is important. Properties of PM are dependent on combustion conditions [3, 4].

There are two main sources of such particles from small-scale biomass combustion:

- Particles from incomplete combustion, including soot, condensable organic particles (tar), and char.
- Particles from the inorganic material in the fuel-ash [5].

The most important parameters for complete combustion conditions are a high combustion temperature, a sufficient amount of combustion air supply, and adequate mixing of combustion air and fuel gas [6]. The combustion temperature affects primarily the burn out of combustion compounds. The oxidation reactions are faster and more complete, and the combustion time shorter in high temperatures than at low ones [3]. Janusz A. Koziriski and Raafat Saade investigated impact of fuel type on soot formation. There were used biomass fuels included paper-mill residue, hard pine-wood and particle board. But they found out that soot formation process was most extensive during the combustion of the particle board and hard pine-wood, where the highest combustion temperatures were obtained. It appears possible that the higher temperatures stimulated the sooting tendency, by intensifying biomass pyrolysis and the rate of conversion of the gas precursors to soot [7].

2 Experimental Measurements

For experimental measurements, there was used wood stove with nominal heat power 9 kW.

In the first stage of the research, there were measured following fuels: beech, spruce wood, birch with bark and birch without bark. Each measurement took 1 h and there was combusted 1.5 kg of fuel. For sampling of PM, there was used an impactor in a measuring track of chimney. Sampling took 30 min and it was realized by gravimetric method. Particles were collected from flowing stream of combustion gases and caught on a membrane filter. During sampling, there was ensured isokinetic condition.

In the second stage of research was investigated the effect of different combustion air temperatures on PM formation. Beech wood was used like a fuel. The

Fig. 1 **a** Impactor. **b** Experimental setup

air was supplied into combustion chamber with following temperatures: −5; 0; 5; 10; 15; 20; 25; 30; 35 and 40 °C. Sampling took 30 min and it was also realized by the impactor with gravimetric method.

During the measuring, there were not reported unusual events which could influence the results (Fig. 1).

3 Results

The Fig. 2 shows results of the particulate matter concentration from combustion of different fuels. It is possible to see, that higher PM concentrations were measured during the combustion of birch with bark and lower PM concentrations were measured during the combustion of birch without bark.

The concentration of particulate matter from combustion of different air temperatures are shown in the Fig. 3. It is noticeable, that the highest PM

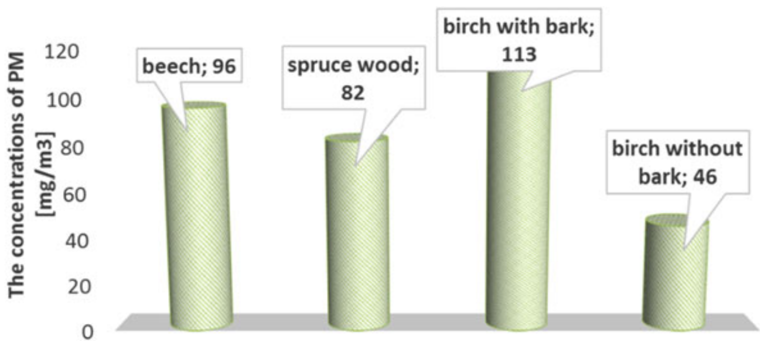


Fig. 2 The concentration of PM from combustion of different fuels

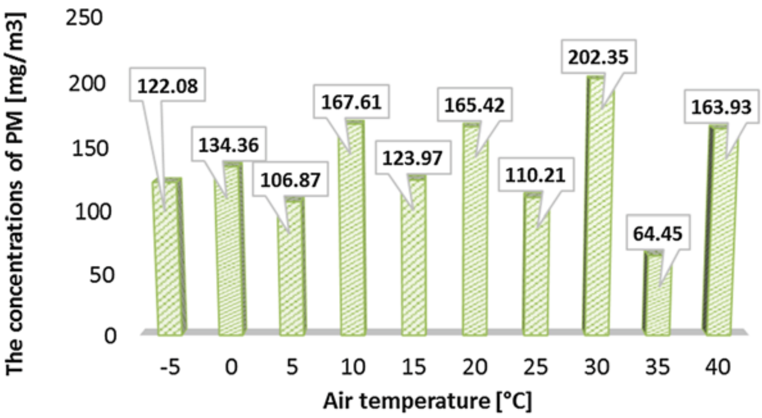


Fig. 3 The concentration of particulate matter from combustion of different air temperatures

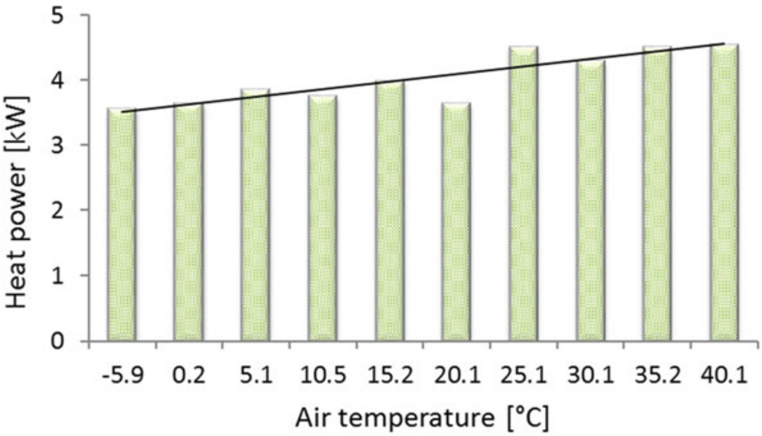


Fig. 4 The impact of air temperature on heat power

concentrations were measured during combustion with 30 °C and the lowest PM concentrations were measured during combustion with 35 °C.

It was found out that temperature of combustion air has not influence on PM concentration, but it has influence on heat power, which is shown in the Fig. 4. Based on the results can be concluded that raising the temperature of combustion air has positive effect on the heat power increase. A dependence between heat power and air temperature is called continual proportion.

The Fig. 5 shows the profile of heat power depending on time. This dependence was created for selected air temperature of −5; 25 and 40 °C. According to results can be noticed the heat power decreases gradually with decreasing amount of fuel.

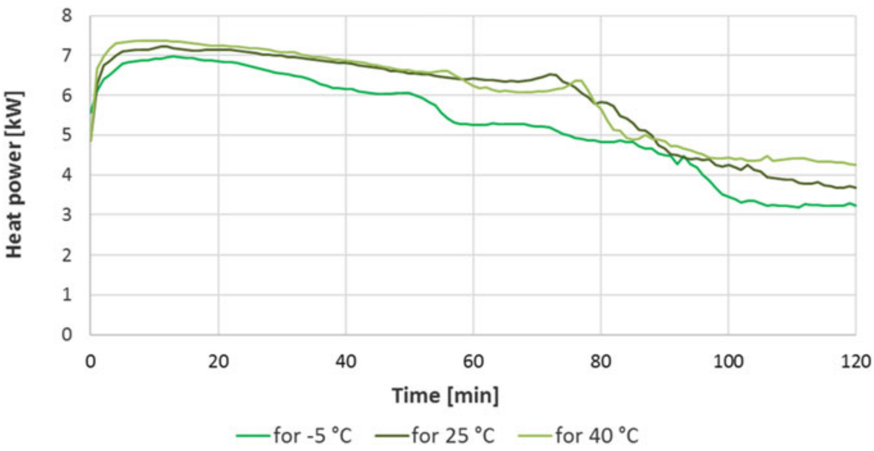


Fig. 5 The dependence of heat power on the time

4 Conclusion

The worldwide effort, as well as the aim of this article, is to reduce PM concentration. Therefore, it is important to know and also apply optimal combusted conditions for their minimum formation.

The purpose of this research was investigation of fuel type and various inlet air temperatures on PM formation. These factors were analyzed on experimental setup consisting of wood stove and analyzers. The measured results show, that bark has a negative effect on PM formation, which means the increase of PM concentration in the flue gases. Furthermore, there was examined the effect of combustion air temperature. There was found out negligible influence of various air temperature on PM concentration. According to measurement, it is noticeable that the air temperature has influence on heat power. Heat power increases with increasing air temperature, but decreases with decreasing amount of fuel. It can be caused by larger amount of fuel, which is consumed for heating of cold air.

Acknowledgements This work has been supported by the project KEGA 046ŽU-4/2016 “Unconventional systems using renewable energy”.

References

1. Nigusie, K.G.: Reduction of fine particle and deposit forming alkali by co-combustion of peat with wood pellets in 150 kWth grate firing boiler. [online]. Master's thesis
2. Guan, L., Harvel, G., Parl, S., Chang, J.S.: Dust flow separator type electrostatic precipitator for a particulate matter emission control from natural gas combution. [online]

3. Tissari, J.: Fine particle emissions from residential wood combustion. [online]. Doctoral dissertation (2008)
4. Vantúch, M., Jandačka, J., Čaja, A.: Emission production from the incineration of municipal waste and coal in heat sources for solid fuel. Appl. Mech. Mater. **832**, 18–22 (2016)
5. Johansson, L.S., Tullin, C., Leckner, B., Sjovall, P.: Particle emissions from biomass combustion in small combustors. [online]. Biomass Bioenerg. **25**(4), 435–446 (2003)
6. Van Loo, S., Koppejan, J. (eds.): Handbook of biomass combustion and co-firing. Twenty University Press, Enchede (2008)
7. Koziriski, J.A., Saade, R.: Effect of biomass burning on the formation of soot particles and heavy hydrocarbons. An experimental study. [online]. Fuel **77**(4), 225–237 (1998)

Increasing the Efficiency of the Process of Burning Wheat Straw in a Central Heat Source by Application of Additives

Matej Palacka, Peter Vician, Jozef Jandačka and Michal Holubčík

Abstract Straw belongs to heavier combustible fuels as it has low ash melting temperature. This article discusses the properties and effects of various additives suitable for application to straw in order to increase the ash melting temperature. From the laboratory-determined results of the application of various additives, the most suitable additive was chosen to improve the process of incinerating wheat straw in real conditions. This additive was calcium oxide. Testing of the additive was carried out in real conditions on operation of drying system situated near Nové Zámky. The drying system receives the heat from burning straw bales on the heat source. In the combustion process there are various problems due to the low melting temperature of ash straw. For this reason, slags and deposits occur in different parts of the combustion chamber and on the heat exchanger. These deposits must be removed at regular intervals, which cause heat source shutdown and drying. Addition of the additive on the surface of the straw bait was performed manually. The influence of additives on slags formation, thermal performance and emission production were measured during the experiment The results of additive testing have confirmed the positive effect of calcium oxide on the efficiency of the straw burning process.

Keywords Straw · Additive · Low melting temperature · Calcium oxide

M. Palacka (✉) · P. Vician · J. Jandačka · M. Holubčík
Faculty of Mechanical Engineering, Department of Power Engineering,
University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia
e-mail: matej.palacka@fstroj.uniza.sk

P. Vician
e-mail: peter.vician@fstroj.uniza.sk

J. Jandačka
e-mail: jozef.jandacka@fstroj.uniza.sk

M. Holubčík
e-mail: michal.holubcik@fstroj.uniza.sk

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_6

1 Introduction

Straw [1, 2], agricultural crops are an important and promising source of biomass for energy purposes. In terms of straw burning is the most important feature of its quick and easy gassability. Another feature of the straw is that the ash formed by the low melting minerals, especially potassium carbonate, calcium carbonate and the silica begins to soften at about 830 °C [3, 4]. Nevertheless at temperatures of 850–900 °C it is easily forming vitreous glass which not only damages the refractory of the furnace, but it is also difficult to remove. These problems have real objects on the world.

2 Solution Problems of Real Object

Solution is the use of agricultural cooperative near Nové Zámky dealing with growing, harvesting, processing and marketing of agricultural products. Treated here with the help of a drying various agricultural products such as rye, corn, peas, barley and many others. The agricultural cooperative (Fig. 1) used to be used for drying a gas dryer, but a few years ago decided to use the opportunity to build new more modern, leaner oven with boiler for combustion of biofuels, notably through the use of agricultural waste produced—phytomass in the form of straw. Cooperative given its farming has an excess of fuel is straw, and that is easy to process and storage, and can be obtained at relatively low cost, which are necessary for the collection and subsequent bundling.

Every year, the operation are approximately 3000 tons of high-quality cereal straw, which has different applications, of which 300 tons is used as fuel.

As a source of heat for drying crops are used boiler BIOLÁNG Kft—TSLB—20 (Fig. 2) with a rated thermal output of 2 MW, Combustion efficiency—86%, volume—127 m^3, weight—24,500 kg, insertion—manual (hydraulic arm) and control electromechanical.

Solution traffic drier crop usually has problems with low temperature melting behavior of ash straw burning and creating sinters to clog the grate combustion in the boiler area, as well as a boiler (Fig. 3).

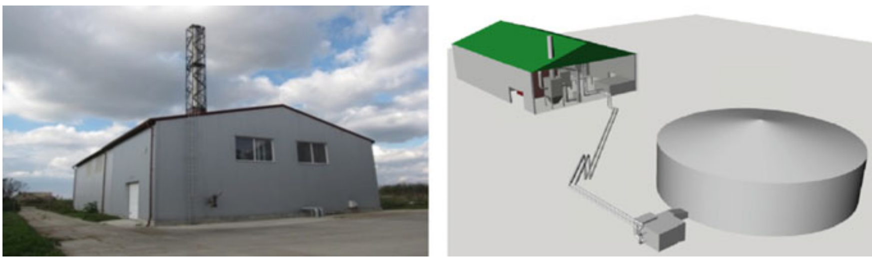


Fig. 1 The agricultural cooperative

Fig. 2 Boiler room

Fig. 3 Problems with low temperature melting behavior of ash

3 Application and Selection of the Additives

Given the results of experiments of various works [5–9] and low investment and operating costs proved to be the most appropriate method of reducing combustion problems phytomass use fuel additives prior to incineration. The most suitable additive to raise the temperature of the ash melting behavior of straw is calcium oxide (Fig. 4).

The addition of 2% of calcium oxide can increase the heat distortion temperature from the average temperature of 915 °C to the average temperature of 1193 °C. Calcium oxide is readily available, inexpensive and easy to apply. It is alkaline and corrosive white crystalline solid with ash flow temperature of 2572 °C. Its density

Fig. 4 Calcium oxide

is 3316 kg m^{-3}. Calcium oxide is typically produced by thermal decomposition of limestone rock containing calcium carbonate ($CaCO_3$). The decomposition is performed by calcination of finely ground rock to a temperature above 825 °C—the burning of limestone. It unwinds with the CO_2.

Methodology of the additives was carried out as follows: the addition of additives—calcium oxide was carried out at the heat generator with a rated thermal output of 2 MW for combustion of straw bales. The average weight per package is approximately 250 kg. The results of previous work it was found that sufficient amount of additive is 1% of the total weight of the straw bales. After a simple conversion was calculated required amount of calcium oxide, namely 2.5 kg per straw bales. With the help of the weight in the dish was weighed 2.5 kg of lime, which was then evenly spilled on top of the straw bales. Straw bales were subsequently burned in standard hot water boilers.

4 Results of the Experiments

The process of adding the additive to wheat straw in the form of calcium oxide has many advantages. A positive fact is also the creation of loose and fine ash. The results of the measurements showed an improvement in the process and the combustion process, which makes it possible to save two wheat straw bales a day. From the materials provided, the value of one stack of straw was calculated is 7.5 €. The institution can save 15 € for 24 h of operation.

The most important benefit is delaying the boiler shutdown in order to clean the heat exchanger and boiler space from slags and ash deposits. The average duration of use of the boiler for drying in the last years was 30 days. Shutdowns from the need to clean the boiler space and the exchanger of heat were necessary after 10 days of operation. This cleaning lasted approximately 2 days. Boiler use time has been significantly expanded up to about 30 days using calcium oxide as an additive. This means that the boiler does not need to be shut down during the whole operation. For this reason, the drying plant can dry a larger amount of material, which could otherwise be destroyed or degraded. An agricultural cooperative can dry about 200 tons of corn in 24 h. When they are forcibly shut down, they have unprocessed 400 tons of corn. The price per one ton of unprocessed maize is 90 €. Losses with a forced downtime amount to almost 36.000 €. This value represents a huge loss for an agricultural cooperative. Adding an additive could save some financial capital. The disadvantage of adding the additive is the cost associated with the purchase and transport of calcium oxide to the agricultural cooperative. The price of calcium oxide per pack weighing 40 kg is 5.52 €. When using 2.5 kg of additive on one straw stack, it will be enough 40 kg of calcium oxide for 16 stacks of straw. The average 24-h consumption with addition of the additive was 32 stalks of straw. The object needs two packages of calcium oxide for 24 h. The price of two packages of calcium oxide is 11.04 €. The table shows all costs and savings.

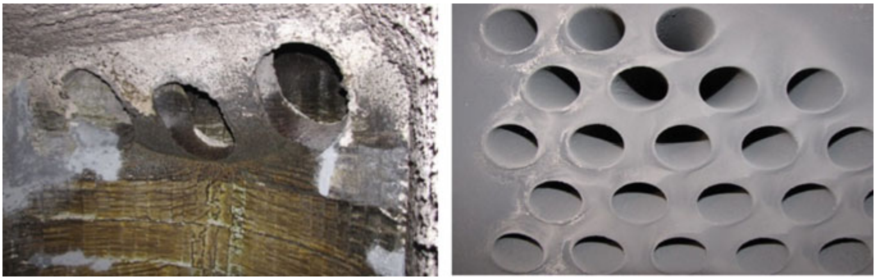


Fig. 5 Reducing the formation of slags

The total agricultural cooperative would be able to save 118.8 € when using calcium oxide. The tables show the costs and savings of the agricultural cooperative Table 1.

Table 1 The costs and savings of the agricultural cooperative

Season	Cost of additive in €	Saving packages in €	Consumption of packages in pieces	Saving packages in pieces	The resulting savings in €
1 day	11.4	15	32	2	3.95
7 days	77.28	105	224	14	27.72
30 days	331.2	450	960	60	118.8

The agricultural team has stacks of straw for free so in this case we do not make any savings. The total cost of using calcium oxide is 331.2 €. These costs are negligible compared to the amount the cooperative loses when the drying system is switched off. The results of additive addition can be seen on the picture (Fig. 5).

5 Conclusion

Based on experiments adding additives has eliminated problems with ash. The most important success is the prolongation of the operation without the necessity of shutdown due to the cleaning of the boiler and exchanger premises during the entire drying period. The agricultural cooperative can work longer and more efficiently without interrupting the work and next advantage is that the agricultural cooperative is able to increase its profit for drying of corn. Problems occurred when adding the additives to stacks of straw with uneven application. This problem could be solved by constructing a special device for uniform application of the additive to straw stacks. Question is the energy and economic aspect of how to use this special constructing device

Acknowledgements This work was supported by the projects APVV-15-0790 "Optimization of biomass combustion with low ash melting temperature".

References

1. Geffertova, J., Geffert, A.: Energy potential of the chosen wastes with biomass content, Acta Facultatis Xylologiae, **53**(1) (2011)
2. Soos, L., Kolejak, M., Urban, F.: Biomass—renewable energy source. Bratislava, Vert (2012). (in Slovak)
3. Chudíková, P., Taušová, M, Erdélyiová, K, Tauš, P.: Potential of dendromass in Slovak Republic and its actual exploitation in thermic economy. Acta Montanistica Slovaca, **15**(SPEC. ISSUE 2), 139–145 (2011)
4. Vitázek, I., Klúčik1, J., Mikulová1, Z., Vereš, P.: Effects on concentration of selected gaseous emissions at biomass combustion. AIP Conf. Proc. (2016)
5. Jenkins, B.M., Baxter, L.L., Miles Jr., T.R., Miles, T.R.: Combustion properties of biomass. Fuel Process. Technol. **54**, 17–46 (1998)
6. Dzurenda, L., Pňakovič, Ľ.: Quantification of the ash content from biofuel—wood according to ISO 1171 (2003) and EN 14775 (2010). Ann. Warsaw Univ. Life Sci. (2014)
7. Carnogurska, M., Prihoda, M., Koško, M., Pyszko, R.: Verification of pollutant creation model at dendromass combustion. J. Mech. Sci. Technol. (2012)
8. Haque, H., Somerville, M.: Techno-economic and environmental evaluation of biomass dryer. In: 5th BSME International Conference on Thermal Engineering, pp. 650–655 (2013)
9. Chabadová, J., Papučík, Š., Nosek, R.: Particle emissions from biomass combustion. AIP Proc. **1608**, 67–70 (2014)

Mathematical Model for Calculating Performance of Parabolic Through Collector

Peter Vician, Matej Palacka, Peter Ďurčanský and Jozef Jandačka

Abstract The work deals with the transformation of solar energy into thermal energy through concentric solar collector. The subject of the research is the parabolic trough collector situated in Žilina. Solar collector including focal absorber was produced according to our own design. The absorber consists of two black coated contradictory pipes serving as inlet/outlet of heat exchanger. The reflector is made of bent polished aluminium sheet. Collector uses automatic tracking system and consists of firm frame attached to concrete floor, which limits the sun tracking to one axis. Trough of the collector is oriented as east-west position with a small deviation of approximately 10°. To determine the required output of collector is necessary to perform optical and thermal analyses. The aim of the work is creating mathematical model to get a theoretical performance of collector. Mathematical model with calculations for specific collector and its geographical position is created in program MS Excel. Although the mathematical model provides theoretical performance parameters it doesn't include the effect of environment and so the values differ from real conditions. The results of work will serve as an information basis for the following research of cogeneration system using a solar collector.

Keywords Solar energy · Parabolic collector · Thermal analysis

1 Introduction

Solar energy is among the cheapest energy source available everywhere. It does not pollute the environment and contribute to the reduction of emission production. That is the reason for recent spent large amounts of money into research and development of equipment and components that use exactly this kind of energy. Technology using solar energy has the potential for commercial use. Use of solar energy can be accomplished in several ways. Photovoltaic panels are used for

---

P. Vician (✉) · M. Palacka · P. Ďurčanský · J. Jandačka
University of Žilina, Univerzitná 8215/1, 010 26 Žilina, Slovakia
e-mail: peter.vician@fstroj.uniza.sk

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_7

electricity generation. The heat energy can be obtained by through or flat thermal panels. By using concentric solar collectors we are able to convert solar energy into heat with higher added value.

The work deals with the transformation of solar energy into thermal energy through the concentric trough collector situated on building of University of Žilina. The collector was made according our own design. Due to its later modification and future application is essential to determine its performance parameters. For the purpose of obtaining preliminary results of collector performance parameters is necessary to understand the inner workings and laws of thermodynamics. Collector uses a single axis tracking system and its rotational axis is positioned in east-west orientation. The reflective surface is made from bended polished aluminium sheet with reflective foil. Thermal insulation of receiver is provided by vacuumed glass cover. The mathematical model for the mentioned collector will serve as an information basis for the following research of cogeneration system using a solar collector.

2 Parabolic Trough Collector

Parabolic trough collectors are low-cost technology systems with light structure which are able to deliver high temperatures up to 400 °C with good efficiency. They are considered as the most mature and advanced of the solar thermal technologies because of considerable experience with the systems and the development of a small commercial industry to produce and market these systems. It suffices to use a single-axis tracking of the sun; therefore, long collector modules are produced. The receiver of a parabolic trough is linear. Usually, a tube is placed along the focal line to form an external surface receiver. The size of the tube, and therefore the concentration ratio, is determined by the size of the reflected sun image and the manufacturing tolerances of the trough. The surface of the receiver is typically plated with a selective coating that has a high absorptance for solar radiation but a low emittance for thermal radiation loss. A glass cover tube is usually placed around the receiver tube to reduce the convective heat loss from the receiver, thereby further reducing the heat loss coefficient. A disadvantage of the glass cover tube is that the reflected light from the concentrator must pass through the glass to reach the absorber, adding a transmittance loss of about 0.9, when the glass is clean. The glass envelope usually has an antireflective coating to improve transmissivity. One way to further reduce convective heat loss from the receiver tube and thereby increase the performance of the collector, particularly for high temperature applications, is to evacuate the space between the glass cover tube and the receiver. The total receiver tube length of PTCs is usually from 25 to 150 m. New developments in the field of PTCs aim at cost reduction and improvements in technology. In one system, the collector mirrors can be washed automatically, drastically reducing the maintenance cost [1–3].

The thermal performance of solar collectors can be determined by the detailed analysis of the optical and thermal characteristics of the collector materials and collector design or by experimental performance testing under controlled conditions. It should be noted that the accuracy of the heat transfer analysis depends on uncertainties in the determination of the heat transfer coefficients, which is difficult to achieve, due to the non-uniform temperature boundary conditions that exist in solar collectors. Such analysis is usually carried out during the development of prototypes, which are then tested under defined environmental conditions. In general, experimental verification of the collector characteristics is necessary and should be done on all collector models manufactured. In some countries, the marketing of solar collectors is permitted only after test certificates are issued from accredited laboratories to protect the customers [1–3].

2.1 Optical Analysis

Concentrating collectors work by interposing an optical device between the source of radiation and the energy-absorbing surface. Therefore, for concentrating collectors, both optical and thermal analyses are required. For optical analysis we first must define the term concentration ratio which is a ratio of the aperture area to the receiver–absorber area. For a tubular receiver, the concentration ratio is given by [4]:

$$C = \frac{A_a}{\pi D} \tag{1}$$

Aperture of the parabola A_a can be obtained from a simple trigonometry and depends on parabola focal distance f and angle between the collector axis and a rim angle φ_r (Fig. 1).

$$A_a = 4f\, tan\left(\frac{\varphi_r}{2}\right) \tag{2}$$

The maximum concentration ratio occurs when rim angle is 90°. For the same aperture, various rim angles are possible. For different rim angles, the focus-to-aperture ratio, which defines the curvature of the parabola, changes. It can be demonstrated that, with a 90° rim angle, the mean focus-to-reflector distance and hence the reflected beam spread is minimized, so that the slope and tracking errors are less pronounced. The collector's surface area, however, decreases as the rim angle is decreased. There is thus a temptation to use smaller rim angles because the sacrifice in optical efficiency is small, but the saving in reflective material cost is great [4].

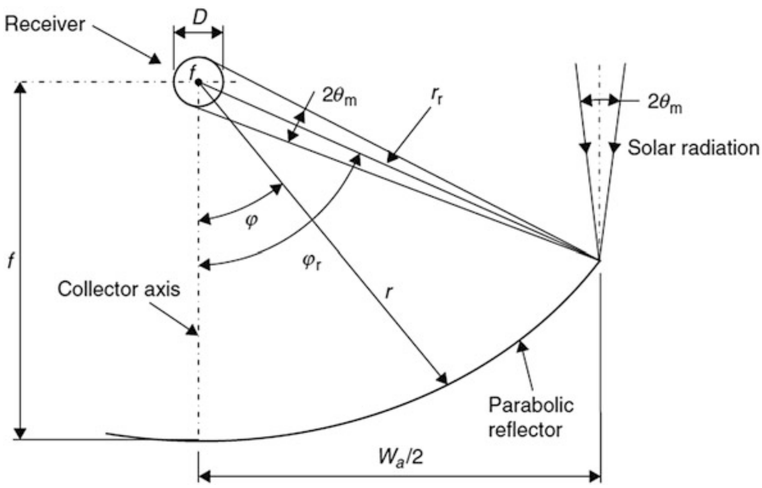


Fig. 1 Cross-section of a parabolic trough collector with circular receiver

2.2 *Optical efficiency*

Optical efficiency is defined as the ratio of the energy absorbed by the receiver to the energy incident on the collector's aperture. The optical efficiency depends on the optical properties of the materials involved, the geometry of the collector, and the various imperfections arising from the construction of the collector, such as reflectance of the mirror ρ, transmittance of the glass cover τ, absorptance of the receiver α, intercept factor γ, geometric factor A_f and angle of incidence θ [4, 5].

$$\eta_o = \rho\tau\alpha\gamma\left[\left(1 - A_f\tan(\theta)\right)\cos(\theta)\right] \tag{3}$$

Geometric factor A_f dictates the geometry of the collector, which is a measure of the effective reduction of the aperture area due to abnormal incidence effects, including blockages, shadows, and loss of radiation reflected from the mirror beyond the end of the receiver and can be calculated [4, 5]:

$$A_f = \frac{A_1}{A_a} = \frac{A_e + A_b}{A_a} \tag{4}$$

The parameter A_e is called the end effect, which occurs during abnormal operation of a parabolic trough collector, when some of the rays reflected from near the end of the concentrator opposite the sun cannot reach the receiver. The amount of aperture area lost is given by [4, 5]:

$$A_e = fW_a \tan(\theta)\left[1 + \frac{W_a^2}{48f^2}\right] \quad (5)$$

The constant A_b represents the loss of aperture area due to opaque plates usually constructed to preclude unwanted or dangerous concentration away from the receiver. For a plate extending from rim to rim, the lost area is calculated by equation [4, 5]:

$$A_b = \frac{2}{3} W_a h_p \tan(\theta) \quad (6)$$

The parabola height is calculated as follows:

$$h_p = \frac{W_a}{4\tan\left(\frac{\varphi_r}{2}\right)} \quad (7)$$

2.3 Thermal Analysis

For generalized thermal analysis of a concentrating solar collector is necessary to derive appropriate expressions for the collector efficiency factor F'; the loss coefficient U_L and the collector heat removal factor F_R. For the calculation of loss coefficient are used standard heat transfer relations for glazed tubes.

The calculations include radiation, conduction, and convection losses. Assuming no temperature gradients along the receiver and negligible convection losses due to evacuated space between the receiver and the glass cover, the loss coefficient is based on the receiver area A_r and area of glass cover A_g [4, 1].

$$U_L = \left[\frac{A_r}{\left(h_{c,c-a} + h_{r,c-a}\right)A_g} + \frac{1}{h_{r,r-c}}\right]^{-1} \quad (8)$$

Next, the collector efficiency factor defined as the ratio of the overall heat loss coefficient and overall heat transfer coefficient needs to be estimated. This should include the tube wall because the heat flux in a concentrating collector is high. Based on the outside and inside tube diameter and tube thermal conductivity, the relation is given by [4, 1]:

$$F' = \frac{U_L^{-1}}{\frac{1}{U_L} + \frac{D_o}{h_{c,r-f} D_i} + \left(\frac{D_o}{2k} ln \frac{D_o}{D_i}\right)} \quad (9)$$

It is usually desirable to express the collector total useful energy gain in terms of the fluid inlet temperature. To do this the collector heat removal factor needs to be used. Heat removal factor represents the ratio of the actual useful energy gain that would result if the collector-absorbing surface had been at the local fluid temperature [4, 1].

$$F_R = \frac{\dot{m}c_p}{A_r U_L}\left[1 - exp\left(-\frac{U_L F' A_r}{\dot{m}c_p}\right)\right] \tag{10}$$

The instantaneous efficiency of a concentrating collector may be calculated from an energy balance of its receiver. Because concentrating collectors can utilize only beam radiation, the total absorbed solar radiation is represented only by G_B and useful energy delivered from a concentrator is [4, 1]:

$$Q_u = F_R\left[G_B \eta_o A_a - A_r U_L (T_i - T_a)\right] \tag{11}$$

Then, the collector efficiency can be obtained by dividing useful energy by total absorbed solar radiation. Therefore:

$$\eta = F_R\left[\eta_o - U_L\left(\frac{T_i - T_a}{G_B C}\right)\right] \tag{12}$$

2.3.1 Convective heat transfer

Estimation of the convective losses is based on construction of collector's receiver. If we consider that receiver is insulated by vacuum in glass cover, the only part of convective loss is that of a glass cover per se, which is calculated as [6]:

$$h_{c,c-a} = \frac{Nu \cdot k}{D_g} \tag{13}$$

Constant k represents the thermal conductivity of ambient air and D_g is the diameter of glass cover. The equation includes criterion Nusselt number, which definition differs according to the nature of liquid flow described by Reynolds number [6].

$$Re = \frac{\rho_a V_a D_g}{\mu_a} \tag{14}$$

All constants in the equation, density ρ, velocity V and dynamic viscosity μ_a are related to ambient air at mean temperature calculated from temperature of ambient air T_a and temperature of glass T_g.

$$T_m = \frac{T_a + T_g}{2} \tag{15}$$

Equation of Nusselt number for *Re* values from interval (0.1; 1000)

$$Nu = 0.4 + 0.54(Re)^{0.52} \tag{16}$$

If values of Re are from interval (1000; 50000)

$$Nu = 0.3(Re)^{0.6} \tag{17}$$

Another case of convective heat transfer is inside of receiver tube. The convective heat transfer coefficient can be obtained from the standard pipe flow equation including thermal conductivity of fluid k_f and inner diameter of receiver tube D_r[6]:

$$h_{c,r-f} = \frac{Nu \cdot k_f}{D_r} \tag{18}$$

Nusselt number for laminar flow of fluid ($Re \leq 2300$) is always constant 4.364. For turbulent flow ($Re > 2300$), the Nusselt number can be calculated according:

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4} \tag{19}$$

Reynolds number is calculated according Eq. (9) where all the constants are related to working fluid. Value of Prandtl number can be obtained from:

$$Pr = \frac{c_p \mu_f}{k_f} \tag{20}$$

2.3.2 Radiation heat transfer

We can divide the total radiation heat transfer to radiation from receiver to glass cover $h_{r,r-c}$ and from glass cover to ambient. For determining the heat transfer coefficients is necessary to know emissivity ε, surface *A* and temperature *T* of both radiating materials [7].

$$h_{r,c-a} = \varepsilon_g \sigma \left(T_g^2 + T_a^2\right)\left(T_g + T_a\right) \tag{21}$$

The σ in the equation is Stefan-Boltzmann constant 5.67×10^{-8} W.m^{-2}.K^{-4}. Radiation heat transfer between receiver and glass cover is more complex due to the mutual irradiation and can be described as [7]:

$$h_{r,r-c} = \frac{\sigma\left(T_r^2 + T_g^2\right)\left(T_r + T_g\right)}{\frac{1}{\varepsilon_r} + \frac{A_r}{A_g}\left(\frac{1}{\varepsilon_g} - 1\right)} \tag{22}$$

In the preceding equations, to estimate the glass cover properties, the temperature of the glass cover is required. The procedure to find Tg is by iteration. Usually, no more than two iterations are required. This temperature is closer to the ambient temperature than the receiver temperature. Therefore, by ignoring the radiation absorbed by the cover, it may be obtained from an energy balance [7]:

$$T_g = \frac{A_r h_{r,r-c} T_r + A_g \left(h_{r,c-a} + h_{c,c-a}\right) T_a}{A_r h_{r,r-c} + \left(h_{r,c-a} + h_{c,c-a}\right)} \tag{23}$$

3 Results

The mathematical model was created for the specific parabolic trough collector situated on the building of University of Žilina as shown in Fig. 2. Reflector surface is made by bended aluminum plate with reflective foil, rim angle is 90°. Focal heat exchanger consists of two contradictory tubes inlet/outlet (Fig. 3). As a working fluid serves air supplied from measuring room secured by ventilation air. Therefore the parameters of inlet air are considered as parameters of ambient air. The volume flow in a tube is set to 0.0163 m^3/s. The excess pressure in the system reaches 0.3 bars. The collector is oriented in east-west position and has fully automatic single axis system for rotation .

The optical analysis was carried out according constants listed in Table 1. Some parameters of the materials were specified only approximately according catalogue. The calculation of intercept factor γ is very complex and requires many unknown constants. Its impact on the optical efficiency is usually small and so for our calculation its value is 0.98.

The most considerable effect has incidence angle, which changes during the day. The Fig. 4 depicts the optical efficiency during the day of 06.15.2017. As we can see the optical efficiency is ranging from minimum of 11% to maximum 71% according to changing incidence angle.

Fig. 2 Parabolic trough collector with one-axis tracking

Fig. 3 Detail if inlet/outlet of receiver and reflexive surface

Table 1 Parameters of the collector for optical analysis

Parameter	Character	Value	Unit
Parabola height	h_p	0.4495	m
Total aperture loss	A_1	1.0776	m^2
Geometric factor	A_f	0.1095	[–]
Intercept factor	γ	0.98	[–]
Reflectance of mirror	ρ_r	0.87	[–]
Transmittance of glass cover	τ	0.90	[–]
Absorptance of receiver	α	0.92	[–]

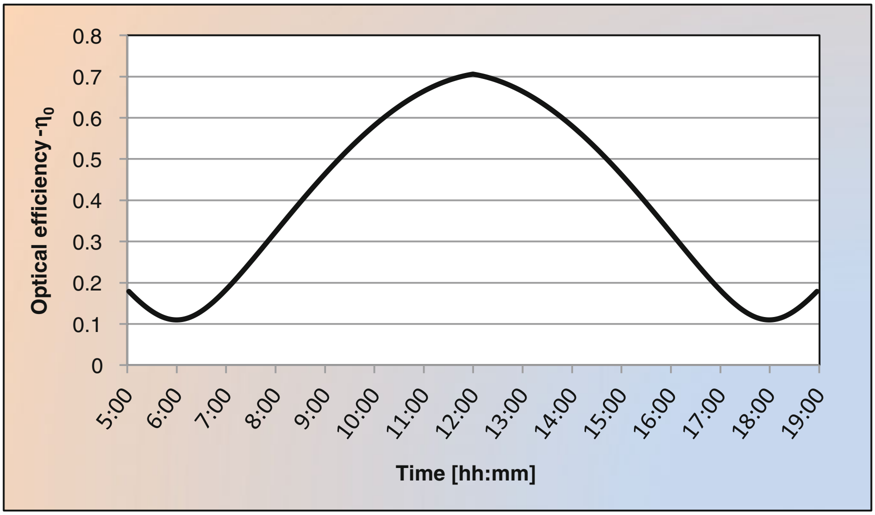


Fig. 4 Optical efficiency of the collector for specific day

Table 2 Parameters of the collector for thermal analysis

Parameter	Character	Value	Unit
Receiver length	L	5.88	m
Outer diameter of receiver	D_o	0.0424	m
Inner diameter of receiver	D_i	0.0375	m
Outer diameter of glass cover	D_g	0.125	m
Temperature of ambient air	T_a	20	°C
Temperature of inlet air	T_i	20	°C
Temperature of receiver surface	T_r	170	°C
Wind velocity	v	1	m/s
Pressure of ambient air	p_a	101,325	Pa
Pressure of working fluid	p_f	130,000	Pa
Glass cover emissivity	ε_g	0.87	[–]
Receiver emissivity	ε_r	0.92	[–]
Mass flow of working fluid	$\dot{m}$	0.0197	kg/s
Tube thermal conductivity	λ_r	15	W/(m.K)

Table 2 contains parameters necessary to calculate the useful heat and thermal efficiency of the collector. As the collector is situated on the building its performance is affected by condition of environment as temperature, solar global radiation, air pressure and wind velocity. Those variables are changing constantly. Parameters like temperature and wind velocity have negligible effect on heat losses due to thermal insulation, although temperature in our case is considered as inlet temperature.

The Fig. 5 shows the useful energy, the total energy of collected beam radiation reduced by thermal losses, within a specific day calculated for corresponding values of beam radiation incident on aperture area and optical efficiency. The highest useful energy 5947 W is obtained during noon when global radiation reaches is maximum 1162 W/m^2 and incident angle equals 0° which is the ideal condition.

Based on the created mathematical model, we can say that the performance of the collector is mostly dependant on the position of trough to the incident sun rays which rapidly affects the optical efficiency and consequently the thermal efficiency.

The mathematical model does not take in consideration the weather conditions and cloudiness. The related charts represent the ideal conditions and thus can differ from real operation. The results of this work provide information about what we can expect from the collector and its purpose in future application.

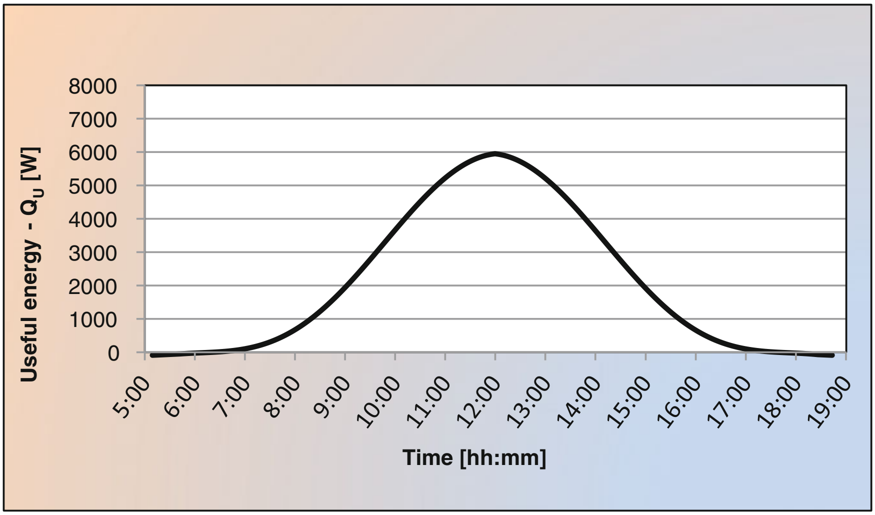


Fig. 5 Useful energy provided by the collector for specific day

Acknowledgements This work was supported by the project VEGA 1/0718/15. "Accumulation of high potential energy through the process of generating hydrates of natural gas and bio-methane"

References

1. Kienzlen, V., Gordon, J.M., Kreider, J.F.: Solar energy engineering (1988)
2. Brakmannet, G.: Concentrated solar thermal power—now!. ESTIA, Brussels (2005)
3. Morrison, G.L.: Solar collectors. In: Gordon, J. (ed.) Solar energy: the state of the art. (James and James, London, 2001)
4. Kalogirou, S.A.: Solar energy, engineering: processes and systems II. Academic Press Elsevier, California (2014)
5. Rabl, A.: Optical and thermal properties of compound parabolic concentrators. Sol. Energy 18, (1976)
6. Bejan, A.: Convection heat transfer. **IV**. (2013)
7. Incropera, F., DeWitt, D.: Fundamentals of heat and mass transfer III. Wiley, New York (1990)
8. LNCS Homepage, http://www.springer.com/lncs. Last accessed 11 Nov 2016

The Development of the Market of the Renewable Energy in Ukraine

Oleg Kucher and Liliia Prokopchuk

Abstract One of the priorities of energy in the world is the use of the renewable energy sources. This paper examines the status and prospects of Ukraine's energy market through the diversification of energy resources. The world experience in implementing the renewable energy sources of the main energy market participants has been revealed. The characteristics of the current state and prospects of the renewable energy in the world and in the European Union have been given. The state of energy usage in final gross energy consumption volume in Ukraine considering main areas has been analyzed and projections till 2020 have been made. The necessity of reducing the total primary energy consumption through the introduction of renewable energy sources has been shown. The existing resource potential for the implementation of energy efficiency and energy saving has been characterized. The document "REmap 2030" which made assessment and showed the projections for production capacity of the renewable energy in Ukraine until 2030 has been created. Active state regulation of the renewable energy in Ukraine is in progress. There exists the program "green tariff" that provides the acceleration of the renewable electricity. A system of measures to develop renewable energy for the period until 2020 has been adopted, which is reflected in the National Action Plan. There are examples of the work of the Ukrainian companies engaged in the production of the alternative energy sources to meet their own needs, as well as its sale to consumers in Ukraine and abroad. It is noted that the use of the renewable energy is an undeniable factor for the improving energy security and reducing the negative impact of energy on the environment. The prognostic potentiality and obstacles of the alternative energy sources production in Ukraine have been stated and possible solutions have been suggested.

Keywords Energy independence · Renewable energy · Biofuels
Market · International experience · Energy · "Green" tariff · Government support

O. Kucher (✉) · L. Prokopchuk
State Agrarian and Engineering University in Podillia, Kamianets-Podilskyi, Ukraine
e-mail: kucheroleg68@gmail.com

L. Prokopchuk
e-mail: prokopchuklm@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_8

1 Introduction

The alternative and renewable energy sources have recently become one of the important criteria for energy security in the world. The main reason is the expected depletion of fossil fuels, the sharp rise in energy prices, uncertainty about the stability and reliability of their supply, impact on the environment, the effects of which are increasingly worrying the society. In the present context, the use of the renewable energy significantly increases the security of energy supply, improves the social and economic situation.

Ukraine belongs to energy—import-dependent states. Therefore, the development of the renewable energy is an important factor in improving its energy security. The reduction of imports of expensive energy leads to the decrease of Ukraine's dependence on other countries and less tangible impact of energy crisis. In this regard, the research of the status and development of the renewable energy in Ukraine is very actual.

2 Methodology and Aim of the Study

We used the following statistical methods:

(1) statistical observation—recording information on certain principles and for certain purposes;
(2) summary and grouping of economic indicators
(3) comparison of indicators: with competitors, standards, dynamics.

The purpose of this article is to study the status and prospects of the renewable energy market in Ukraine, the characteristics of this market and identify the key problems and further steps to diversify Ukraine's energy market.

3 Results of the Research

One of the priorities of energetics development in the world is the use of the EU countries Kyoto commitment to reduce emissions of "greenhouse" gases. Among the various factors that affect the level and prospects of the renewable energy development of, the current system of state economic incentives, as shown by the positive experience of the EU countries, plays a crucial role in these countries [1].

An important task of Ukraine in improving energy independence is diversification of energetics by means of increasing alternative fuels and renewable energy sources. The Law of Ukraine "On energy saving" defines the legal, economic, social and environmental bases of energy saving. It stipulates that this activity is aimed at obtaining sustainable and economical energy usage. The law refers to non-conventional energy sources—solar energy, energy of earth, seas, oceans and rivers. It is also noted in the Law that training and education of the population in the area of energy is necessary.

The alternative energy sources, which include natural winds, solar and geothermal energy are free, safe and not associated with harmful emissions. In addition, their preponderance is autonomous, there is no need to transmit energy over long distances, the process is usually accompanied with large losses and environmental pollution, including electromagnetic pollution during high voltage transportation. Taking into consideration the high energy consumption and low natural gas reserves, the introduction of the alternative energy sources is particularly important in Ukraine.

The USA, Japan and China are among the countries where technologies and the renewable sources market are highly developed. Austria, Spain, Germany, Portugal, Finland and Sweden are among the EU countries in this area. One of the priority areas of renewable energy is its production of biofuels. China and Germany are leaders for the production and use of biogas [2].

The problems of the efficient use of the traditional energy sources in Ukraine are even more acute than in other countries. The main reasons include obsolete technologies, reduction of natural resources for the production of electricity and heat, as well as significant amounts of harmful emissions. In addition, there are large losses during transportation, distribution and use of electricity and heat. The monopoly dependence on energy imports is worsening the situation on the energy markets of the country.

The issue of energy security, the reduction of dependence on imported energy, particularly on natural gas are becoming increasingly important. Significant changes have recently happened in the energy sector of the country. Projects of the energetic solid biofuels use and the replacement of natural gas have got the widespread implementation.

To implement energy efficiency and energy conservation, Ukraine uses the best practices. The Finnish company's "NESTE" experience in producing liquid biofuels, is very useful. The plants use food industry and agriculture wastes [4].

In 2013 Ukrainian-Polish Center of renewable energy technologies and energy efficiency project was launched in cooperation between the Embassy of Poland in Ukraine and National Technical University of Ukraine "Kyiv Polytechnic Institute". The main objective of the project is the creation and maintenance of a joint Ukrainian-Polish Center of renewable energy technologies and energy efficiency [5].

Ukraine has taken important steps towards transforming the energy sector of the country on the issue of energy efficiency and energy independence. The Membership in the Energy Community provides Ukraine with an opportunity to increase competition in the domestic market, read and accept European technical standards and improve the investment climate. To attract investors, especially foreign, the Ukrainian market Ukraine is harmonizing its legislation with European, providing guarantees and incentives for business [6].

The program “green tariff” was introduced in Ukraine in 2008. Its aim is to encourage electricity generation from renewable sources.

As a result, new facilities of the capacity of 120 MW working on “green” tariff were installed in 2016 in Ukraine which is 4 times more than in 2015. Specifically, 90 MW of this amount is the power of solar power. On January 1, 2017 the power facilities that generate electricity from renewable sources and work by green tariff is 1118 MW in Ukraine [4].

A positive trend in demand for solar panels from the population is being witnessed nowadays. Today more than 1300 families in fact fully satisfy its energy needs through solar energy [4].

During 2007–2015 the total primary energy supply was increasing continuously. And in 2015 it was at 90,090, which is 50,760 thousand t.o.e. (56.3%) more than in 2007. However, in 2015 compared to 2014 there was a decline in the total supply of primary energy to 15,593 which is 14.8%. At the same time, the supply of energy from renewable sources for the period increased and in 2015 it was 2700 thousand t.o.e. or 3.0% of its total supply.

Analysis of energy supply in the directions showed that among renewable energy hydropower reduced its rates to 408 thousand t.o.e., accounting for 53.2%. However, during this period energy supply of biofuels and waste increased to 594 thousand t.o.e., which is 39.4%; wind and solar power increased from 4 thousand t.o.e. in 2007 to 134 thousand t.o.e. in 2015. The total supply of energy from renewable sources in 2015 compared to 2007 increased by 316 thousand tons of oil equivalent, accounting for 13.3%. Of the renewable energy sources in the structure of total primary energy supply in 2015, hydropower occupies 0.5% of biofuels and waste energy—2.3%, and wind and solar power—only 0.1% (Table 1) [8].

Table 1 Energy consumption from renewable sources in 2007–2015

Indicator	Unit	2007	2013	2014	2015
Total supply of primary energy	Thousand tons of oil equivalent	139,330	115,940	105,683	90,090
Including					
Hydropower	Thousand t.o.e.	872	1187	729	464
% of total	%	0.6%	1.0%	0.7%	0.5%
Energy biofuels and waste	Thousand t.o.e.	1508	1875	1934	2102
% of total	%	1.1%	1.6%	1.8%	2.3%
Wind and solar power	Thousand t.o.e.	4	104	134	134
% of total	%	0.0%	0.1%	0.1%	0.1%
Total energy from renewable sources					
General supply of energy from renewable sources	Thousand t.o.e.	2384	3166	2797	2700
Share of energy supply from renewable sources	%	1.7%	2.7%	2.6%	3.0%

Source Own research

Table 2 The contribution of renewable energy to each sector's energy consumption considering final energy consumption (Thousand tons of oil equivalent)

Expected gross final energy consumption from renewable sources by sector	2009	2016	2020
In heating and cooling systems	1473	3690	5850
Electricity	980	1540	2235
In the transport sector	52	298	505
Estimated total energy consumption from renewable sources	2505	5528	8590

Source Own research

National Action Plan for renewable energy until 2020 has been adopted in Ukraine [6].

The National Action Plan envisaged achieving the share of renewable energy in 2020 at 11%. In particular, in the heating and cooling systems the share of energy from renewable sources will be increased from 3.4% in 2009 to 12.4% in 2020, in the power industry—from 7.1 to 11.0%. In the transport sector growth will be from held from 1.5% in 2009 to 10.0% in 2020.

The National Action Plan presents calculations to the contribution of renewable energy in the energy consumption of each sector to its final volume (Table 2). The total consumption of energy from renewable sources in 2009 equaled to 2505 thousand t.o.e. It is planned to bring consumption up to 8590 thousand t.o.e. till 2020, compared to the rate in 2016, that is more that 55.4%. In particular, the expected gross final consumption of energy from renewable sources in heating and cooling will equal 5850 thousand t.o.e. in 2020, almost four times more than the level of consumption in 2009 and 58.5% compared to 2016.

The consumption of electricity from renewable sources in 2020 compared to 2009 will increase by more than half and by 45.1% more than in the transport sector in 2016. In transport sector it is planned to increase the rate of consumption ten times in 2020 as compared with 69.5% in 2016.

Thus, according to the National Action Plan on Renewable Energy, the expected total energy consumption in 2020 will be at 78,080 thousand tons of oil equivalent level, and the expected amount of energy from renewable sources that corresponds to a plan for 2020 will amount to 8590 thousand t.o.e. The planned share of energy from renewable sources in gross final energy consumption volume in 2020 will be 11%. To achieve these objectives the capacities of 5.2 GW of renewable electricity and 11.6 GW of renewable power system should be commissioned. To fulfill these commitments, Ukraine should actively attract investors into this sector.

According to the National Commission for state regulation in the energy and utilities at the end of 2016 the industry of renewable energy in Ukraine already has 170 companies and 291 facilities that provide heat to the population through alternative energy. Thus, the leading poultry producer in Ukraine public joint-stock company "Myronivskyi bread products" owns 19 enterprises, which are engaged in the sunflower processing. The product is processing sunflower husk granular, which is widely used. Using sunflower husks as solid biofuel quality, JSC "Myronivskyi bread products" fully satisfies their needs in biofuels, and has as its sale to consumers in Ukraine and abroad [9].

In March 2017 the company "Myronivskyi bread products" presented a new project to build a biogas plant on the farm in Ladyzhyn Vinnytsia region. The total power output of the power station will be 20 MW. The first stage of the 10 MW power station will be introduced in 2017–2018, the second 10 MW power station—in 2019–2020. The idea of the project is the full utilization of chicken manure and biogas production from it to produce electricity. The total investment for this project is 50 million dollars. This station will replace 87 million m^3 of gas per year [10].

Public JSC "Kyivenergo" produces alternative energy through recycling wastes having its special separated unit of recycling plant "Energy" in Kyiv. Despite low levels of recycling technology and the lack of practice, the plant "Energy" processes about 230 tons of solid waste per year. It uses only 20% of the annual volume of garbage in the capital. As a result of recycling 150 thousand Gcal of heat is produced per year. It is used for heating and hot water supply in over 80, 000 flats in the metropolitan residential area "Pozniaky", which provides saving over 30 million m^3 of natural gas per year [8].

The main energy source for a third of the world's population is biomass, mainly in the form of wood. Ukraine also focuses its attention on increasing the use of alternative local fuels, whish is of great significance and has not been realized yet. With only 30% of crop waste to produce heat "not out of gas", the potential replacement of gas will amount to 9.3 billion m^3 of gas per year. In addition, energy crops could potentially displace 20 billion m^3 of gas per year [4].

The development of the bioenergy sector in Ukraine should be consistent and substantiated. It is important to take into account the possible effect on the national economy and the environment. The basic components of the biomass potential in Ukraine is agricultural residues and woody biomass. Agricultural biomass is concentrated in central, south-eastern and southern regions of the country where soils are the most fertile. The northern part of the country is rich in woody biomass, it is covered by 25–30% with pine forests, and the western part—Ukrainian Carpathians, where dominant mass is spruce, beech, fir and oak forests.

According to Bioenergy Association of Ukraine, due to heat and power from biomass, Ukraine produced biofuels that can replace the power of 3.7 billion cubic meters of gas in 2016. The production of biofuels is increasing by 38% here. Ukraine consumes about two-thirds of this amount for its own needs, the rest for export. As the National Action Plan states, Ukraine will replace 7.2 billion $m^3$of gas with biofuels till 2020. That is roughly the amount that the state annually pumps into its underground gas storage for the winter period [11].

Soil and climatic conditions in most regions of Ukraine are favorable for growing perennial energy crops that can rapidly transform solar energy into biomass energy-intensive. These plants do not need rich soil, they do not require significant fertilizer and pesticides use, they prevent soil erosion, contribute to the preservation and improvement of agro-ecosystems and provide low cost biomass. This allows to cultivate energy plants on unproductive lands.

Miscanthus, as well as millet or switch grass (Panicum virgatum) are new perspective energy crops for Ukraine. These perennial cereals have been grown for many years in America, Canada and Western Europe as a source of bioenergy. Miscanthus compared to other crops is the most effective plant for the production of solid biofuels. This plant possesses crop capacity of the dry biomass of about 25 tons/ha and has high calorific value. One ton of dry miscanthus is equivalent to 400 kg of crude oil, 1.7 tons of wood, 515 m^3 of natural gas, or 620 kg of coal. Miscanthus stems have a high energy value. The experience of growing miscanthus in Ukraine shows that it is possible to acquire 20–25 tons of dry mass per hectare from a two-year—old -miscanthus plantation during the subsequent 20 years [13].

Back in the 90s the United States and Canada began using switch grass as energy crops for solid biofuels. Its indiscriminateness to the moisture and nutrients in the soil, high natural resistance to disease and pests, enables getting stable dry biomass yield on unproductive lands. Grown in the dry areas switch grass has a height of 1.0–2.5 m, and the yield of dry biomass −7 t/ha to 14.2 t/ha, depending on the varietal characteristics. Switch grass biomass crop can be harvested within 15 years [13].

There are many legal documents, strategies and initiatives concerning energy efficiency and renewable energy in Ukraine. The Energy Strategy of Ukraine approved by the Government for the period till 2030 notes that the use of renewable energy is an undeniable factor for improving energy security and reducing the negative impact of energy on the environment. The calculating materials by 2030, proposed in the document, were included in the National Action Plan for Renewable Energy (NPDVE) at Baseline Alternative Development until 2030. They were calculated on the trends in the period of 2014–2020, according to NPDVE. 57% of gross energy consumption in Ukraine during 2009–2030 is in the heating and cooling sector in 2030 and about 28% accounts in the electricity sector. The share of the transport sector in this period will be 15%. The expected gross final energy consumption of Ukraine taking into account energy efficiency, according to NPDVE, 2030 [14] (Table 3).

In terms of renewable energy Ukraine is guided by the best international practices. Close cooperation with foreign countries is being established. Memorandum of cooperation with Finland, Denmark, Slovenia, Slovakia was signed. The British experience in implementation of projects on renewable energy is of great important for Ukraine, as Great Britain is one of the leading and economically powerful

Table 3 Expected gross final energy consumption in Ukraine, taking into account the increase of energy efficiency, according to NPDVE, till 2030

Indexes	2009	2016	2020	2030
Heating/cooling	43,640	46,280	47,100	49,767
Electricity (generation)	13,791	17,440	20,300	24,323
Transport	8943	9700	10,680	13,547
Gross energy consumption	66,374	73,420	78,070	87,636

Source Own research

countries in Europe. Israel's innovative experience in this field is quite useful and necessary for Ukraine as well [4].

Ukraine's participation in the International Renewable Energy Agency (IRENA) allows to establish close cooperation with developed countries on renewable energy, bring best practices and innovative mechanisms for financing projects in this area. "REmap 2030" is the result of the cooperation of the International Renewable Energy Agency (IRENA) and Ukrainian experts in the development of renewable energy in Ukraine. This working document uses the National Action Plan for Renewable Energy as a basic variant of the period up to 2020 and 2030.

According to REmap 2030, the share of renewable energy in total final energy consumption may reach 21.8% and the total installed capacity of power plants could reach 23.3 GW. The analysis helped to make suggestions as for the possible maximization of the potential of renewable energy sources. Wind and solar power is the greatest potential among renewable energy sources [7, 14].

The state regulation of renewable energy is of great importance in Ukraine. Following the example of other European countries, there is a system to stimulate the development of renewable energy. It includes denominated in euro "green" tariffs, differentiated by type, capacity and timing of commissioning of power. In addition, the state undertakes to buy stations working on renewable energy electricity by "green" tariff till 2030.

In 2017 Ukraine became an honorary member of the large-scale International Exhibition EXPO 2017 "Energy of the Future". Ukraine will present their own startups at the national stand which will feature Ukrainian wind turbine, solar concentrator for the production of heat, shutters, generating electricity, and the sample of the passive house that has minimal energy consumption. New is drafted projects on renewable energy, which are promising for investments will also be shown.

During the exhibition Ukraine will present the best legislative developments, advanced equipment and materials in the field of energy efficiency and renewable energy in all areas: solar, wind, hydropower, energy crops, the production of heat and electricity from agricultural waste and others. Ukraine's participation in the exhibition will provide an opportunity, to present the potential of renewable energy at the international level and to welcome potential investors to work in Ukraine. [15].

The development of renewable energy includes modern technologies, implementation of national science, job places, power decentralization, development of small and medium business, additional taxes to the budgets of all levels, etc. Renewable energy plays an important role in the Ukraine's strategic objectives in the energy sector, but the potential available in the field of energy efficiency, which, in particular, may be used for reduction of natural gas must also be taken into account.

In the area of renewable energy Ukraine has powerful resources of small hydropower rivers, which equals about 63 thousand. Their capacity is up to 28% of the total hydropotential in Ukraine. The development of small hydropower makes it possible to solve the problem of power supply in remote rural areas especially in

Western Ukraine, where micro and mini hydropower plants could be the basis for their energy supply.

However, today the electric power system of Ukraine is at risk because of the outdated equipment, stations' inefficient work, and old power lines. 95% of hydro and thermal power plants is too old to be used. Most power plants using coal, which were built in the 1970s need upgrading or have to be replaced. So to replace the old stations, new renewable energy facilities should be constructed.

The necessary measures that will ensure the maintenance of sustainable practices need to be taken in Ukraine in order to solve the complex issues of power. There are all necessary conditions for the development of renewable energy such as wind, solar, geothermal energy, biomass and small hydro power stations. A well-formed structure of renewable energy will reduce a significant portion of total demand of Ukraine for natural gas consumed in electricity. Biogas can be used in the power system [3].

Nowadays Ukraine faces all energy challenges, follows world trends and develops clean energy. Ukraine has the necessary resources to do this, as well as possesses significant potential in renewable energy. According to the State Agency for Energy Efficiency and Energy Conservation the technically feasible renewable energy potential is 98 million tons of fuel per year.

However, there are many problems facing the development of alternative energy in Ukraine. The key barriers to renewable energy are low confidence in the system of incentives for its development. In particular, the elimination of tax breaks for renewable energy, reducing the size of green tariffs, etc. A complex system of approvals, a large number of permits, complicated licensing procedures and low potential grid to the accession of new power generating capacities are the barriers to market entry. The guarantees of repayment of the produced energy and the guarantees for the establishment of 'green' tariff in the planning phase of the project are not provided.

The following steps are necessary to overcome these obstacles:

– to implement a more predictable state policy on renewable energy. This can be achieved through the development of a long-term vision and strategy for development of the sector on the basis of all market participants' proposals.
– to conduct a communication campaign aiming at the confirmation of public policy sector of renewable energy sources and encouraging market entry of international strategic investors.
– to simplify and optimize the licensing procedures (for example, by creating a single window);
– to support legislative initiatives to provide guarantees concerning the purchase of the produced energy and the establishment of "green" tariff in the design phase [7].

The existing technologies for renewable energy have different levels of economic efficiency and different technical level. But very low or non-existing levels of greenhouse gases are their main advantage. A complete modernization of the energy sector aiming at maintaining competitiveness in the global energy market and increasing overall energy efficiency must happen according to the project of the development of the renewable energy till 2030.

4 Conclusions

Renewable energy plays an important role in implementing strategic objectives in the field of energy in Ukraine. Available natural, scientific and industrial capabilities make it possible to significantly increase the pace of increasing volumes of renewable energy in the country. It is necessary to involve both its own and foreign investments following the experience of European countries. To stimulate investment activity in this area it is important to create favorable conditions. A large-scale implementation of renewable energy sources in Ukraine will make a significant step in reducing the country's energy dependence, environmental protection and creating the conditions for integration into the European community.

Stabilization of the economic and political situation and the continuation of existing economic incentives in the form of "green" tariffs should become the guarantee to the development of renewable energy in Ukraine. Under these circumstances, and considering the available technical potential, Ukraine will be able to provide nearly half of the country's needs in electricity in 2030.

References

1. Prospects of the development of the renewable alternative energetika.in.ua/ua/books/book-5/part-1/section-3
2. Will the Ukrainian gas replace bioenergy https://ukr.lb.ua/economics/2017/02/23/359442_chi_zaminit_gaz_ukrainska.html
3. Alternative and renewable energy sources in Ukraine in the light of new European initiatives http://old.niss.gov.ua/monitor/november08/2.html
4. State Agency for Energy Efficiency and Energy Conservation in Ukraine http://saee.gov.ua/uk/news/1779
5. Ukrainian-Polish Center of renewable energy technologies and energy efficiency http://upc-re.kpi.ua/stage-1/
6. About the National Action Plan for renewable energy for the period till 2020/ KMU order №902-r of 01.10.2014 p. http://zakon4.rada.gov.ua/laws/show/902-2014%D1%80/page
7. Report on the development of renewable energy sources in Ukraine http://www.minregion.gov.ua/wp-content/uploads/2017/03/Rozvitok-VDE-v-Ukrai–ni.pdf The report was in March 2017
8. https://ukr.lb.ua/economics/2017/02/23/359442_chi_zaminit_gaz_ukrainska.html
9. The use of biofuels as an alternative energy source http://www.kyivregioneconomy.com/single-post/2017/04/04
10. http://www.kmu.gov.ua/control/uk/publish/article?Art_id=249794241&cat_id=244276429
11. Ukrainian Energetics-2017: phasing out of gas in favor of biomass https://www.radiosvoboda.org/a/28193935.html

12. Dombrovskyi Oleksandr, Sergiy Savchuk, Georgii Geletukha, Tetiana Boiko vidnovlyuvani_dzherela_enerhiyi### alternatyvni_dzherela_enerhiyi achieve vidnovlyuvana_enerhetyka#
13. The concept of the production and use of solid biofuels in Ukraine http://eurowine.com.ua/?q=node/21302
14. Prospects for renewable energy development in Ukraine till 2030 http://www.irena.org/remap/
15. EXPO 2017| Stateenergyefficiency of Ukraine saee.gov.ua/uk/expo2017

The Financial Efficiency of Biogas Stations in Poland

Serhiy Zabolotnyy and Mariia Melnyk

Abstract The aim of the paper is to give an overview of financial efficiency of biogas plants in Poland. The research presents the analysis of selected biogas stations in Poland such as Biogazownia Drozdowo Sp. z o.o., Biogazownia Ostrzeszów Sp. z o.o., Biogazownia Prusinowice Sp. z o.o., Spółka Rolna Dretyń Biogazownia Sp. z o.o. The hypotheses of the research states that the biogas stations with higher profitability ratios are characterized by higher level of liquidity. In Poland the most popular is the usage of biomass among renewable energy sources. Biomass is used to produce biogas in large and small agricultural biogas stations. The production of biogas takes place under anaerobic conditions involving the usage of a number of microorganisms.

Keywords Financial efficiency · Biogas stations · Biogas production
Agro-industrial complexes · Renewable energy sources · Profitability

1 Introduction

The modern world faces a huge energy crisis, which associates with exhaustion of conventional energy resources. Therefore, power generation getting from alternative sources increasingly attracts both scientists and businessmen. Biogas is one of such type of source, which in the nearest future—together with wind and solar energy—will be an important source of renewable energy. Biogas power stations

The original version of this chapter was revised: Incorrect author name has been corrected. The erratum to this chapter is available at https://doi.org/10.1007/978-3-319-72371-6_81

S. Zabolotnyy (✉)
Warsaw University of Life Sciences (SGGW), Warsaw, Poland
e-mail: serhiy_zabolotnyy@sggw.pl

M. Melnyk (✉)
Sumy National Agrarian University, Sumy, Ukraine
e-mail: lypcheu@ukr.net

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_9

have enormous potential, which can positively influence social and economic development and improvement of the environment [1].

To ensure a prominent level of financial efficiency of biogas stations, managerial staff must assess the financial condition of both enterprise and existing potential competitors. As a rule, the desire of managerial staff of a company to maximize profits entails a risk of liquidity loss.

An analysis of solvency and profitability of biogas stations will make it possible to identify errors in its activities, reserves of its growth and help more successfully carry out their activities. The purpose of the research is to determine priorities in management of liquidity and profitability of biogas stations in Poland. To achieve this goal, it is necessary to solve the following tasks: to consider theoretical aspects of profitability and liquidity; to conduct the analysis of liquidity and profitability of specific biogas stations. Different views on the content of the concept "financial efficiency" are generalized.

The conducted analysis of liquidity and profitability of biogas stations allows us to determine priority areas of financial management during this time of period.

The value of liquidity indicators of some biogas stations exceeds the normative value, which indicates inefficient usage of funds, which could be involved in the development of Polish biogas stations. It also means the presence of unclaimed cash in accounts—it causes the need to take decisions, which should balance these indicators.

In modern terms, to provide economic sustainability, companies have to improve their own economic activities according to the concept of management, which will help fundamentally change the economic environment for their operation and enable further development [2].

2 Methodology and Aim of the Study

The goal of the research is to study financial condition and efficiency of biogas plants in Poland. The focus of the research is made on profitability and liquidity relations of research objects.

The study was based on the generally accepted methods for data quantification, processing, presentation, statistical observation, summary and grouping of observation materials, correlation and regression analysis. Liquidity and profitability ratios were used [3].

Assessing the financial efficiency of biogas stations, we used the following methods which relate to quantitative methods of economic analysis:

(1) statistical observation—recording information on certain principles and for certain purposes;
(2) calculations of average values (average arithmetic simple);

(3) series of dynamics: absolute growth, growth rates;
(4) summary and grouping of economic indicators according to certain characteristics;
(5) comparison of indicators: with competitors, standards, dynamics;
(6) graphical methods [4].

The analysis of indicators began with consideration of absolute values. These indicators are the main ones in financial accounting. In the analysis they are used to calculate average and relative values.

Typical features of the method of the analysis are:

(1) Usage of the system of analytical indicators which comprehensively characterize financial and economic activity of an organization;
(2) Research of reasons for the change in these indicators;
(3) Identification and measurement of cause-effect relationships between them [5].

Relative values are indispensable in the analysis of dynamics of phenomena. With their help time series of financial indicators were built. They include coefficients of return on assets, equity, absolute and instantaneous liquidity coefficients which characterize the change in the given indicator over time (in relation to the basic indicator taken as 100%).

The method of comparison with the previous period was also used. It is the comparison of economic indicators of the current period with those of the previous period.

Also, the comparison with the best indicators was made—the best practice gives an effect when the comparison is conducted with indicators of similar enterprises.

The most used method was the method of horizontal analysis (temporary)—the comparison of each position of reporting with the corresponding position of the previous period, consisted in the construction of several analytical tables. During the horizontal analysis absolute and relative changes in the values of different balance accounts the reporting period were determined.

3 Renewable Energy Market in Poland

Biogas in Poland is an important source of energy that can increase the stability of gas supply. Poland possesses huge resources for production of agricultural biogas. The energy potential of biogas related to agricultural biomass is estimated to reach approximately 48.595 GWh/year [6].

In 2013, 10 new biogas plants were opened. This is a good result given that at the end of 2012 the total number of biogas plants was less than 30, and in 2012 were commissioned 12. Currently, trends in the market show an increase in the planned capacity of installed biogas plants. According to the Institute of Renewable Energy, about 212 biogas plants were designed, and in the near future 37 facilities will be built [7].

The main attention should be paid to the production of agricultural biomass in the producing of energy from renewable sources in Poland. Poland has a high level of biomass production compared with the rest of the EU member countries. This is directly related to the highly developed agro-industrial sector [8].

The stable development of the agro-industrial complex and rural areas also depends on how efficiently agricultural biogas will be used. This sustainable development is an integral part of the development of the European Union.

The development of energy in Poland is conditioned by the norms of the European Union. Poland, as a member of the European Union, is committed to diversifying energy sources. By 2020, renewable energy should account for 15% of the final energy consumption in Poland. Compared to other countries of the European Union, this should be: in Austria—34%, Germany—18% and the Czech Republic—13% [9].

From 7.2% in 2005, Poland aims to achieve a 15% target for renewable energy in 2020. Solid biomass (wood) and hydropower currently account for about 90% of electricity production based on renewable energy sources. Poland has great potential for more efficient use of solid biomass, as well as for energy generation from waste, sludge, energy crops and landfill gas. It is expected that Poland will be able to fulfill the EU goal of 5.75% of biofuel in the transport sector. Poland is the only country in the EU that had a positive GDP growth in 2009 after the economic crisis [10].

The situation in Poland in 2012/2013 in terms of the stability of legal norms for the energy sector was far from the state of stability and predictability. Negative assessment of work on the necessary amendments to the Energy Law does not apply to its objectives, since they are mainly determined by EU rules, they were also related to the need to regulate the sector. Exist three basic laws, namely the Law on Energy, the Gas Law and the Law on Renewable Energy Sources influence the regulation of this sector and its financing [11].

4 Side of Financial Efficiency of Biogas Stations in Poland

4.1 Return on Assets

Return on assets (ROA) is the financial coefficient which characterizes the return on the usage of all assets of an organization. The coefficient shows the ability of the organization to generate profit without considering a structure of its capital (financial leverage), the quality of asset management. Unlike the indicator "return on equity capital" this indicator considers all assets of the organization, and not only its own funds.

The coefficient of the return on assets is calculated using the following formula:

Return on assets = (Net profit (loss)/Assets) $\times$ 100% [12].

Table 1 The coefficients of return of assets of biogas stations in Poland for 2013–2015 (%)

Enterprises	2013	2014	2015	Deviation (±)
Biogazownia Drozdowo Sp. z o.o.	2.79	−8.02	23.8	21.01
Biogazownia Ostrzeszów Sp. z o.o.	−0.39	−0.11	2.4	2.79
Biogazownia Prusinowice Sp. z o.o.	−31.39	58.61	−16.09	15.3
Spółka Rolna Dretyń Biogazownia Sp. z o.o	−8.28	−3.06	−2.48	5.8

Source Own research

The coefficient of profitability of assets shows how much money (regardless of the source of their attraction) was required to obtain 1 zloty profit. This coefficient is an important indicator of competitiveness of the enterprise, to determine a level of which the obtained value of the return on assets should be compared with the industry average [13].

Let us examine coefficients of profitability of assets on the example of five Polish enterprises, such as Biogazownia Drozdowo Sp. z o.o., Biogazownia Jezierzyce Sp. z o.o., Biogazownia Ostrzeszów Sp. z o.o., Biogazownia Prusinowice Sp. z o. o., Spółka Rolna Dretyń Biogazownia Sp. z o.o. the main activities of which are production, transmission and distribution of electricity (Table 1).

According to this table, we can conclude that return on assets of biogas stations, which are under consideration, has increased for 2013–2015. Return on assets of Biogazownia Drozdowo Sp. z o.o. increased from 2.79% in 2013 to 23.8% in 2015. This indicates that the efficiency of the biogas station has increased. It was caused by the fact that net profit in 2015 was significantly higher than in previous years.

The norm for the coefficient of return on assets, as well as for all coefficients of profitability is C (coefficient) >0. If the value is less than zero—this is the reason to think seriously about efficiency of an enterprise. It will be caused by the fact that the enterprise works at a loss [13]. This situation can be observed in the case of Spółka Rolna Dretyń Biogazownia Sp. z o.o. As we can notice here, the coefficient of return on assets for 2013–2015 grew by 5.8 pp., but in each of the analyzed year, it was less than zero. We can conclude that the company during that period was unprofitable, which is negative for the enterprise, but dynamics indicates the growth of profitability, which also indicates the profitability of the enterprise in the nearest future.

If we consider return on assets of Biogazownia Ostrzeszów Sp. z o.o., we can say that during that period the coefficient increased by 2.79 pp. and only in 2015 the biogas station became profitable, which is positive for the enterprise, as evidenced by the growing tendency of coefficients for the entire research period.

The highest indicator of return on assets for three years has Biogazownia Prusinowice Sp. z o.o. In 2014, it was 58.61%, which indicates a prominent level of profitability of the biogas station. In this case, it is a high rate of profitability. In 2015, the coefficient of return on assets fell to −16.09, and the main reason for the decline in this coefficient was the decrease in net profit in that year.

Return on assets is highly dependent on the industry in which an enterprise operates. As electric power industry is quite capital-intensive industry this indicator is lower, if we compare it with the sphere of services that does not require large capital investments and investments in working capital.

According to the table, we can say that coefficients of profitability for 2013–2015 tend to growth, which indicates profitability of biogas stations in the future. As we have already mentioned above, coefficients of return on assets is the important indicator of competitiveness of an enterprise, and to determine its level, we have compared coefficients of biogas stations with the main competitors in the renewable energy market. According to this chart, we can see that leading positions on the level of return on assets is held by Biogazownia Drozdowo Sp. z o.o., which indicates its high competitiveness.

4.2 Return on Equity

In this subsection we will calculate and analyze return on equity of biogas stations which are under consideration because it is one of the main coefficient which is used by investors and owners of enterprises. This coefficient shows effectiveness of usage of invested money in biogas stations. The difference between return on equity (ROE) and return on assets is that ROE shows effectiveness not of all assets (as ROA) and only those which belong to owners of an enterprise [13].

We will calculate the coefficient of return on equity using the next formula:

The coefficient of return on equity = net profit/shareholders' equity.

As it was mentioned above, this ratio is used by investors and owners of an enterprise to assess the efficiency of shareholders' equity. The higher index of the coefficient is, the profitable investments are. If return on equity is under zero, there is a reason to think about expedience and effectiveness of investments in the future. As a rule, the ratio of the coefficient is compared to alternative investments of money in stock of other enterprises, loan securities and, in some cases, in a bank.

It is important to indicate that the very high ratio may effect negatively financial stability of an enterprise. From one side, the higher return on equity is, the better it is. But, the high ratio may appear because of very high financial instruments, i.e. a big part of borrowed capital and a small part of equity that negatively effect financial stability of an enterprise. It shows the main rule of business—the bigger profit is, the bigger risk is. Let us calculate and analyze the coefficient of return on equity of Polish biogas stations which are under consideration for 2013–2015 in Table 2.

According to the table we can conclude that investments which were laid-down in Biogazownia Drozdowo Sp. z o.o. were used effectively because the index of return on equity is more than zero even if dynamics is negative and has tendency to reduction. During researched period the coefficient of return on equity decreased by

Table 2 The coefficients of return of equity of Polish biogas stations for 2013–2015 (%)

Enterprises	2013	2014	2015	Deviation (±)
Biogazownia Drozdowo Sp. z o.o.	268.42	114.85	125.15	−143.27
Biogazownia Ostrzeszów Sp. z o.o.	−5.89	−1.09	−28.74	−22.85
Biogazownia Prusinowice Sp. z o.o.	11.47	−117.94	22	10.53
Spółka Rolna Dretyń Biogazownia Sp. z o.o	−11.73	−3.28	−2.67	9.06

Source Own research

143.27 pp. In 2015 the coefficient of return of equity was 125.15% and in comparison with 2014 this index increased by 10.3 pp. The reason of it was increase of equity in 2015 that is positive for the enterprise and indicates effectiveness of usage of capital which is invested by owners of enterprises. The decrease of the index from −5.89 to −28.74% during 4 years is observed in Biogazownia Ostrzeszów Sp. z o.o. It indicates that investments in equity of this company are not expedient because the coefficient of return is less than zero and has a tendency to reduction.

In cases of Biogazownia Prusinowice Sp. z o.o. coefficient of equity for the period 2013–2015 has a tendency to increase. In 2015 this coefficient was 22% that is 10.53 percentage points (pp) bigger in comparison with 2013. Positive tendency is also observed in Spółka Rolna Dretyń Biogazownia Sp. z o.o. In 2015 the coefficient was −2.67% that is 9.06 pp. higher in comparison with 2013. But, this index is less than zero. We can say that invested capital is used effectively.

We can explain the huge difference between ROA and ROE by the fact that all biogas stations are parts of their parent companies, so own capital is small and the result of calculations shows a big difference between this ratios.

4.3 *Liquidity Ratio*

4.3.1 Quick Liquidity Ratio

Quick liquidity ratio characterizes the ability of an organization to pay off its short-term liabilities. The coefficient of quick liquidity is calculated by division of liquid deducting inventory by short-term liabilities. This could be also written as:

The coefficient of quick liquidity = (prepayments and deferred current assets + short-term financial assets + short-term accounts receivable)/short-term liabilities [14].

Another version

The coefficient of quick liquidity = (circulating assets − resources)/short-term liabilities. This coefficient shows possibility to pay off current liabilities, if the

Table 3 The coefficients of quick liquidity ratio of Polish biogas stations for 2013–2015

Enterprises	2013	2014	2015	Deviation (±)
Biogazownia Drozdowo Sp. z o.o.	59.9	0.80	20.39	−39.51
Biogazownia Ostrzeszów Sp. z o.o.	47.05	1.18	0.80	−46.25
Biogazownia Prusinowice Sp. z o.o.	–	1442.50	1247.08	1247.08
Spółka Rolna Dretyń Biogazownia Sp. z o.o	0.67	2.47	2.09	1.43

Source Own research

situation will be really critical, one may offer that inventory holdings have not liquidating value.

Holdings are seemed to be the least liquid assets. It is very difficult to convert them into cash [15] (Table 3).

The higher quick liquidity ratio is, the better financial condition of the company is. It is obvious that in Biogazownia Drozdowo Sp. z o.o. the coefficient is more than 1 in 2013 and 2015. The value of 1.0 and more is a norm. It indicates the ability of the enterprise to fulfill short-term liabilities using all current assets.

At the same time, the coefficient may differ in different branches. When the coefficient is less than 1, liquid assets do not cover current liabilities, as a result, there is a risk to lose paying capacity that is a negative signal for investors. Such type of situation we can observe in Biogazownia Drozdowo Sp. z o.o. in 2014, in Biogazownia Ostrzeszów Sp. z o.o. in 2015 and in Spółka Rolna Dretyń Biogazownia Sp. z o.o in 2013.

It should be mentioned that the coefficients of quick liquidity of Biogazownia Ostrzeszów Sp. z o.o. during the researched period tends to reduction. The main reason was increase in short-term liability in 2014 and 2015 in comparison with 2013 to 3394.54 thousand zloty and 1178.54 thousand zloty accordingly.

Researching dynamics of liquidity ratio of Spółka Rolna Dretyń Biogazownia Sp. z o.o. for 2013–2015, one may indicate that they approached the most to normative values and during the researched period of time increased to 2.09 that shows the ability of the biogas station to fulfill its short-term financial liabilities in time.

4.3.2 Cash Ratio

Cash ratio is financial ratio which is used to analyze liquidity of a company calculating the coefficient between all cash assets, cash equivalent assets and all current liabilities. Cash ratio characterizes the ability of a company to pay off current liabilities (and in what part) using liquid calculating assets and other free assets. Current amount of cash and also its equivalents—market securities, deposits and other absolute liquid assets are taken into consideration [14].

Cash is current monetary funds which are saved in a cash register of an enterprise. Cash register is formed by initial part of cash and difference between intake and outlay. Because current reserves do not bring profit, entrepreneurs try to reduce them to the minimum which is reasonable for paying for clients, counteragents and other current expenses [14].

As the model Cash Ratio measures only the most liquid assets regarding to current liabilities, this ratio is researched as the most conservative liquid ration [14].

In other words, ratio demonstrates the ability of a company to pay its current liabilities not laying on selling its inventory holdings and getting bill receivable. It characterizes the ability immediately to pay off current short-term liabilities of enterprises—that is, availability of resources which can satisfy demands of creditors in the critical situation. As a result, this ratio is taken into consideration by future providers in relatively short terms of crediting. Absolute liquidity of an enterprise is less important for strategic investors [3].

The formula of cash ratio:

CR (Cash Ratio) = cash and cash equivalents/short-term liabilities [14].

Let us calculate absolute liquid cash ratio of Polish biogas stations which are under consideration in Table 4.

According to this table, we can conclude that for 2013–2015 biogas stations were able to pay off current liabilities at the expense of liquid working capital and other free assets. Considering dynamics of coefficients of monetary liquidity of Biogazownia Drozdowo Sp. z.o.o., we can conclude that the liquidity is growing rapidly, in 2015 this ratio was 12.4, which is 10.8 more than in 2013.

We can observe the reverse trend considering dynamics of liquidity ratio of Biogazownia Ostrzeszów Sp. z. o.o. In 2015 it was 0.74, which is 43.53 less than in 2013. Despite apparent easiness of the analysis (the higher ratio is, the better it is), it is not so simple. From the one hand, of course, the more part of the short-term liabilities the biogas stations can instantly pay off, the more stable it will be.

From the other hand, large cash balances are evidence of their inefficient usage. That is, if in 2015 the coefficient was 0.74, which is closer to the normative value, the better it is. If there is a constant growing balance of financial resources in financial activities of biogas stations, it is expedient either to reinvest in the same activity, for example, to build another biogas station, or to reward shareholders or employees.

Table 4 The cash ratio of Polish biogas stations for 2013–2015

Enterprises	2013	2014	2015	Deviation (±)
Biogazownia Drozdowo Sp. z o.o.	1.60	0.77	12.40	10.80
Biogazownia Ostrzeszów Sp. z o.o.	44.27	0.76	0.74	−43.53
Biogazownia Prusinowice Sp. z o.o.	22.27	–	78.66	56.39
Spółka Rolna Dretyń Biogazownia Sp. z o.o	0.58	2.46	2.08	1.50

Source Own research

It is also important to note here that decline in the absolute liquidity ratio can point not only at deteriorating solvency and liquidity of Biogazownia Ostrzeszów Sp. z o.o, but at increasing of efficiency of usage of assets. This often happens when the value of the coefficient is much higher than the normative value, which we notice in this case.

Considering coefficients of cash liquidity of Biogazownia Prusinowice Sp. z o.o. and Spółka Rolna Dretyń Biogazownia Sp. z o.o we can also conclude that the financial situation of these biogas stations has improved.

5 Conclusion

Recent years have shown a significant development of the biogas industry in Poland. Over the past couple of years, the number of biogas units has almost doubled, which may indicate profitability of investments. Also, an analysis of the profitability ratios shows the high profitability and effectiveness of the biogas plants for 2013–2015. Liquidity ratios also show a high level of solvency of biogas stations on short-term debts.

Also, a high liquidity ratio is observed in almost all biogas stations, this indicates that management is not operating effectively enough. This indicates the availability of unused cash, excess inventory that exceeds current needs. The indicators of profitability make it possible to assess the effectiveness of the management of the enterprise using its assets.

References

1. Alayi, R., Shamel, A., Kasaeian, A., Harasii, H., Topchlar, M.A.: The role of biogas to sustainable development (aspects environmental, security and economic). J. Chem. Pharm. Res. **8**(4), 112–118 (2016). http://www.jocpr.com/articles/the-role-of-biogas-to-sustainabledevelopment-aspects-environmental-security-and-economic.pdf
2. Kucher, O.: Problems of management and marketing in the enterprises activity of agriculture. In: Scientific Achievements in Agricultural Engineering, Agronomy and Veterinary Medicine, Issue 1, pp. 31–41 (2017) (ISBN: 978-83-65180-17-9)
3. Szymanska, D., Lewandowska, A.: Biogas power plants in poland—structure, capacity, and spatial distribution. In: Sustainability, №7 (2015). doi:https://doi.org/10.3390/su71215846
4. Hindls, R. Economic statistics or statistical methods in economics? In: Statistika **94**(4), 67–72 (2014). https://www.czso.cz/documents/10180/25609550/32019714q4067.pdf/1508a283-be63-40e2-bcf2-d3c4338563f5?version=1.0 (Prague, Czech Republic)
5. Yakubiv, V.: Accounting and analytical methods of diagnostics improvement for enterprises' organizational development. In: Economic Annals XXI **3–4**(1), 68–71 (2015). http://soskin.info/userfiles/file/2015/3-4_1_2015/Yakubiv.pdf
6. Rejman-Burzyńska, A., Maksymiak-lach, H., Jędrysik, E. The energy potential of biogas—an estimation of biogas production resources in Poland. Chemik **67**(5), 450–453 (2013). http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-96596d4f-9b77-4160-bd8742d51ba20a27/c/5_13__Burzynska_GB.PDF

7. Pazera, A., Slezak, R., Krzystek, L., Ledakowicz, S., Bochmann, G., Gabauer, W., Helm, S.: Biogas in Europe: food and beverage (FAB) waste potential for biogas production. In: 2nd International Scientific Conference Biogas Science Energy and fuels. American Chemical Society (2015). https://doi.org/10.1021/ef502812s
8. Baum, R., Wajszczuk, K., Pepliński, B., Wawrzynowicz, J.: Potential for agricultural biomass production for energy purposes in Poland: a review. Contemp. Econom. **7**(1), 63–74 (2013). https://doi.org/10.5709/ce.1897-9254.74
9. Chodkowska-Miszczuk, J., Szymańska, D.: Gricultural biogas plants—a chance for diversification of agriculture in Poland. Renew. Sustain. Energy Rev. **20**, 514–518 (2013). http://dx.doi.org/10.1016/j.rser.2012.12.013
10. Foged, H.L., Johnson, L.K.: The environmental technology and bioenergy sector in Poland. Market description. In: Innovation Network for Biomass, pp. 6–7 (2010). http://www.inbiom.dk/Files/Files/Publikationer/bioenergy_market_description_poland_web.pdf
11. Rosicki, R., Rosicki, G.: Biogas, agricultural biogas and biogas plants in Poland—selected statistical and legal aspects. Fac. Political Sci. Journal (2013). https://repozytorium.amu.edu.pl/bitstream/10593/11340/1/Biogas,%20agricultural%20biogas%20and%20biogas%20plants%20in%20Poland%20-%20selected%20statistical%20and%20legal%20aspects.pdf
12. Alghifari, E.S., Triharjono, S., Juhaeni, Y.S.: Effect of return on assets (ROA) against Tobin's Q: studies in food and beverage company in Indonesia stock exchange years 2007–2011. Int. J. Sci. Res. (IJSR) **2**(1) (2013). India Online ISSN: 2319-7064. https://www.ijsr.net/archive/v2i1/IJSRON2013372.pdf
13. Reuters, T.: Tax and accounting. Financial analysis CS: sample reports (2008). https://cs.thomsonreuters.com/ua/acct_pr/fina/cs_us_en/pdfs/fina_sample_reports.pdf
14. Kirkham, R.: Liquidity analysis using cash flow ratios and traditional ratios: the telecommunications. J. New Bus. Ideas Trends **10**(1), 1–13 (2012). http://jnbit.org/upload/JNBIT_Kirkham_2012_1.pdf
15. Costea, C.D., Hostiuc, F.: The liquidity ratios and their significance in the financial equilibrium of the firms. In: The Annals of The "Ştefan cel Mare" University Suceava, vol. 9, No. 1, pp. 252–261. Fascicle of The Faculty of Economics and Public Administration (2009). http://www.seap.usv.ro/annals/ojs/index.php/annals/article/viewFile/176/18

The Influence of Weather Conditions and Operating Parameters on the Efficiency of Solar Power Collectors Based on Empirical Evidence

Aldona Skotnicka-Siepsiak, Maciej Wesołowski, Maciej Neugebauer, Janusz Piechocki and Piotr Sołowiej

Abstract The influence of solar irradiance, ambient temperature and buffer tank temperature on the efficiency of solar collectors was evaluated in the climatic conditions of north-eastern Poland (climatic zone IV) characterized by relatively low irradiance (annual average of 900 kWh/m^2). Two types of solar power collectors (flat-plate and evacuated tube collectors) were compared in terms of energy gains, collector efficiency and glycol temperature between May and September 2016. The collectors were mounted on the roof of a building on the campus of the University of Warmia and Mazury in Olsztyn. The roof had a pitch of 45°, the collectors had a tilt angle of 30°, and they faced west of true south. Measurements were performed separately for the analyzed solar collector systems operating simultaneously in identical weather conditions. The combined absorber surface was 4.64 m^2 in flat-plate collectors and 3.23 m^2 in the evacuated tube collector. Both systems were connected to a water buffer tank. Empirical data were recorded with a controller and were processed and stored in a computer. The factors responsible for differences in the efficiency of the examined collectors are discussed in the paper.

Keywords Flat-plate solar collectors · Evacuated tube collectors
Efficiency of solar collectors

A. Skotnicka-Siepsiak (✉)
Institute of Building Engineering, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: aldona.skotnicka-siepsiak@uwm.edu.pl

M. Wesołowski · M. Neugebauer · J. Piechocki · P. Sołowiej
Department of Electrical, Power, Electronic and Control Engineering, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: mwesolowski@uwm.edu.pl

M. Neugebauer
e-mail: mak@uwm.edu.pl

J. Piechocki
e-mail: jpt@uwm.edu.pl

P. Sołowiej
e-mail: pit@uwm.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_10

1 Introduction

The continued depletion of fossil fuel resources has increased the popularity of systems capable of harnessing solar energy. At the end of 2016, solar power collectors spanned a total area of 652 million square meters around the globe (456 GWth). However, this impressive result does not reflect current market trends, in particular in China and most European countries, where heat pumps and photovoltaic panels are gradually detracting from the popularity of domestic solar thermal systems [1]. A reverse trend is noted on the Polish market of renewable energy sources. According to the Institute for Renewable Energy, solar thermal collectors are the most popular renewable energy microgeneration systems in Poland with around 174,000 systems in place. In comparison, only around 25,000 heat pumps (including geothermal) and 90,000 automatic, dedicated biomass boilers have been installed in Poland to date [2].

In this study, the efficiency of solar thermal collectors was analyzed in the climate of north-eastern Poland. The experimental set-up was composed of flat-plate solar collectors (active absorber area of 4.64 m^2) and an evacuated tube collector (active area of 3.23 m^2) connected to a buffer storage tank with the volume of 1000 dm^3. The influence of selected factors on the efficiency of both solar collector systems was analyzed.

The tested weather conditions were the temperature of ambient air and solar irradiance which differ across geographic locations. In the present study, the measured parameters were compared with Typical Meteorological Year (TMY) data for 1971–2000 in the examined location [3]. The efficiency of solar collectors is frequently analyzed in a real-life environment due to global climate change and differences between statistical data and measured parameters. Halawa, Chang and Yoshinaga examined the applicability of solar power collectors for heating household water in Australia, Taiwan and Japan [4]. The potential of solar power collectors was evaluated in Beirut by Sakkal et al. [5]. Merrouni et al. [6] analyzed the location of solar power collectors in Morocco. The applicability of solar collectors for sustainable energy generation in Nigeria was evaluated by Giwa et al. [7]. The efficiency of solar power collectors in a cold climate was investigated by Musard [8].

The influence of selected operating parameters on the efficiency of solar power collectors was also evaluated in the literature. Solar collectors are influenced by many factors that are unrelated to climate. In a study by Elbreki et al., these factors were divided into climate parameters, design parameters and operational parameters [9]. Flow rate is one of the key determinants of the efficiency of solar power systems. This parameter is often analyzed in the literature. Heat transfer under laminar flow conditions was investigated by Weitbrecht et al. [10]. Gao et al. [11] analyzed the influence of thermal mass and flow rate on the efficiency of water-in-glass and U-pipe evacuated tube solar collectors. Cunio and Sproul [12] examined a typical solar pool heating system and found that systems with a low-power pump and reduced flow rate did not significantly compromise the efficiency of solar power collectors. Razika et al. demonstrated that collector efficiency is a linear function of mass flow rate, volume flow rate, velocity and inclination angle. When the inclination angle and the volumetric flow rate increase, collector efficiency increases [13]. Some authors have proposed optimal flow rates. Hobbi and Siddiqui [14] analyzed flat-plate collectors in a solar water heating system with forced circulation and noted that the collector loop flow rate should range from 20 to 40 kg/h m^2. Bava et al. [15] developed a numerical model to evaluate flow distribution. In some studies, the influence of flow rate on collector efficiency was evaluated [16]. In the collector system described in this study, the effects of flow rate will be addressed by future research. In the present experiment, flow rate was kept constant (5 l/min for flat-plate collectors and 7 l/min for evacuated tube collectors) to eliminate the influence of variable flow on system efficiency.

The influence of the following factors was also analyzed: (1) water temperature in the buffer storage tank, (2) temperature of glycol at the collector outlet, and (3) difference between the temperature of the working fluid at the collector outlet and ambient temperature. The above parameters were selected to facilitate measurements in small domestic systems. In the literature, various operating parameters have been analyzed to determine their impact on the operation and efficiency of solar power systems. They include temperature stratification in the buffer tank and its influence on system efficiency. Cristofari et al. [17] demonstrated that a stratified tank significantly outperforms a fully mixed tank. A stratified tank produced greater energy savings (5.25% per year) than a fully mixed tank. Stratification and its influence on energy accumulation were analyzed by Haller et al. [18]. Rodríguez-Hidalgo et al. [19] demonstrated that the average annual efficiency of a solar collector was most significantly influenced by wind losses (−15.6%), collector aging (−15.0%), incident angle modifier (−7.6%), thermal inertia (−3.2%) and external radiation losses (−1.3%).

2 Materials and Methods

2.1 Test Stand

The experiment was carried out between 1 May and 30 September 2016 at the Institute of Construction Engineering of the University of Warmia and Mazury in Olsztyn. Data for 6–11 July 2016 were not recorded due to technical problems. The hydraulic design of the analyzed solar power collector systems is presented in Fig. 1.

The tested systems were composed of an evacuated tube collector and flat-plate collectors mounted on a roof with 45° pitch and facing west of true south. Solar irradiance, temperature of ambient air, temperature at the collector inlet and outlet (measured separately for the evacuated tube collector and flat-plate collectors), flow

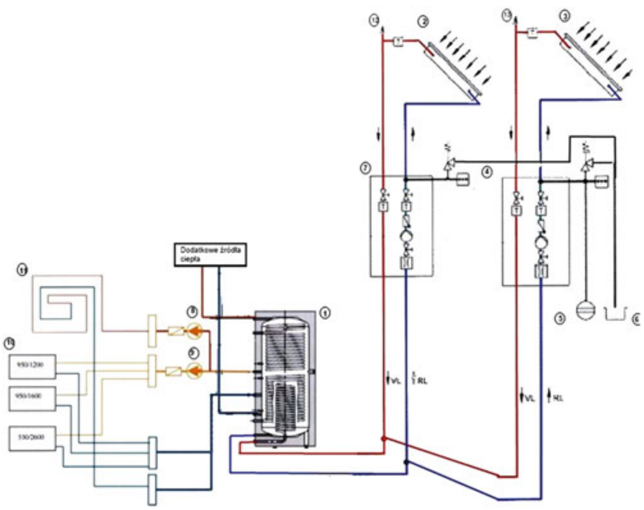


Fig. 1 Hydraulic design of the analyzed system. (1) Water buffer tank, (2) flat-plate collectors (absorber area of 4.64 m^2), (3) evacuated tube collector (absorber area of 3.23 m^2), (4) pump module of an evacuated tube collector, (5) expansion vessel, (6) emptying tank, (7) pump module of a flat-plate collector, (8) floor circuit pump, (9) radiator circuit pump, (10) radiators, (11) floor heating (4.75 m^2), (12) vent valves in the flat-plate collector system, (13) vent valves in the evacuated tube collector system

Table 1 The efficiency and heat loss factors of solar power collectors determined in Solar Keymark tests [20]

	Flat-plate	Evacuated tube
Optical efficiency [%]	74.3	78.9
Heat loss factor k_1 [W/(m^2 K^2)]	4.16	1.36
Heat loss factor k_2 [W/(m^2 K^2)]	0.0124	0.0075

rate in the evacuated tube collector and flat-plate collectors were measured at hourly intervals. Solar irradiance was measured with the use of the Kipp&Zonnen CMP3 pyranometer (directional error at 80° with 1000 W/m^2 beam <20 W/m^2). Temperature was measured with Siemens QAP21.2 cable temperature sensors, Siemens QAE2111.010 immersion temperature sensors and Siemens QAC22 outside temperature sensor to the nearest 0.4 °C. The efficiency and heat loss factors of the analyzed solar power collectors determined in Solar Keymark tests are presented in Table 1.

2.2 Calculations

The measured parameters were used to calculate the efficiency of solar power collectors with the use of the following formula:

$$\eta = \eta_0 - \frac{k_1 \cdot \Delta T}{E_g} - \frac{k_2 \cdot \Delta T^2}{E_g} \quad (1)$$

where: η_0—optical efficiency; k_1, k_2—heat loss factors; ΔT—temperature differential between the absorber and ambient outside air temperature; E_g—irradiance.

Instantaneous efficiency was calculated with the below formula:

$$\eta = \frac{Q}{A \cdot E_g} = \frac{\sum_{i=1}^{n} \rho(i) * c_w(i) * V'(i) * (\vartheta_v(i) - \vartheta_R(i))}{A \cdot E_g} \quad (2)$$

where: Q—heat expressed in [W]; $\rho(i)$—liquid density, expressed in [kg/m^3]; $c_w(i)$—specific heat of liquid, expressed in [Wh/kg deg]; $V'(i)$—average flow rate of liquid, expressed in [m^3/h]; $\vartheta_v(i)$—liquid temperature at collector outlet, expressed in [°C]; $\vartheta_R(i)$—liquid temperature at collector inlet, expressed in [°C]; i—time interval 1 h; A—collector gross area [m^2].

The influence of the above parameters on the efficiency of the solar collector system was determined by linear regression analysis in the Analysis ToolPak add-in program in Excel.

3 Results

3.1 Weather Conditions

Weather conditions were favorable for the operation of solar power collectors in the experimental period between May and September 2016.

The average hourly temperatures of ambient air measured in the experiment and obtained from a TMY database [3] are presented in Fig. 2. The measured average hourly temperature was 17.5 °C, and it was 2.8 °C higher than the average TMY temperature of 14.7 °C. The minimum average hourly temperature was determined at 5.4 °C based on measured data and at −3.2 °C based on TMY data. The measured maximum average hourly temperature was 32.1 °C, and it was 1.1 °C higher than the maximum TMY value of 31.0 °C.

The analyzed data covered a total of 3552 h (data for 6–11 July 2016 are not available), including 1371 h with zero irradiation in experimental measurements and 1504 h with zero irradiation in the TMY database. Irradiation exceeded 800 Wh/m^2 during 366 h of measurements and only 67 h in the TMY database.

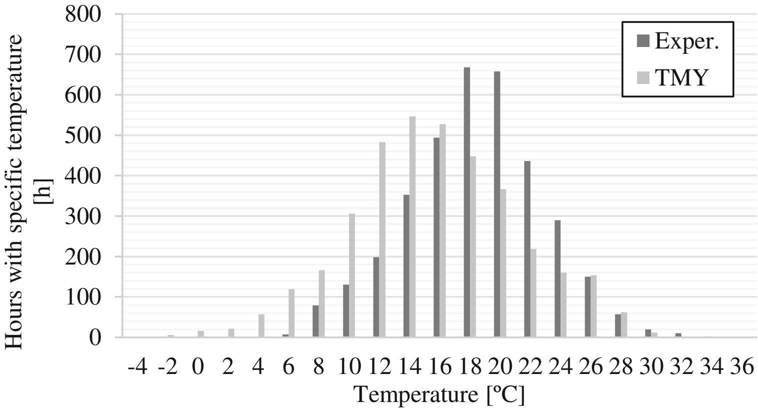


Fig. 2 Distribution of air temperatures between May and September 2016 in Olsztyn based on the performed measurements and a meteorological database (TMY) [3]

3.2 Energy Gains in the Analyzed Solar Power Collectors

In the analyzed period, total energy gains per 1 m^2 for the whole period, reached 87.0 kWh/m^2 in the flat-plate collector system and 265.6 kWh/m^2 in the evacuated tube collector system (Table 2). Maximum hourly energy gain was determined at 0.13 kWh/m^2 in the flat-plate collector at 2 PM on 14 August, and at 1.00 kWh/m^2 in the evacuated tube collector at 3 PM on 26 May.

3.3 Efficiency of the Analyzed Solar Power Collectors

Based on the results of the calculations performed with the use of formula (1), the average efficiency of a flat-plate solar collector was 63% (median of 67%) and the average efficiency of an evacuated tube collector was 72% (median of 71%).

Table 2 Montly energy gains from solar installations kWh and per 1 m^2 kollektor in [kWh/m^2]

Month	Flat-plate, kWh [kWh/m^2]	Evacuated tube, kWh [kWh/m^2]
May	84.6 [18.2]	193.8 [60.0]
June	96.0 [20.7]	205.9 [63.7]
July	73.4 [15.8][a]	145.0 [44.9][a]
August	81.4 [17.5]	165.4 [51.2]
September	68.9 [14.8]	148.1 [45.8]
Total	404.3 [87.0]	858.2 [265.6]

[a]Data not available for 6–11 July 2016

In a real-life environment, flat-plate collectors were characterized by a smaller difference between ambient temperature and absorber temperature (average difference of 7.9 K for a flat-plate collector and 10.0 K for an evacuated tube collector). The measured efficiency of flat-plate collectors was also lower than that given by the manufacturer (Fig. 3). Figure 3 shows the tendency of changes in measured values for analyzed collectors.

The influence of the following explanatory variables on the efficiency of solar power collectors was determined in a linear regression analysis based on hourly values:

X_1 solar irradiance;
X_2 temperature of ambient air;
X_3 temperature at the bottom of the buffer storage tank;
X_4 temperature of the working fluid at collector outlet;
X_5 difference in temperature between ambient temperature and temperature at collector outlet.

The influence of the analyzed parameters on collector efficiency is presented in Table 3.

The values X_n in Table 3 refer to statistical functions of linear regression analysis which explains the influence of the analyzed factors on the investigated variable.

Formulas 1 and 2 are explained in Sect. 2.2 Calculations. Coefficient of determination R^2 reaches higher values when the percentage of explained variation of dependent variable by a given predictor is higher. Coefficient "b" in the equation $y = bX_n + a$ is an unstandardized regression coefficient and reflects the slope of regression line.

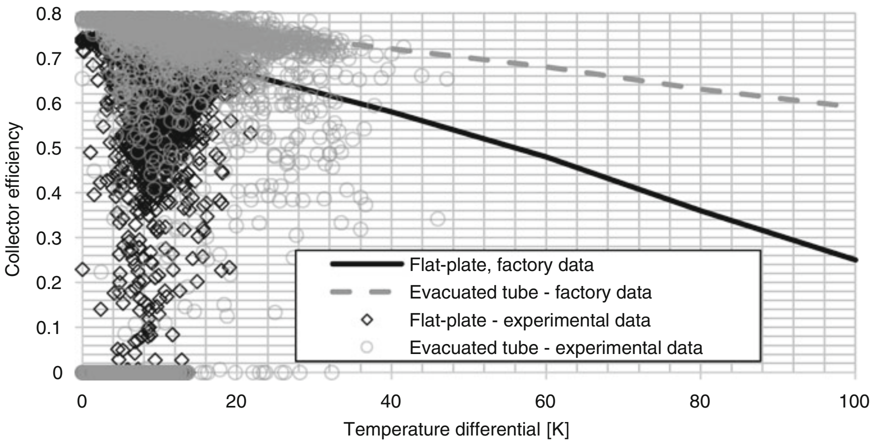


Fig. 3 Efficiency of solar power collectors—comparison of experimental and published data [20]

Table 3 Statistical distribution of parameters influencing the efficiency of solar collectors

Explanatory variable	Flat-plate		Evacuated tube	
	Formula (1)	Formula (2)	Formula (1)	Formula (2)
X_1	$R^2 = 0.3465$	$R^2 = 0.081$	$R^2 = 0.3083$	$R^2 = 0.0770$
	$y = 0.007X_1 + 0.2422$	$y = -0.0198X_1 + 0.3075$	$y = 0.007X_1 + 0.3033$	$y = -0.0131X_1 + 0.4294$
X_2	$R^2 = 0.0265$	$R^2 = 0.0010$	$R^2 = 0.0470$	$R^2 = 0.0133$
	$y = 0.0119X_2 + 0.1607$	$y = 0.0005X_2 - 0.2086$	$y = 0.0177X_2 + 0.1279$	$y = 0.0028X_2 - 0.3216$
X_3	$R^2 = 0.0011$	$R^2 = 0.0770$	$R^2 = 0.0091$	$R^2 = 0.0106$
	$y = 0.0032X_3 + 0.2884$	$y = -0.0067X_3 + 0.3847$	$y = 0.0104X_3 + 0.1765$	$y = -0.0038X_3 - 0.4643$
X_4	$R^2 = 0.1820$	$R^2 = 0.0749$	$R^2 = 0.1400$	$R^2 = 0.0787$
	$y = 0.0180X_4 - 0.1221$	$y = -0.0050X_4 - 0.3540$	$y = 0.0097X_4 + 0.1402$	$y = 0.0056X_4 - 0.2004$
X_5	$R^2 = 0.2510$	$R^2 = 0.1508$	$R^2 = 0.1126$	$R^2 = 0.0492$
	$y = 0.0348X_5 + 0.2346$	$y = -0.0089X_5 + 0.3043$	$y = 0.0118X_5 + 0.3668$	$y = 0.0053X_5 + 0.3012$

Solar irradiance had the greatest influence on the efficiency of both collector systems (Fig. 3). In comparison with the evacuated tube collector, flat-plate solar collectors were more than twice as susceptible to the difference between ambient temperature and the temperature at the collector outlet. This is the second key predictor of the efficiency of flat-plate collectors, whereas the efficiency of the evacuated tube collector was more significantly influenced by the temperature at the collector outlet. The next predictor was the temperature of ambient air which exerted nearly a twice greater influence on the evacuated tube collector than on flat-plate collectors. System efficiency increased with a rise in ambient temperature. The temperature inside the buffer was the least influential variable. However, the unstandardized regression coefficient was more than three-fold higher in the evacuated tube collector, which indicates that collector efficiency increased at a faster rate with a rise in buffer tank temperature (Fig. 4).

Significant variations were also observed in the rate of changes in collector efficiency resulting from differences between ambient temperature and the temperature at the collector outlet. The above temperature differential led to a nearly

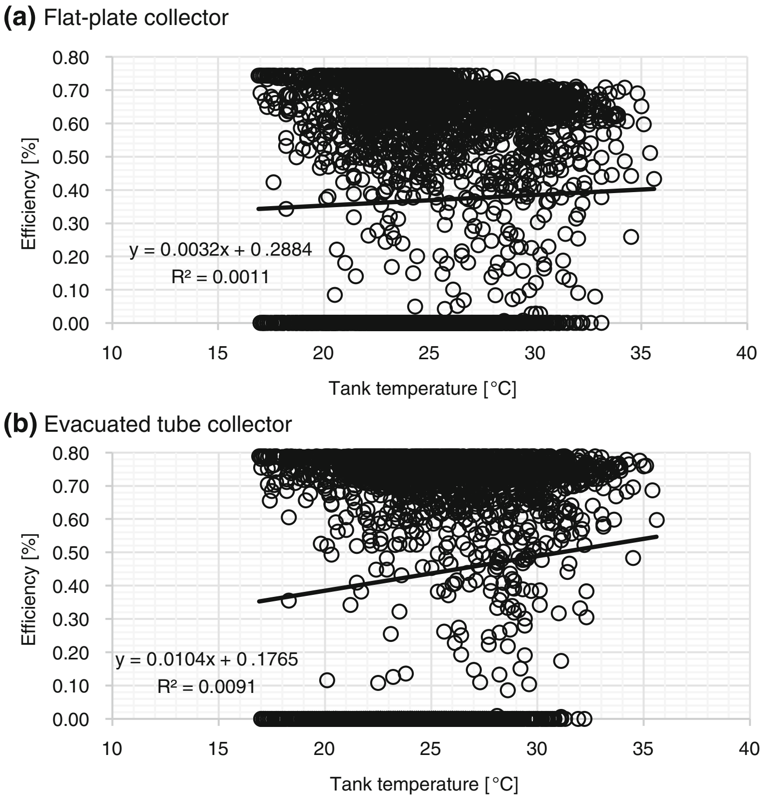


Fig. 4 Correlations between the efficiency of flat-plate collectors

2.5-fold higher increase in the efficiency of the evacuated tube collector than flat-plate collectors.

An efficiency analysis based on formula (2) supported the determination of the statistical distribution of parameters influencing the efficiency of solar collectors (Table 3). It should be noted that formula (2) produced significantly lower efficiency values than formula (1). Average hourly efficiency (calculated based on hours with positive energy gain) reached 22% in flat-plate collectors and 37% in the evacuated tube collector, whereas the median was determined at 14% in flat-plate collectors and 33% in the evacuated tube collector. Due to the inertia of the analyzed collectors and delayed responses of hydraulic actuator devices to changes in external conditions during steady flow of the working fluid, the relevant calculations were performed for daily values.

The average daily efficiency of flat-plate collectors was most significantly influenced by the difference between ambient temperature and the temperature at the collector outlet. Daily efficiency increased with a drop in the above temperature differential. In the evacuated tube collector, the temperature differential was 1.8-fold less significant and was characterized by a reverse correlation—daily efficiency increased with a rise in the temperature differential. The daily efficiency of the evacuated tube collector was most significantly influenced by the temperature at the collector outlet, and an increase in this parameter led to a rise in collector efficiency. Solar irradiance has a similar impact on the efficiency of the evacuated tube collector (R^2 of approx. 0.08), whereas the efficiency of flat-plate collectors was also influenced by buffer tank temperature and the temperature of the working fluid at the collector outlet. The influence of buffer tank temperature on the efficiency of the evacuated tube collector was approximately 7-fold lower. The strength of the association between daily efficiency of the evacuated tube collector and ambient temperature was similar. The influence of ambient temperature on the efficiency of flat-plate collectors was even 10-fold lower.

4 Conclusions

1. The measured average hourly temperatures of ambient air were 2.8 °C higher than TMY data, and the number of hours with irradiance higher than 800 Wh/m^2 was 300 higher in the measured dataset than in the TMY database.
2. Between May and September 2016, the specific heat capacity of flat-plate collectors was determined at 87 kWh/m^2 when average hourly efficiency reached 22% in the performed calculations (formula 2) and 63% in the Solar Keymark test (formula 1). The energy gain of the evacuated tube collector was 178.6 kWh/m^2 (according Table 2) higher when average hourly efficiency reached 37% in the performed calculations (formula 2) and 72% in the Solar Keymark test (formula 1). The observed variations in efficiency could be attributed to differences between the standard testing conditions in the Solar Keymark test and the parameters measured in a real-life environment.

3. The results of linear regression analysis revealed that solar irradiance is the key determinant of efficiency in both collector systems. The difference between the temperature of the working fluid inside the collector and ambient temperature had a negative effect on the efficiency of both types of collectors, where the drop in efficiency associated with an increase in the above temperature differential was more than twice higher in flat-plate collectors than in the evacuated tube collector. As buffer temperature increased, the resulting drop in efficiency was three-times higher in flat-plate collectors than in the evacuated tube collector.

References

1. Solar Heating & Cooling Programme International Energy Agency: Solar heat worldwide global market development and trends in 2016, http://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2017.pdf. Last accessed 2017/06/03
2. Instytut Energii Odnawialnej, Krajowy Plan Rozwoju Mikroinstalacji Odnawialnych Źródeł Energii do roku 2030, http://ieo.pl/pl/raporty/53-krajowy-plan-rozwoju-mikroinstalacji-oze-do-roku-2030-ieo-dla-wne/file. Last accessed 2017/06/05
3. Ministerstwo Infrastruktury i Budownictwa: Homepage, http://mib.gov.pl/files/0/1796817/wmo122720iso.zip. Last accessed 2017/06/03
4. Halawa, E., Chang, K.C., Yoshinaga, M.: Thermal performance evaluation of solar water heating systems in Australia, Taiwan and Japan—a comparative review. Renew. Energy **83**, 1279–1286 (2015)
5. Sakkal, F., Ghaddar, N., Diab, J.: Solar collectors for the Beirut climate. Appl. Energy **45**(4), 313–325 (1993)
6. Merrouni, A.A., Mezrhab, A., Mezrhab, A.: PV sites suitability analysis in the Eastern region of Morocco. Sustain. Energy Technol. Assess. **18**, 6–15 (2016)
7. Giwa, A., et al.: A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. Renew. Sustain. Energy Rev. **69**, 620–641 (2017)
8. Mussard, M.: Solar energy under cold climatic conditions: a review. Renew. Sustain. Energy Rev. **74**, 733–745 (2017)
9. Elbreki, A.M., et al.: The role of climatic-design-operational parameters on combined PV/T collector performance: a critical review. Renew. Sustain. Energy Rev. **57**, 602–647 (2016)
10. Weitbrecht, V., Lehmann, D., Richter, A.: Flow distribution in solar collectors with laminar flow conditions. Sol. Energy **73**(6), 433–441 (2002)
11. Gao, Y., et al.: Effects of thermal mass and flow rate on forced-circulation solar hot-water system: comparison of water-in-glass and U-pipe evacuated-tube solar collectors. Sol. Energy **98**, 290–301 (2013)
12. Cunio, L.N., Sproul, A.B.: Performance characterisation and energy savings of uncovered swimming pool solar collectors under reduced flow rate conditions. Sol. Energy **86**(5), 1511–1517 (2012)
13. Razika, I., Nabila, I., Madani, B., Zohra, H.F.: The effects of volumetric flow rate and inclination angle on the performance of a solar thermal collector. Energy Convers. Manag. **78**, 931–937 (2014)
14. Hobbi, A., Siddiqui, K.: Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Sol. Energy **83**(5), 700–714 (2009)
15. Bava, F., Dragsted, J., Furbo, S.: A numerical model to evaluate the flow distribution in a large solar collector field. Sol. Energy **143**, 31–42 (2017)

16. Chen, Z., Furbo, S., Perers, B., Fan, J., Andersen, E.: Efficiencies of flat plate solar collectors at different flow rates. Energy Proc. **30**, 65–72 (2012)
17. Cristofari, Ch., et al.: Influence of the flow rate and the tank stratification degree on the performances of a solar flat-plate collector. Int. J. Therm. Sci. **42**(5), 455–469 (2003)
18. Haller, M.Y., et al.: Methods to determine stratification efficiency of thermal energy storage processes—review and theoretical comparison. Sol. Energy **83**(10), 1847–1860 (2009)
19. Rodríguez-Hidalgo, M.C., et al.: Flat plate thermal solar collector efficiency: transient behavior under working conditions part II: model application and design contributions. Appl. Therm. Eng. **31**(14), 2385–2393 (2011)
20. VIESSMANN: Vitosol System Design Book (Viessmann Manufacturing Company Inc. 2016)

Energy and Environmental Potential of Grasslands in Poland

Wojciech Golimowski, Krystian Butlewski, Weronika Gracz, Damian Marcinkowski and Ryszard Konieczny

Abstract Grasslands are crucial in the surrounding ecosystem. Over the last five years a share of grasslands in agriculture decreased from 3.32 m ha in 2010 to 3.00 m ha in 2015, contrary to the number of cattle—from 5.86 m LSU in 2013 to 5.96 m LSU in 2015. The cultivation of grasses, legumes or mixtures of grasses positively affects the reproduction of the soil organic matter, where a reproduction coefficient ranges from +0.95 to +2.10. Just to illustrate, the cultivation of cereals—about 0.5; corn—1.1; and roots—1.2. In the carbon dioxide balance the reduction of CO_2 in grasslands is estimated to be 7 kg ha^{-1} h^{-1}. Considering the diminishing area of grasslands, the objective of research was to estimate the quantity of carbon dioxide reduced by grasslands, the potential of unused biomass and the energy potential of grasslands. Those calculations have been conducted for Polish provinces over the last four years. Research estimates that the reduction of CO_2 in meadows of grasslands in Poland amounted to 103.3 m Mg in 2016 with an upward trend over the last four years, whereas the potential of unused biomass equalled to 18.3 m Mg with a downward trend. The energy potential of grasslands was estimated for fuels such as briquette (82.4 PJ), torrefied biomass (62.5 PJ), and biogas (10.5 PJ) in 2016 with a downward trend over the last four years.

W. Golimowski (✉) · K. Butlewski · W. Gracz · D. Marcinkowski
Department of Biomass Processing Technologies, Institute of Technology and Life Sciences, 67 Biskupińska Str., 60-463 Poznań, Poland
e-mail: w.golimowski@itp.edu.pl

K. Butlewski
e-mail: k.butlewski@itp.edu.pl

W. Gracz
e-mail: w.gracz@itp.edu.pl

D. Marcinkowski
e-mail: d.marcinkowski@itp.edu.pl

R. Konieczny
Department of Agroengineering and Quality Analysis, Wrocław University of Economics, 180/120 Komandorska Str., 53-345 Wrocław, Poland
e-mail: ryszard.konieczny@ue.wroc.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_11

Keywords Grasslands · Renewable energy source · Biogas · Greenhouse gases

1 Introduction

Grasslands play a major role in the surrounding ecosystem, give shelter and food to animals, and reduce greenhouse gases. In Poland the area of grasslands diminished from 3.9 m ha in 2000 to 3.1 m ha in 2014. There are both meadows and pastures. It is easy to notice that year by year a share of pastures in the total area of grasslands dynamically decreased from 35% in 2000 to 16% in 2014 (Fig. 1). The average crop expressed as a mass of meadow hay grew from 3.7 t ha^{-1} in 2000 to 5.2 t ha^{-1} in 2014 [1, 2].

The agricultural production conducted in grasslands primarily involves the production of roughage for cattle, particularly dairy cattle. The cattle population in a group of livestock, ruminants in 2013 amounted to almost 95% [3]. The data of the Agency for Restructuring and Modernisation of Agriculture that registers livestock in Poland indicate that the livestock population (ruminants, except for calves) averagely increases by 2% per annum (Fig. 2).

Ruminants that include such livestock as cattle, sheep, goats, horses primarily graze roughage in the form of plant mass. An estimated daily full feed ration is 10% of the animal's body weight [4]. To enhance the production efficiency, e.g. milk production, a carefully balanced compound feed is applied. In the animal production ruminants are fed with roughage and concentrate feed. The concentrate feed is a source of necessary nutrients of the animal's diet. As an example, a daily ration of a dairy cow with a capacity of 20 kg of milk equals to 35 kg of roughage and about 5 kg of concentrate feed. Any change to the ration of concentrate feed considerably affects an increase in the production efficiency [5].

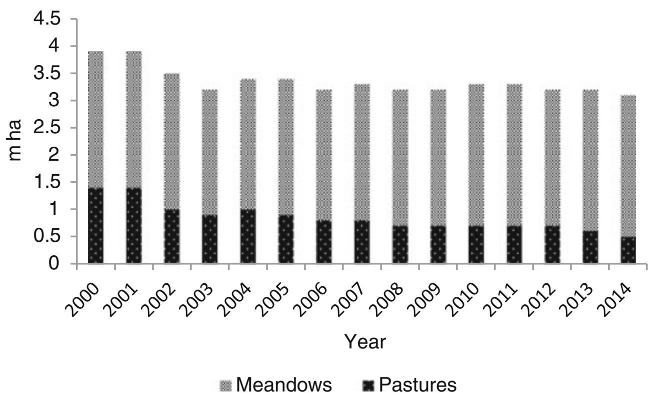


Fig. 1 Area of grasslands in Poland in the years 2000–2014

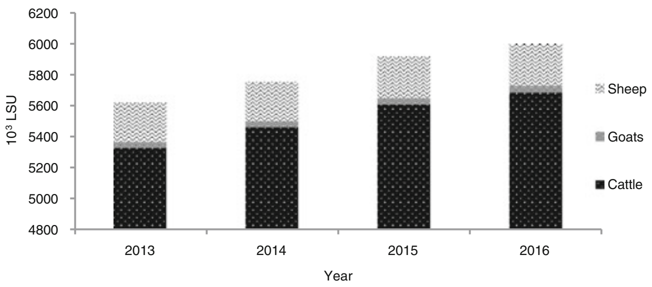


Fig. 2 Cattle population (except for calves), goats and sheep in Poland in the years 2013–2016

Apart from being a valuable source of food for animals, grasslands are also crucial for the environment. The cultivation of grasses prevents soil erosion, is a source of organic matter and keeps water in the soil [6]. The cultivation of grasses, legumes or mixtures of grasses positively affects the reproduction of the soil organic matter, where a reproduction coefficient ranges from +0.95 to +2.10. Just to illustrate, the cultivation of cereals—about 0.5; corn—1.1 and roots—1.2 [7]. Research conducted by Linfeng et al. into the impact of the climate change on the absorption of greenhouse gases by grasslands reveals that the balance of CO_2 and methane is negative. Research indicated that in the period from July to September the balance of CO_2 was −8.5 kg CO_2 ha^{-1} h^{-1} (2013) and −6.1 kg CO_2 ha^{-1} h^{-1} (2014), balance of methane was −0.37 g C ha^{-1} h^{-1} (2013) and −5.5 g C ha^{-1} h^{-1} [7]. Other research proves that the emission reduction is significantly lower and equals to around 1.2 kg CO_2 ha^{-1} h^{-1} throughout the calendar year [8]. Despite great ecological advantages, the potential of grasslands exceeds the demand for feed, which leads to the conversion of grasslands into arable lands.

To halt this shrinkage of grasslands in agricultural areas, it is necessary to develop efficient and cost-effective biomass management methods. One of the major elements is to constantly monitor the potential of biomass production [9]. Biomass deriving from various kinds of grasses is a globally appreciated energy raw material [9–12]. The energy value of grasses is 16–18 MJ kg^{-1} [13]. It may be a raw material for solid fuels, i.e. briquettes, pellet, torrefied biomass or biocarbon [14, 15]. There are technologies for the production of liquid fuels, e.g. bioethanol, or gas fuels, e.g. biogas or syngas [16–20].

The objective of research was to calculate the reduction of CO_2 by meadows in grasslands and to determine an estimated biomass potential, considering the total livestock population in Poland. The calculations were made for Polish provinces and expressed in an energy unit for certain selected solid and gas biofuels. The research results are a source of data necessary to develop renewable energy source systems in Poland.

2 Research Methodology

Research was undertaken according to the data of the Agency for Restructuring and Modernisation of Agriculture that provides financial support mechanisms to Polish farmers, of the Central Statistical Office [21], and of reference books. The acquired data reflected the livestock population, the area of crops and plans for biomass in Poland in the years 2013–2016. The data on factors of CO_2 emission from grasslands, calorific values and efficiency of biofuels were obtained from the reference books [6, 14, 15, 17].

The calculations were conducted according to the following algorithms. The reduction of CO_2 was calculated on the basis of:

$$R_{TUZ} = \sum_{i=1}^{n} x * Wr_{CO_2} * U_{rok} [\text{Mg}] \tag{1}$$

where:

n	provinces;
x	area of grasslands [ha];
Wr_{CO_2}	quantity of CO_2 reduction in grasslands (7.3 kg ha^{-1} h^{-1}) [kg ha^{-1} h^{-1}];
U_{rok}	plant vegetation time within one year (7th month = 5110 h) [h].

The biomass potential from grasslands, including the demand for the livestock feed in Poland, was calculated on the basis of:

$$B_{TUZ} = \sum_{i=1}^{n} x * U_{past} * P_{past} + \sum_{i=1}^{n} x * U_{łąk} * P_{łąk} - \sum_{i=1}^{n} DJP_{b,k,o} * D_{b,k,o} * T + \text{Rez [Mg]} \tag{2}$$

$$Rez = \sum_{i=1}^{n} \left(U_{pow} * P_{upr}\right) [\text{Mg}] \tag{3}$$

where:

U_{past}	share of pastures in grasslands [%];
$U_{łąk}$	share of meadows in grasslands [%];
P_{past}	pasture crops in grasslands [Mg ha^{-1}];
$P_{łąk}$	meadow crops in grasslands [Mg ha^{-1}];
$DJP_{b.k.o.}$	number of LSU of cattle, goats, sheep, respectively;
$D_{b.k.o.}$	grass silage ration for cattle, goats and sheep, respectively;
T	number of days per year [days];
Rez	shortage of roughage [Mg];
U_{pow}	area of crops of forage plants [ha];
P_{upr}	yield of forage plants [Mg ha^{-1}]

The energy potential was calculated on the basis of selected energy media (briquette, biochar and biogas) in the following way:

$$B_{OZE} = \frac{B_{TUZ}}{P_{łąk}} * P_e \text{ [MJ]} \quad (4)$$

where:

P_e energy crop converted into fuel media [Mg ha^{-1}].

3 Research Results

The estimated data and research show the potential to produce biofuels in grasslands without any adverse impact on the environment. In the general balance of CO_2 emission to the atmosphere grasslands are characterised by a negative level of emission (Table 1). The quantity of CO_2 absorbed by grasses in meadows of grasslands (R_{PGL}) is the greatest, over 10 m Mg CO_2 per annum, in the following provinces: Mazowieckie (MZ), Podlaskie (PL), Warmińsko-Mazurskie (WM). By analysing the changes to the area of grasslands over the last four years, the absorption of CO_2 is observed to increase by over 20% in the Dolnośląskie (DŚ), Lubuskie (LS), Podlaskie (PL), Warmińsko-Mazurskie (WM) and Zachodniopomorskie (ZP) provinces. On the other hand, the Małopolskie (MP), Śląskie (ŚL) and Wielkopolskie (WP) provinces show a decline in the potential of CO_2 emission by −30, −20 and −10%, respectively.

The potential of biomass from grasslands, including the demand of livestock for feed, may be a source of raw materials for the biofuel production in half of the Polish provinces. The results are shown in Table 2. The data for the years 2013–2014 were obtained from the Central Statistical Office, whereas the data for the years 2015–2016 were acquired from the Agency for Restructuring and Modernisation of Agriculture. The great differences between the values are observed between 2014 and 2015. The data for the years 2013 and 2014 are statistical, whereas the data for the years 2015 and 2016 are provided by agricultural producers. The data on the cattle population were captured from the Agency for Restructuring and Modernisation of Agriculture, whereas the data on the feed potential were obtained from the Central Statistical Office. Due to some discrepant data provided only to compare the reliability of the data sources, the biomass potential for the last two years was analysed. The greatest biomass potential (over 2 m MG per annum) was estimated for the following provinces: Lubelskie (LB), Warmińsko-Mazurskie (WM), and Zachodniopomorskie (ZP). In those provinces it is worth investing in biomass energy production systems. There are no opportunities for the production of biomass energy from grasslands in the following provinces: Kujawsko-Pomorskie (KP), Łódzkie (ŁD), Mazowieckie (MZ) and Śląskie (ŚL). All the available feed and meadow biomass is required to feed livestock.

Table 1 Area of meadows in grasslands and CO_2 reduction

Pro-vince	2013		2014			2015		2016		
	Area [10^3 ha]	R_{TUZ} [10^6 Mg]	Area [10^3 ha]	R_{TUZ} [10^6 Mg]	2013 =100	Area [10^3 ha]	R_{TUZ} [10^6 Mg]	Area [10^3 ha]	R_{TUZ} [10^6 Mg]	2015 =100
DLŚ	117.6	4.39	111.6	4.16	−5.44	132.6	4.95	136.5	5.09	2.75
KP	86.5	3.23	85.6	3.19	−1.15	86.5	3.23	85.2	3.18	−1.57
LB	198.8	7.42	206.1	7.69	3.51	208.7	7.78	211.4	7.89	1.39
LS	78.4	2.92	90.4	3.37	13.44	105.2	3.93	109.2	4.07	3.44
ŁD	132.3	4.93	135.0	5.04	2.12	135.8	5.07	135.4	5.05	−0.40
MP	196.6	7.33	185.6	6.92	−5.90	132.4	4.94	136.6	5.10	3.14
MZ	425.4	15.87	427.1	15.93	0.38	442.8	16.52	438.0	16.34	−1.10
OP	35.7	1.33	35.2	1.31	−1.36	39.1	1.46	40.3	1.50	2.67
PK	171.9	6.41	174.4	6.50	1.45	168.1	6.27	168.1	6.27	0.00
PL	318.1	11.87	321.4	11.99	1.00	377.5	14.08	377.0	14.06	−0.14
PM	96.0	3.58	100.2	3.74	4.18	115.8	4.32	117.0	4.36	0.92
ŚL	79.7	2.97	68.5	2.55	−16.30	56.2	2.10	58.8	2.19	4.11
ŚK	96.3	3.59	91.1	3.40	−5.65	98.2	3.66	100.2	3.74	2.14
WM	194.3	7.25	232.7	8.68	16.47	278.2	10.38	279.6	10.43	0.48
WP	227.1	8.47	234.6	8.75	3.19	208.6	7.78	211.0	7.87	1.14
ZP	110.1	4.11	135.1	5.04	18.42	157.4	5.87	164.5	6.14	4.40
SUMA	2564.6	95.7	2634.4	98.3	2.65	2743.1	102.32	2768.8	103.28	0.90

R_{TUZ} quantity of reduced CO_2 by grasslands

Table 2 Biomass potential for energy purposes

Pro-vince	2013		2014			2015		2016		
	B_{TUZ} [10^6 Mg]	Part [%]	B_{TUZ} [10^6 Mg]	Part [%]	2013 =100	B_{TUZ} [10^6 Mg]	Part [%]	B_{TUZ} [10^6 Mg]	Part [%]	2015 =100
DL	1.77	84.2	1.97	85.4	10.32	1.87	84.3	1.93	84.4	2.96
KP	0.58	31.6	0.42	24.5	−39.12	0.15	10.3	0.10	7.0	−49.56
LB	2.35	68.2	2.67	70.8	11.74	2.23	67.1	2.27	67.5	1.89
LS	1.06	82.4	1.42	85.7	25.18	1.48	85.6	1.54	85.9	4.05
ŁD	1.03	34.3	2.03	54.7	49.06	−0.15	−5.8	−0.16	−6.2	6.01
MP	1.70	51.0	1.96	56.0	13.36	0.59	27.8	0.70	32.0	15.89
MZ	3.41	34.6	4.14	44.7	17.56	−0.18	−2.6	−0.28	−4.0	34.83
OP	0.47	59.9	0.65	66.8	27.18	0.34	50.5	0.35	50.9	3.64
PK	1.92	79.6	1.73	81.0	−10.77	1.47	77.3	1.52	79.9	3.19
PL	4.04	55.0	4.09	55.2	1.36	1.66	26.5	1.45	23.2	−14.43
PM	1.68	92.8	1.33	69.0	−26.19	1.46	70.4	1.46	69.7	−0.06
ŚL	0.93	61.1	0.98	69.0	5.10	0.13	17.5	0.15	18.9	11.46
ŚK	0.77	42.0	0.55	40.6	−41.53	0.29	23.2	0.35	27.2	16.20
WM	2.54	63.0	3.68	67.1	30.97	3.26	61.7	3.22	60.6	−1.16
WP	3.00	56.2	3.12	56.2	3.79	1.60	38.6	1.19	28.5	−33.97
ZP	1.52	83.2	2.07	86.9	26.73	2.43	88.3	2.55	88.5	4.56
SUMA	28.8	55.5	32.8	60.1	12.27	18.6	22.0	18.33	39.7	−1.57

Table 3 Energy potential of grasslands in selected energy media in the years 2013–2016

Pro-vince	2013			2014			2015			2016		
	B [PJ]	BG [PJ]	TB [PJ]	B [PJ]	BG [PJ]	TB [PJ]	B [PJ]	BG [PJ]	TB [PJ]	B [PJ]	BG [PJ]	TB [PJ]
DL	7.36	0.94	5.59	6.94	0.88	5.27	8.13	1.03	6.17	8.38	1.07	6.36
KP	2.02	0.26	1.53	1.57	0.20	1.20	0.67	0.09	0.51	0.45	0.06	0.34
LB	10.15	1.29	7.70	10.92	1.39	8.29	10.47	1.33	7.94	10.67	1.36	8.10
LS	4.87	0.62	3.70	5.94	0.76	4.51	6.58	0.84	4.99	6.86	0.87	5.20
ŁD	3.37	0.43	2.56	5.43	0.69	4.12	−0.58	−0.07	−0.44	−0.62	−0.08	−0.47
MP	7.43	0.94	5.64	7.69	0.98	5.84	2.70	0.34	2.05	3.21	0.41	2.43
MZ	10.78	1.37	8.19	14.06	1.79	10.67	−0.84	−0.11	−0.64	−1.29	−0.16	−0.98
OP	1.58	0.20	1.20	1.71	0.22	1.30	1.45	0.18	1.10	1.50	0.19	1.14
PK	10.05	1.28	7.63	10.55	1.34	8.01	9.71	1.24	7.37	10.03	1.28	7.62
PL	13.09	1.66	9.93	13.25	1.68	10.05	7.43	0.94	5.64	6.49	0.83	4.93
PM	6.74	0.86	5.11	5.15	0.66	3.91	5.98	0.76	4.54	5.98	0.76	4.54
ŚL	3.66	0.47	2.78	3.60	0.46	2.73	0.75	0.10	0.57	0.85	0.11	0.64
ŚK	2.96	0.38	2.25	2.77	0.35	2.10	1.71	0.22	1.30	2.04	0.26	1.55
WM	9.14	1.16	6.94	11.47	1.46	8.71	12.63	1.61	9.59	12.49	1.59	9.48
WP	9.48	1.21	7.20	9.79	1.24	7.43	5.94	0.76	4.51	4.43	0.56	3.37
ZP	6.87	0.87	5.21	8.86	1.13	6.73	10.44	1.33	7.92	10.94	1.39	8.30
SUMA	109.55	13.93	83.15	119.69	15.22	90.85	83.16	10.58	63.12	82.39	10.48	62.54

B briquette
BG biogas
TB torrefied biomass

By comparing the share of biomass from grasslands to the unused biomass, the smallest share (below 20%) is estimated in the following provinces: Dolnośląskie (DŚ), Lubuskie (LS), Podkarpackie (PK), and Zachodniopomorskie (ZP). In those provinces, over 80% of the available biomass from grasslands may be used for energy purposes.

Grasslands may be a source of wet biomass that may, for example, be pickled and fed to livestock or of dry biomass such as hay. Both forms of biomass may be intended for the production of energy media. Table 3 shows the energy potential for the Polish provinces expressed as energy of briquette, biochar and biogas. The greatest share of energy is attributable to briquettes as carbon included in the biomass is completely used. In the remaining energy media only part of carbon composes the fuel, whereas its remaining part is included in by-products. Briquette is the most primitive form of fuel with a very limited application. Due to its relatively high humidity and the presence of chlorine it is not suitable for the direct incineration in industrial boilers. Torrefied biomass is an equivalent of hard coal, its calorific value equals to 24–28 MJ kg^{-1}, and humidity is below 2%. This fuel is widely applied in industrial furnaces. Biogas is the most universal fuel that is widely applied in the industrial energy and may be used in the transport industry. By analysing the last two years, the greatest energy potential exceeding 5 PJ was achieved in the following provinces: Dolnośląskie, Lubelskie, Lubuskie, Podkarpackie, Podlaskie, Pomorskie, Warmińsko-Mazurskie, and Zachodniopomorskie. Those provinces have the largest energy potential and it is worth considering the construction of renewable energy source systems there. There are no opportunities to obtain raw materials for the energy production in the following provinces: Kujawsko-Pomorskie, Łódzkie, Mazowieckie and Śląskie. Those provinces have the energy potential of below 1 PJ.

4 Conclusions

- Each year the area of grasslands in agricultural areas decreases by 5%. Contrary to other agricultural crops, grasslands reproduce the soil organic matter, hence some actions are required to stop the their reduction.
- The cultivation of grasslands indirectly affects the reduction of CO_2 emission in the general balance. It is estimated that the areas of meadows in grasslands decrease the emission of CO_2 in Poland by over 100 thousand Mg.
- By analysing the demand of livestock for feed with respect to the potential of biomass from grasslands, it has been proven that the potential of biomass production exceeds the demand for that biomass. The balance of mass balance and calorific value indicates that the estimated energy potential is 83 PJ in 2016 and it decreased by 27 PJ compared to 2013. The support for the effective use of biomass from grasslands enables halting the decreasing area.

- The research results may be used to indicate locations for renewable energy sources investments with the largest biomass potential in the region and to commence the production of biofuels and, consequently, to launch new markets for agricultural products.

Acknowledgements This study was conducted as part of the Multiannual Programme for the period 2016–2020 under the Resolution of the Council of Ministers No 154/2016 dated 12 December 2016.

References

1. Barszczewski, J.: Stan Trwałych użytków zielonych i ich wykorzystanie w kraju. Mon. pt. Racjonalne wykorzystanie potencjału produkcyjnego trwałych użytków zielonych w Polsce w różnych warunkach glebowych i systemach gospodarczych. Wydawnictwo Instytut Technologiczno-Przyrodniczy w Falentach, ISBN 978-83-62416-90-5, 15–35 (2015)
2. Jankowska-Huflejt, H.: Znaczenie trwałych użytków zielonych w gospodarce rolnej. Title of monography: Gospodarowanie na trwałych użytkach zielonych, ISBN 978-83-65426-24-6, 9–44 (2016)
3. Kamiński, E.: Gospodarowanie na trwałych użytkach zielonych. Publisher: Instytut Technologiczno-Przyrodniczy w Falentach, ISBN 978-83-65426-24-6, 196 (2016)
4. Jamrosz, D., Potkański, A.: 2004. Żywienie zwierząt i paszoznawstwo. PWN, ISBN 83-01-14277-4, 556 (2004)
5. Jugowar, L.J., Myczko A., Węglarzy K., Winnicki S.: Hodowla bydła—współczesne zagadnienia produkcji mleka i żywca wołowego w Polsce z uwzględnieniem wymagań środowiskowych. ISBN 978-83-7607-290-6, 160 (2016)
6. Li, L., Fan, W., Kang, X., Wang, Y., Cui, X., Xu, C., Kevin, L.G., Hao, Y.: Responses of greenhouse gas fluxes to climate extremes in a semiarid grassland. Atmos. Environ. **142**, 32–42 (2016)
7. Miatkowski, Z., Turbiak, J., Burczyk, P., Myczko, A., Karłowski, J.: Prognozy zmian aktywności w sektorze rolnictwa, zawierające informacje niezbędne do wyliczenia szacunkowej wielkości emisji gazów cieplarnianych. Homepage: https://bip.minrol.gov.pl/Opracowania-ekspertyzy-publikacje/PROGNOZY-ZMIAN-AKTYWNOSCI-W-SEKTORZE-ROLNICTWA-ZAWIERAJACE-INFORMACJE-NIEZBEDNE-DO-WYLICZENIA-SZACUNKOWEJ-WIELKOSCI-EMISJI-GAZOW-CIEPLARNIANYCH. 29 May 2016
8. Zhao, Z., Dong, S., Jiang X., Liu, S., Ji, H., Yu, L, Han, Y., Sha, W.: Effects of warming and nitrogen deposition on CH_4, CO_2 and N_2O emissions in alpine grassland ecosystems of the Qinghai-Tibetan Plateau. Sci. Total Environ. **592**, 565–572 (2017)
9. Konieczny, R., Fedko, M., Łaska, B., Golimowski, W.: Nowe modele monitorowania zasobów biomasy oraz dostępne technologie jej konwersji w instalacjach OZE (na przykładzie gmin wiejskich województwa wielkopolskiego). Falenty—Poznań. Wydaw. ITP. ISBN 978-83-65426-13-0, 178 (2015)
10. Carvalho Rocha, J.R.A.S., Campolina Machado, J., Crescêncio Souza Carneiro, P., Da Costa Carneiro, J., Resende, M.D.V., Pereira, A.V., Souza Carneiro, J.E.: Elephant grass ecotypes for bioenergy production *via* direct combustion of biomass. Industrial Crops and Products 95, 27–32 (2017)
11. Tsapekos, P., Kougias, P.G., Egelund, H., Larsen, U., Pedersen, J., Trénel, P., Angelidaki, I.: Mechanical pretreatment at harvesting increases the bioenergy output from marginal land grasses. Renew. Energy **111**, 914–921 (2017)

12. Xu, J., Li, M.: Innovative technological paradigm-based approach towards biofuel feedstock. Energy Convers. Manag. **141**, 48–62 (2016)
13. Murphy, J.D., Power, N.M.: An argument for using biomethane generated from grass as a biofuel in Ireland. Biomass Bioenerg. **3**(33), 504–512 (2009)
14. Telmo, C., Lousada, J., Moreira, N.: Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood. Biores. Technol. **101**, 3808–3815 (2010)
15. Niedziółka, I., Kochel-Jakuboska, M., Kraszkiewicz, A., Szpryngiel, M.: Analiza cech fizycznych brykietów z biomasy roślinnej. Inżynieria Rolnicza **2**(143), 233–243 (2013)
16. Jakubiak, M., Kordylewski, W.: Toryfikacja biomasy. Archiwum Spalania **1–2**(10), 11–27 (2010)
17. Mohapatra, S., Mishra, C., Behera, S.S., Thatoi, H.: Application of pretreatment, fermentation and molecular techniques for enhancing bioethanol production from grass biomass—a review. Renew. Sustain. Energy Rev. **78**, 1007–1032 (2017)
18. Mikołajczak, J., Wróblewska, B., Jurkowski, A.: Możliwości i bariery w produkcji biogazu z biomasy trwałych użytków zielonych w Polsce. Woda Środowisko Obszary Wiejskie **2**(26), 139–155 (2009)
19. Myczko, A., Myczko, R., Kołodziejczyk, T., Golimowska, R., Lenarczyk, J., Janas, Z., Kliber, A., Karłowski, J., Doga, M.: Budowa i eksploatacja biogazowni rolniczych- poradnik dla inwestorów zainteresowanych budową biogazowni rolniczych. ISBN 978-83-62416-23-3, 140, (2011)
20. Irfan, M., Chen, Q., Yue, Y., Pang, R., Lin, Q., Zhao, X., Chen, H.: Co-production of biochar, bio-oil and syngas from halophyte grass (*Achnatherum splendens* L.) under three different pyrolysis temperatures. Biores. Technol. **211**, 457–463 (2016)
21. Główny Urząd Statystyczny 2013–2015. Produkcja upraw rolnych i ogrodniczych w 2013–2015 dział: rolne i pastewne. Homepage: http://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-statystyczny-rolnictwa-2016,6,10.html, 24 June 2017

Review of Ash Deposition Coefficients for Selected Biomasses

Waldemar Gądek and Sylwester Kalisz

Abstract Ambitious EU environmental policy decreasing CO_2 emissions from combustion of fossil fuels impact on whole EU economy. Utilization of biomass as carbon neutral fuel helps to address these challenges Combustion and co-combustion of biomass, especially agriculture residue biomass, is associated with many technical problems such us: bed agglomeration, slagging and fouling, chlorine corrosion, decreased boiler efficiency which do not occur in conventional fossil fuels combustion. In this study six fuels were investigated on their deposition ability (2 types of straw, Miscanthus and herbaceous pellets, RDF—Refuse-Derived Fuel and reference coal). Biomasses were selected as the most commonly used in Polish and German power industry. Analysis comprised chlorine and sulphur contents of the fuel, ash oxides analysis and ash fusion temperatures. The main objectives of this work were to predict ash deposition tendency of chosen fuels using ash deposition indices and compare it with reference fuel. Next weaknesses of selected indicators are pointed out.

Keywords Biomass · Ash deposition · Slagging · Fouling · Combustion

1 Introduction

Ambitious EU environmental policy decreasing CO_2 emissions from combustion of fossil fuels known as "2030 Framework for Climate and Energy" impact on whole EU economy [1]. Utilization of biomass as carbon neutral fuel helps to address these challenges [2, 3]. However combustion and co-combustion of biomass, especially agriculture residue biomass, is associated with many technical problems

W. Gądek (✉) · S. Kalisz
Silesian University of Technology, Institute of Power Engineering
and Turbomachinery, Konarskiego 20, 44-100 Gliwice, Poland
e-mail: waldemar.gadek@polsl.pl

S. Kalisz
e-mail: sylwester.kalisz@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_12

such as: bed agglomeration, slagging and fouling, chlorine corrosion, decreased boiler efficiency which do not occur in conventional fossil fuel combustion [4]. Those problems are associated with high alkali metal (K and Na) contents in the fuel, especially potassium plays a negative role. In the presence of sulphur, chlorine and silica alkali silicate would be formed, these compound are characterized by low melting or softening point what may result in high deposit formation on boiler heat exchanger [5–7]. Negative side effects of biomass combustion are as follows:

- **slagging**—this process mainly occurs in boiler combustion chamber, on furnace walls, platen steam superheater, burner areas [5, 6, 8]. Deposits are formed where ash is exposed on radiant heat of flames in high temperature range from 1050 to 800 °C [8]. Slagging deposits consist often of an inner ash powdery layer covered by a molten or partly molten ash deposits followed by alkali and silicate compounds [5, 7]. This dangerous phenomena results in overheating the steam superheaters.
- **fouling**—this process mainly occurs in convective passes of boiler on heat exchange surfaces such as: pendant superheters, reheaters, economizer and air preheters [5, 6, 8]. Fouling deposits are divided into two subgroups: high temperature fouling (temp. range 1300–900 °C) and low temperature fouling (temp. range 900–300 °C) [6, 8]. High temperature fouling is related with semi-fused sintered ash. On the other hand low temperature fouling is coupled with weakly sintered deposits. Previously vaporized in high temperature species are condensed at lower temperature in convective passes and the range of fouling depends on concentration of inorganic compounds in the stream of flue gases [6]. This actually results in the inner deposits layer on bank of tubes that is composed of condensed alkali salts with trap on its surface for non-sticky particles which influence increasing the deposit thickness [6].
- **bed agglomeration**—is also known as defluidization. This process is related with combustion of biomass in fluidized bed boilers. Biomass ashes with low melting point may surround and trap bed material (usually sand material). Alkali and silicate ash compounds create layer which carefully covers sand particles which results in increasing the sand particle size and weight [9]. Moreover, covered particles can agglomerate together and create the ash—bridges between particles [9]. In the worst case the agglomerated ash and bed materials are too heavy for conditions of fluidization and stop the fluidization process.

All described issues are coupled with biomass combustion. The aim of this study is characterization of chosen fuels for assessment on deposit formation during combustion of biomass. To achieve that goal empirical, predictive ash deposition tendency coefficients were used. Study presented in this work is a starting point for large scale laboratory tests using 30 kWt slagging reactor.

1.1 Predictive Coefficients for Biomass Ash Deposition

For many years different ash behavior predictive coefficients were developed including: Silica content (SiO_2), Chlorine content of the fuel (Cl), Basic to Acidic oxides (B/A), Bed Agglomeration Index (BAI), Babcock index (Rs), Ash Fusibility Index (AFI), Fouling index (Fu), Slag viscosity index (Sr) and Ash Fusion Temperatures AFT in oxidation conditions: Initial Deformation Temperature (IDT), Softening Temperature (ST). Indicators and their formulas used for calculations are widely described in Refs. [9–12]. However they not always show the real ash deposition tendency because they have been developed to verify coal ash rather than biomass ash deposition tendency [10]. Table 1 shows ranges of slagging and fouling indices.

2 Methodology

2.1 Materials

In this study six fuels were investigated such as: DS – cereal straw, SP-K—wheat straw, BZ—herbaceous pellets, DM—miscanthus, RDF—Refuse-Derived Fuel and WS—Polish Coal from Sobieski mine in order to compare fuels with non or intermediate slagging capabilities. Biomasses were selected as the most commonly used in Polish and German power industry which are characterized by high deposition tendency. Figure 1 shows selected fuels in as received state. In the case of RDF fraction analysis shows that RDF consist of: 50.1% of plastics mixture, 28.6% textiles, 6.6% wood and 14.8% paper. In the case of RDF there was a great challenge to get uniform sample for further laboratory investigations. All fuels were milled in knife mill and sieved to fraction <0.2 mm.

Table 1 Slagging and fouling indices with their ranges [10]

Indicators	Low	Medium	High	Extremely high
SiO_2	<20	20–25	>25	
Cl in fuel	<0.2	0.2–0.3	0.3–0.5	>0.5
B/A	<0.5	0.5–1.0	1.0–1.75	
BAI			<0.15	
Rs	<0.6	0.6–2.0	2–2.6	>2.6
AFI	>1342	1232–1342	1052–1232	<1050
Fu	<0.6	0.6–40	>40	
Sr	>72	65–72	<65	
ST	>1390	1250–1390	<1250	
IDT	>1100	900–1100	<900	

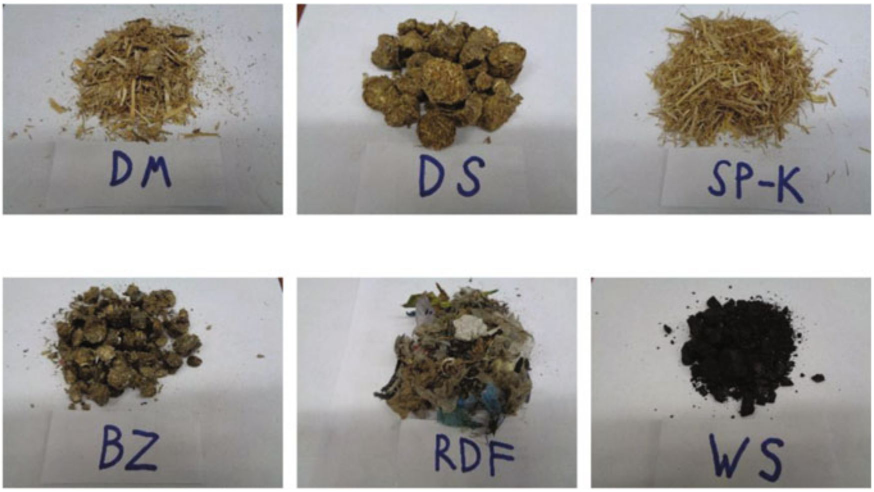


Fig. 1 Pictures with investigated fuels: DS—cereal straw, SP-K—wheat straw, BZ—herbaceous pellets, DM—miscanthus, RDF—Refuse-Derived Fuel and WS—Polish Coal Sobieski

2.2 Experimental Section

For this study all selected fuels were analysed in certified laboratory using official procedures established by European Standard Technology Committee. Chlorine and sulphur contents of the fuel were analysed according to [13, 14]. For ash fusibility experiments and ash oxides analysis biomasses were ashed in muffle furnace at 550 °C in the case of RDF and coal, fuels were ashed at 815 °C according to [15, 16]. For fusibility tests ash were formed into pyramids. Maximal temperature of experiments does not exceed 1500 °C under oxidizing conditions. Initial Deformation Temperature (ITD) Softening temperature (ST), Hemispherical temperature (HT), Fluid Temperature (FT) and its specific shapes were determined by camera and computer system according to procedure described in [17]. Major elements of ash Al, Ca, Fe, Mg, P, K, Si, Na, Ti, Mn, Sr were determined using procedure [18] by Plasma Spectrometer Thermo iCAP 6500 Duo ICP.

3 Results and Discussion

3.1 Ash Fusibility Experiments

Ash fusibility experiments are basic ash characterisation tests. This procedure may simply identify melting behaviour of ash. Figure 2 shows fusion points of ash according to ash fusibility analysis. The greatest importance for the process of slagging and fouling play two first characteristic temperatures: Initial Deformation

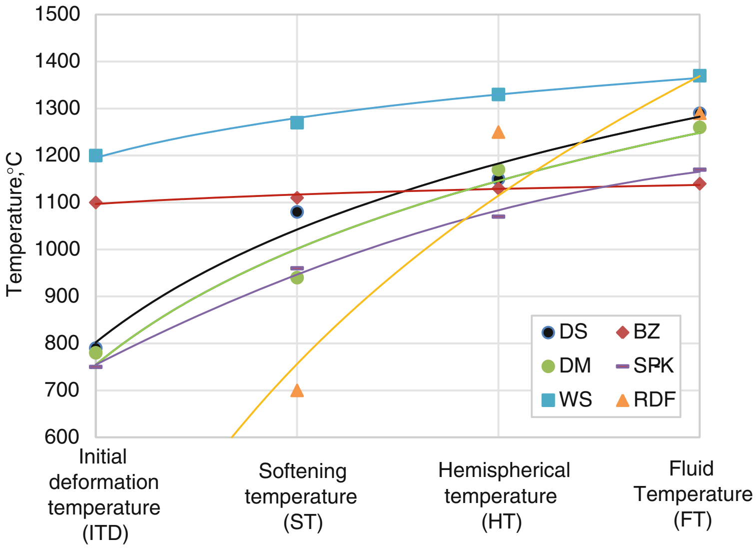


Fig. 2 Results of ash fusibility experiments

Temperature and Softening Temperature. The highest melting curve of WS coal, shows that reference fuel with IDT—1200 °C and ST—1270 °C is on range with non or small danger of slagging and fouling. Next BZ is characterized by intermediate potential of deposit formation, IDT—1100 °C and ST—1110 °C. The melting of BZ ash occur rapidly, achieving FT—at 1140 °C. Three another agricultural biomasses DM, DS and SP-K achieve IDT in the range of 750–790 °C and ST 940–1080 °C. In Fig. 2 fusion curves of these biomasses are located close to each other. On this basis, one can conclude that these biomasses are described by high potential of ash deposition tendency. ST of RDF achieve temperature 700 °C, and IDT were not captured because of experiments range (700–1500 °C). Investigated RDF is described by highest potential of ash deposition tendency. It is extremely unstable fuel and results of experiments (ash oxides analysis, ash fusibility) depend on proper mixing and milling of different fractions of the fuel. From ash fusibility experiments fuels can be ranked from the smallest to the greatest potential of ash deposition tendency as follow: WS < BZ < DS < DM < SP-K < RDF.

3.2 Ash Oxides Analysis and Deposition Indices

Ash oxides analysis is one of the most common method for ash characterization. In Table 2 results of ash oxides analysis are shown. The conducted study clearly indicates agriculture biomasses are characterized by high potassium content K_2O 14.02%—BZ, 16.75%—DM, 18.09%—DS, 18.59%—SP-K compared to coal

Table 2 Ash oxides analysis of selected fuels normalized at 100 wt%

Fuel	SiO_2 (%)	CaO (%)	K_2O (%)	P_2O_5 (%)	Al_2O_3 (%)	MgO (%)	Fe_2O_3 (%)
DS	55.50	9.59	18.09	2.79	4.13	2.85	1.84
BZ	45.58	15.49	14.04	4.41	4.86	4.28	2.04
DM	61.83	9.43	16.75	4.47	1.03	1.50	0.77
SP-K	61.22	7.51	18.59	3.29	1.23	2.17	0.83
WS	54.94	1.95	2.39	0.18	24.99	1.37	9.93
RDF	33.56	9.02	0.87	0.22	34.73	1.99	3.14
Fuel	SO_3 (%)	Na_2O (%)	TiO_2 (%)	Cl in ash (%)	BaO (%)	SrO (%)	Mn_3O_4 (%)
DS.	2.18	0.95	0.22	1.69	0.05	0.04	0.07
BZ	4.06	1.02	2.47	1.26	0.13	0.05	0.30
DM	2.53	0.33	0.08	1.13	0.03	0.02	0.09
SP-K	2.43	0.32	0.10	1.98	0.08	0.02	0.22
WS	0.80	2.47	0.87	n.m.	0.07	0.03	0.02
RDF	2.28	12.72	1.04	n.m.	0.22	0.03	0.19

Fuel	SO_3 (%)	Na_2O (%)	TiO_2 (%)	Cl in ash (%)	BaO (%)	SrO (%)	Mn_3O_4 (%)
DS.	2.18	0.95	0.22	1.69	0.05	0.04	0.07
BZ	4.06	1.02	2.47	1.26	0.13	0.05	0.30
DM	2.53	0.33	0.08	1.13	0.03	0.02	0.09
SP-K	2.43	0.32	0.10	1.98	0.08	0.02	0.22
WS	0.80	2.47	0.87	n.m.	0.07	0.03	0.02
RDF	2.28	12.72	1.04	n.m.	0.22	0.03	0.19

n.m. not measured

2.39%—WS. Potassium is mainly responsible for slagging and fouling phenomena. Silica content in all investigated fuels is higher or on similar level, exception is RDF where SiO_2 content is 33.56%. All investigated fuels are in high range of silica content in high deposit range. Silica in the presence of chlorine, alkali metals, sodium, potassium affect on formation of eutectics with low temperature melting point [10, 19, 20]. Coal WS is characterized by the high Na_2O content of 2.47% so it seems to have high tendency for deposition compared to biomasses. But in fact the selected reference fuel has moderate or low deposition tendency. On the other hand RDF Na_2O content is on extremely high level at 12.72% compared to other fuels. One can conclude RDF is described by high potential of slagging/fouling tendency. A great convenience is to use a ash deposition indices which are presented in Table 1. Using only ash oxides analysis it is hard to conclude which fuels are described by high ash deposition tendency.

From ash oxides analysis several predictive ash deposition indices may be evaluated [9–12]. Results are shown in Table 3. The indices have been highlighted with gray scale in order to increase readability as follows: high slagging and fouling range—black, intermediate—gray, weak—light gray. The selected indicators do not

Table 3 Results of ash deposition coefficients for selected fuels

Fuel	S[a] (%)	SiO_2 (%)	Cl[b] (%)	B/A	BAI	Rs	AFI	Fu	Sr	IDT (°C)	ST (°C)
DS	0.43	55.5	0.43	0.60	0.10	0.261	862	11.5	79.5	790	1080
BZ	0.10	45.5	0.09	0.78	0.14	0.078	1106	11.7	67.6	1100	1110
DM	0.06	61.8	0.09	0.53	0.04	0.032	858	9.0	84.1	780	940
SP-K	0.09	61.2	0.19	0.52	0.04	0.047	814	9.9	85.3	750	960
WS	1.52	54.9	0.36	0.23	2.04	0.344	1226	1.1	80.6	1200	1270
RDF	0.44	33.5	0.63	0.40	0.23	0.177	<70 0	5.5	70.4	<700	700

[a]Sulphur content of fuel in db—dry basis

[b]Chlorine content of fuel in db

coincide with ash fusibility experiments, and they do not show always the correct tendency. However, some of them: B/A, SiO_2, BAI, AFI, Fu, IDT, ST are partly consistent with ash fusibility experimental studies.

4 Conclusions

In this study several biomasses, one refused derive fuel and coal were examined in order to determine ash deposition tendency using experimental procedure and deposition indices. Phenomena of ash deposition tendency during combustion and co-combustion of biomasses affects negatively utilization of these fuels. The increasing accuracy of the ash deposition prediction methodology allows for selection of fuels that can be used in power industry. Research conducted in this study categorize investigated agricultural biomasses as fuel with high potential of ash deposition tendency. However biomasses would be more accurately examined on large scale laboratory test stands. Methodology of evaluation deposition tendency of biomasses during combustion and co-combustion will be further developed.

Acknowledgements The research was funded by BioEffGen project (Advanced pretreatment and characterization of Biomass for Efficient Generation of heat and power) funded by National Centre of Research and Development in STAIR program “Polish–German sustainability research call”.

References

1. Council, E.U.: EUCO 169/14. EU Council, Brussels (2014)
2. Van Loo, S., Koppejan, J.: The Handbook of Biomass Combustion and Co-firing. Earthscan, London (2010)
3. Basu, P.: Biomass Gasification and Pyrolysis. Academic Press, Burlington, MA (2010)
4. Kalisz, S., Pronobis, M., Baxter, D.: Co-firing of biomass waste-derived syngas in coal power boiler. Energy **33**, 1770–1778 (2008)
5. Vega-Nieva, D., Garcia-Maraver, A., Ortiz, L.: Slagging and fouling risks derived from the combustion of solid biofuels. WIT Trans. State Art Sci. Eng. **85**, 137–147 (2015)
6. Płaza, P.: The development of a slagging and fouling predictive methodology for large scale pulverised boilers fired with coal/biomass blends (2013)
7. Vassilev, S., Baxter, D., Vassileva, C.: An overview of the behaviour of biomass during combustion: part I. Phase-mineral transformations of organic and inorganic matter. Fuel **112**, 391–449 (2013)
8. Barnes, I.: Slagging and fouling in coal-fired boilers. IEA Clean Coal Centre, London (2009)
9. Gatternig, B.: Predicting Agglomeration in Biomass Fired Fluidized Beds (2017)
10. Garcia-Maraver, A., Mata-Sanchez, J., Carpio, M., Perez-Jimenez, J.: Critical review of predictive coefficients for biomass ash deposition tendency. J. Energy Inst. **90**, 214–228 (2017)
11. Dyjakon, A.: Analysis of slagging and fouling propensities of biofuels in terms of their combustion and co-combustion in the boilers. Agric. Eng., 5–18 (2012) (Z.2)
12. Munir, S., Nimmo, W., Gibbs, B.: The effect of air staged, co-combustion of pulverised coal and biomass blends on NO_x emissions and combustion efficiency. Fuel **90**, 126–135 (2011)
13. PN-EN ISO 16994:2016-10: Biopaliwa stałe—Oznaczanie całkowitej zawartości siarki i chloru (2016)
14. PN-G-04584:2001: Paliwa stałe—Oznaczanie zawartości siarki całkowitej i popiołowej automatycznymi analizatoram (2001)
15. PN-ISO 1171:2002: Paliwa stałe—Oznaczanie popiołu (2017)
16. PN-EN ISO 18122:2016-01: Biopaliwa stałe—Oznaczanie zawartości popiołu (2016)
17. CEN/TS 15370-1:2007: Solid biofuels. Method for the determination of ash melting behaviour. Characteristic temperatures method (2007)
18. PN-EN ISO 16967:2015-06: Biopaliwa stałe—Oznaczanie pierwiastków głównych—Al, Ca, Fe, Mg, P, K, Si, Na i Ti (2015)
19. Miles, T., Miles, T., Baxter, L., Bryers, R., Jenkins, B., Oden, L.: Boiler deposits from firing biomass fuels. Biomass Bioenerg. **10**, 125–138 (1996)
20. Nutalapati, D., Gupta, R., Moghtaderi, B., Wall, T.: Assessing slagging and fouling during biomass combustion: A thermodynamic approach allowing for alkali/ash reactions. Fuel Process. Technol. **88**, 1044–1052 (2007)

Does Wetland Biomass Provide an Alternative to Maize in Biogas Generation?

Sławomir Roj-Rojewski, Agnieszka Wysocka-Czubaszek, Robert Czubaszek and Piotr Banaszuk

Abstract The substantial amount of the agricultural biogas plants is now facing economical problems due to rising operational costs, which force them to quest for the cheaper alternative to silage maize. The aim of the study was to examine the biogas and methane yield of two wetland species: common reed and reed canary grass, and compare it to the biogas productivity of commonly used mixture of maize, poultry manure, and swine manure. In batch assay the methane yield of poultry manure was the highest and reached about 530 NL CH_4 kg^{-1} VS. The methane yield of maize silage was lower and equaled to 435 NL CH_4 kg^{-1} VS. Much lower values were received from reed canary grass and swine manure (204 and 171 NL CH_4 kg^{-1} VS, respectively) and the lowest from common reed (148 NL CH_4 kg^{-1} VS). Due to notably smaller biogas and specific methane yields grasses from landscaping are unlikely to wholly replace maize silage. However, they can be considered as interesting co-substrate, with methane productivity that is comparable to swine manure. Collecting grasses is relatively cheap, as it does not require fertilization and crop protection expenditure, while mowing of biomass can contribute to protection of biodiversity of wetlands and abandoned meadows.

Keywords Biogas · Biomethane potential test · Wetland biomass
Reed canary grass · Common reed · Maize silage · Manure

S. Roj-Rojewski (✉) · A. Wysocka-Czubaszek · R. Czubaszek · P. Banaszuk
Bialystok University of Technology, Bialystok, Poland
e-mail: s.roj@pb.edu.pl

A. Wysocka-Czubaszek
e-mail: a.wysocka@pb.edu.pl

R. Czubaszek
e-mail: r.czubaszek@pb.edu.pl

P. Banaszuk
e-mail: p.banaszuk@pb.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_13

1 Introduction

A development and progression in biogas production across the Europe vary substantially. The leading country—Germany has in operation more than 9000 plants of different scale with the installed power of 4.2 GW [1], while others, especially eastern European countries, just begun their way in the anaerobic digestion of biomass. Poland locates among biogas beginners with 301 plants and the total installed power of 304 MWe [2] operating throughout the country. Despite considerable biomass resources and high energy potential of agriculture, which allows the production of up to 6 billion m^3 of biogas per year [3], there are only 95 so called agriculture biogas plants in operation. They have a total capacity of 0.4 billion m^3 per year of biogas and installed power of 101 MWe [4]. In the vast majority of them biogas is generated by the co-fermentation of energy crops (mainly maize silage) mixed with liquid manure (slurry) or water. Maize silage has dominated the agricultural biogas market in Europe; it accounts e.g. for 73% of plant substrates in Germany [5], which results from high dry matter yield and the good usability for methane fermentation [6].

Due to substrate monotony, the biogas sector is particularly vulnerable to the fluctuation of supplies and prices of biomass, which badly affect its economic viability. Growing cultivation of maize and other energetic plants for anaerobic digesters is more and more often pointed as a not sustainable practice affecting food security and environment, which consequently should be not encouraged by politics [7–9].

Thus, there is an urgent need to quest for alternative, more environmental and social friendly substrates, like organic wastes, biomass from landscaping or conservation of wetlands and semi-natural meadows. Currently, in Poland, permanent grasslands can provide about 2.3 million Mg of biomass for energy generation, without detriment to the supply of forage [3]. The significant amount of biomass, mainly *Phragmites australis*, *Phalaris arundinacea* and *Carex* sp. can be harvested in wetlands subjected to extensive conservation measures [10]. Its use for energy purposes could improve the situation of agricultural biogas plants facing economic problems due to rising costs of maize silage. The aim of the study was to examine the biogas and methane yield of two wetland species: common reed (*Phragmites australis* (Cav.) Trin. ex Steud) and reed canary grass (*Phalaris arundinacea* L.) and compare it to the biogas productivity of commonly used mixture of maize, poultry manure, and swine manure.

2 Methods

This paper presents and compares the results of two separate bio-methane potential tests (BMP) conducted in 2015.

2.1 Experiment 1

In the first experiment we examined commonly used substrates: maize, poultry manure and swine manure and their mixtures. The substrates and inoculum to BMP tests were obtained from Adler Biogaz, biogas plant (Ryboły, Poland). Following mixes were tested: mix 1 composed of 15% of swine manure, 15% of poultry manure, and 70% of maize silage; mix 2 composed of 10% of swine manure, 10% of poultry manure, and 80% of maize silage; mix 3 composed of 5% of swine manure, 5% of poultry manure, and 90% of maize silage.

All substrates were cut into particles about 2 cm in size. The BMP assay was performed in duplicate in 1 L glass bottles using the OxiTop Control System OC 110® (WTW Germany) and eudiometers at 40 ± 1 °C. No pH adjustment was made. The inoculum to substrate ratio ISR was 2:1 on the volatile solids (VS) basis, established according to Raposo et al. [11]. Working volume was 300 mL in OxiTop bottles or 500 mL in eudiometers. The VS of substrate in the bottles was 6.2–6.5 g for the OxiTops and 10.4–11.3 g for eudiometers, what resulted in TS (total solids) of mixtures around 8%. Each bottle headspace has been flushed with nitrogen gas for ca. 2 min to ensure the anaerobic conditions. The batch assay was incubated for 21 days. Each bottle was mixed manually once a day. In the OxiTop experiment biogas production was continuously measured on the basis of a pressure changes in the reactor by the OxiTop measuring head. Eudiometers were used only for more accurate daily measurement of composition of biogas using portable biogas analyzer DP-28BIO (NANOSENS, Poland). For technical reasons, in the eudiometers solely mixes were tested. The average content of methane given in the literature was used to calculate specific methane yield from anaerobic digestion of the single substrates (maize silage—52%, swine manure—60%, poultry manure—60% [12]). Biogas and methane production is given in norm liter per kg of added volatile solids (NL kg^{-1} VS), i.e. the volume of biogas or methane production is based on normal conditions: 273 K and 1013 mbar. The methane potential of the inoculum was subtracted from that of the substrates. Methane content in biogas was computed as a mean for all 21 days of BMP experiment. Crop yield of maize in Mg TS ha^{-1} was calculated using average crop yield for last year equals 45 Mg FM ha^{-1} (verbal information from the farmer). In addition, the area specific methane yield (m^3 CH_4 ha^{-1}) was calculated using values for specific methane yield and the TS yield per hectare.

2.2 Experiment 2

In the second experiment we examined biogas yield from the common wetland plants: common reed and reed canary grass, harvested in mid-summer of 2015 in wetlands protected in Narew National Park. The plant material was dried for 24 h at the room temperature and silaged without any additives. The inocula from the same place were used in both experiments, but they were taken at different times. The BMP procedure was similar to the first experiment, with the exception of temperature (37 ± 1 °C), VSinoculum to VSsubstrate ratio (1:1) and working volume (400 mL in OxiTop bottles, 667 mL in eudiometers). ISR was established according to Seppälä et al. [13], who studied BMP of boreal herbaceous grasses, including reed canary grass. The amount VS of substrates was 12.7–13.3 g in the bottles OxiTop and 21.2–22.2 g in eudiometers, what resulted in TS of mixtures around 8%. The batch assay was incubated for 35 days. A longer period of incubation comparing to experiment 1 was established due to smaller ISR [14] and weaker biodegradability of wild varieties of grasses, what is mainly caused by larger content of lignin [15, 16].

The aboveground biomass of analyzed grasses was measured on July 9 2016. It was determined by harvesting an area of 0.2 m^2 in 5 replicates at the height 10–15 cm from the ground (meadows are mowed at this height). Grass samples were dried to a constant weight at 80 °C. Crop yield and biogas generation from the grasses were determined also for samples harvested in late summer and early fall, but in this paper results only from mid-summer harvest were chosen due to the highest productivity, just as it has been reported by Massé et al. [17].

In both experiments the following parameters of biomass were measured: the total solids and volatile solids according to standard methods [18], pH in mixtures of substrates and inoculum with HQD 40 (Hach, USA), total carbon TC by TOC-L (Shimadzu, Japan), total Kjeldahl nitrogen TKN by Kjeldahl method in Vapodest 50 s analyser (Gerhardt, Germany). Total phosphorus TP was determined after nitric acid/hydrogen peroxide microwave digestion in ETHOS One (Milestone s.r.l., Italy) and measured with ammonium metavanadate method with using spectrophotometer UV-1800 (Shimadzu, Japan). Analyzes were performed in duplicate (experiment 1) or triplicate (experiment 2).

3 Results

3.1 Inoculum

Inocula used in both experiments had slightly different properties (Table 1). In the second experiment inoculum was characterized by higher TS and TKN, lower VS, similar TC and TP compared to that used in the first experiment. The pH of substrate mixtures and inoculum placed in OxiTop bottles in experiment 1 varied from 7.1 (maize silage) to 7.8 (swine manure) and in experiment 2 ranged from 7.9 (common reed) to 8.0 (reed canary grass). These values were in the optimum range for methane production, which pH amounts to 7–8 [19].

Table 1 Mean values of physical-chemical properties of feedstocks

Feedstock	TS [%ww]	VS [%TS]	TC [%TS]	TKN [%TS]	C:N [–]	TP [%TS]
Experiment 1						
Inoculum	5.5 (0.0)	82.2 (7.5)	37.5 (0.0)	3.46 (0.00)	11	1.05 (0.00)
Swine manure	63.1 (1.5)	80.0 (2.6)	37.0 (1.0)	3.33 (0.06)	11	0.30 (0.05)
Poultry manure	34.7 (4.1)	82.0 (0.5)	36.7 (0.4)	1.92 (0.16)	19	0.24 (0.06)
Maize silage	26.4 (0.3)	94.6 (0.4)	40.9 (1.1)	1.37 (0.03)	30	0.07 (0.01)
Mix 1	32.6 (0.8)	89.1 (0.1)	45.4 (1.0)	2.20 (0.08)	21	0.43 (0.23)
Mix 2	29.5 (0.3)	92.5 (0.1)	47.2 (1.3)	1.97 (0.09)	24	0.26 (0.21)
Mix 3	28.4 (0.2)	93.9 (0.0)	46.6 (0.6)	1.84 (0.05)	25	0.21 (0.04)
Experiment 2						
Inoculum	6.6 (0.6)	76.0 (0.9)	38.0 (5.3)	4.84 (0.63)	8	1.19 (0.12)
Common reed silage	59.9 (1.6)	92.2 (0.7)	41.6 (0.6)	3.64 (0.42)	11	0.20 (0.04)
Reed canary grass silage	38.6 (1.0)	91.6 (0.3)	41.5 (1.4)	3.87 (0.14)	11	0.23 (0.01)

Standard deviations in parenthesis
TS total solids, *VS* volatile solids, *TC* total carbon, *TKN* total Kjeldahl nitrogen, *TP* total phosphorus, mix 1: 15% of swine manure, 15% of poultry manure, 70% of maize silage; mix 2: 10% of swine manure, 10% of poultry manure, 80% of maize silage; mix 3: 5% of swine manure, 5% of poultry manure, 90% of maize silage

3.2 BMP Test of Maize, Poultry Manure, Swine Manure and Their Mixtures

The substrates used for the experiment 1 varied in their chemical composition (Table 1). The highest TS had swine manure (63.1%ww) and the lowest—maize silage (26.4%ww). The opposite was when it comes to VS (80.0%TS and 94.6%TS, respectively). Mixes exhibited the highest TC content (45.4–47.2%TS) and TP content (0.21–0.43%TS), while swine manure gave the highest TKN content of 3.33%TS. The lowest value of TC was found for poultry manure (36.7%TS). For maize silage the lowest values of TKN (1.37%TS) and TP (0.07%TS) were observed. The C:N ratio varied between 11:1 in swine manure and 30:1 in maize silage.

Biogas yield (BY) of tested substrates varied over a wide range between 209.5 NL kg^{-1} VS for swine manure and 806.9 NL kg^{-1} VS for poultry manure (Table 2). The specific methane yield (SMY) was also the lowest for swine manure —170.9 NL CH_4 kg^{-1} VS. The most productive was poultry manure—529.9 NL CH_4 kg^{-1} VS, while maize silage (435.5 NL CH_4 kg^{-1} VS) and mixes (369.3–402.0 NL CH_4 kg^{-1} VS) placed in between extremes.

Table 2 Mean values of biogas yield and specific methane yield in feedstocks

Feedstock	Biogas yield		Specific methane yield	
	(NL kg^{-1} VS)	(NL kg^{-1} TS)	(NL CH_4 kg^{-1} VS)	(NL CH_4 kg^{-1} TS)
Experiment 1				
Swine manure	209.5 (9.0)	167.5 (7.2)	170.9 (5.3)	136.7 (4.2)
Poultry manure	806.9 (9.9)	661.6 (8.1)	529.9 (5.9)	434.5 (4.8)
Maize silage	648.3 (17.0)	613.1 (16.1)	435.5 (10.2)	411.8 (9.7)
Mix 1	540.3 (9.2)	489.0 (8.4)	369.3 (3.2)	334.2 (2.9)
Mix 2	567.6 (4.3)	521.6 (3.9)	384.3 (1.9)	353.2 (1.7)
Mix 3	595.9 (1.2)	555.6 (1.1)	402.0 (1.0)	374.8 (1.0)
Experiment 2				
Common reed silage	277.5 (6.3)	255.8 (5.8)	148.0 (2.8)	136.4 (2.5)
Reed canary grass silage	384.8 (8.3)	352.6 (7.6)	200.3 (4.3)	183.5 (4.0)

Standard deviations in parenthesis
Mix 1: 15% of swine manure, 15% of poultry manure, 70% of maize silage; mix 2: 10% of swine manure, 10% of poultry manure, 80% of maize silage; mix 3: 5% of swine manure, 5% of poultry manure, 90% of maize silage

In the co-digestion experiment the highest SMY—402.0 NL CH_4 kg^{-1} VS was obtained for the mix 3, which was composed of 90% of maize, 5% of poultry manure and 5% of swine manure (Table 2). This value was slightly lower than SMY of maize silage alone. The increasing proportion of manures up to 20% in mix 2 and up to 30% in mix 3 resulted in the decline of methane generation (384.3 and 369.3 NL CH_4 kg^{-1} VS, respectively).

The biogas obtained from all tested mixtures had a similar composition and contained on average about 59% CH_4, 36–37% of CO_2 and 0.5–0.6% O_2. During the trial, concentration of methane changed from 6 to 76% with the highest values recorded on the 10th day of incubation. The average concentration of NH_3 and N_2O was very low and amounted 0.1–1.2 and 448–457 ppm, respectively. Greater values were recorded in H_2S content. Its highest mean value was found in mix 1–723 ppm and the lowest in mix 3–424 ppm, containing the largest share of maize silage (90%).

3.3 BMP Test of Common Reed and Reed Canary Grass

Common reed and reed canary grass silages exhibited similar chemical properties (Table 1). Their VS was around 92%TS, TC 41.5%TS, TKN 3.6–3.9%TS, TP

0.2%TS and C:N 11:1. More difference occurred in the case of TS, which was much higher in common reed—around 60%ww, while in reed canary grass was around 39%ww.

BY of reed canary grass was higher comparing to common reed (384.8 and 277.5 NL kg^{-1} VS, respectively), and the same was for SMY (200.3 and 148.0 NL CH_4 kg^{-1} VS, respectively) (Table 2).

Wetland biomass yielded mean methane content 51.0–53.5% with the maximum not exceeding 63% in 18th day for common reed and 70% in 22nd day for reed canary grass. Mean concentration of other gases was: 39.3–41.2% CO_2, 0.71–0.79% O_2, 37.9–123.7 ppm NH_3 and 474–488 ppm N_2O. Only hydrogen sulfide content was relatively high and reached on average 1324 ppm for common reed and 2328 ppm for reed canary grass.

4 Discussion

The elemental composition of the substrate belongs to the crucial factors determining effectiveness of its conversion into a biogas. This particularly applies to the relationship between carbon and nitrogen content. Most of the literature recommends C:N ratio being in the range of 20:1 to 30:1 for optimal methanogens growth [20–22]. The higher values would result in a decrease of biogas yield, since methanogens consume more quickly nitrogen and its shortage can inhibit a decomposition and assimilation of organic C. When C:N is too low ammonia nitrogen release occurs and pH increases above 8.5, producing an inhibiting effect on methanogens [23]. The C:N ratio in maize silage and the mixes matched the optimum range, while in poultry manure was slightly sub-optimal (19:1) (Table 1). Even worst parameters had the swine manure and wetland grasses (11:1), which resulted in similar specific methane yield. For common reed it amounted 148.0 NL CH_4 kg^{-1} VS, for reed canary grass—200.3 NL CH_4 kg^{-1} VS, and for swine manure—170.9 NL CH_4 kg^{-1} VS. For mixes the biogas and methane yields rose with increasing C:N ratio from 21:1 (mix 1), via 24:1 (mix 2), up to 25:1 (mix 3).

The production of biogas may be highly influenced by the content of phosphorus. Weiland [24] estimated optimal C:N:P ratio in biogas substrate to amount 120:3:1. In turn, Effenberger and Lebuhn [25] found the best yields of biogas when C:N:P values ranged from 100:5:1 to 200:5:1. Among the analyzed substrates, the near optimal C:N:P ratios were found for the mix 1 and poultry manure, in which it equaled 105:5:1 and 153:8:1, respectively. Maize silage alone had too high carbon content in relation to phosphorus (584:20:1).

BY and SMY of tested maize were quite high compared to the data published in the literature (BY 450–700 NL kg^{-1} VS [26], SMY 203–375 NL CH_4 kg^{-1} VS [27]). Much higher values were found in case of poultry manure (BY 250–450 NL kg^{-1} VS [26]), while swine manure exhibited slightly lower biogas yield (BY 270–450 NL kg^{-1} VS [26]). Two analyzed wetland species were characterized by lower biogas production than that reported in the literature (common reed:

SMY 220–260 NL CH_4 kg^{-1} VS [28]; reed canary grass: SMY 340–430 NL CH_4 kg^{-1} VS [29]). However, a vast majority of published data concerns plant species of intensively cultivated meadows and studies on wetland plants are sparse. According to Lemmer and Oechsner [30] SMY of grassland communities from protected landscape areas equaled to about 80 NL CH_4 kg^{-1} VS, which was similar to our results and methane yield estimated for biomass of wild meadows (BY of reed canary grass 120 NL kg^{-1} VS [16]) or extensive grasslands (BY 297–559 NL kg^{-1} VS, SMY 137–315 NL kg^{-1} VS [31]).

The production of biogas in experiment 1 constantly rose until the days 12–19th when process practically stopped, and a flattening phase began (Fig. 1), with an exiguous production of biogas in the following days. The different trajectory characterized biogas production curves from the wetland plants, which reached the flattening phase on the 30–31 days of analysis. It should be noted that differences in the kinetics of the reaction between experiment 1 and 2 might be related to different inoculum/substrate ratios. For higher values of this factor, the biogas production rate was found to be slightly higher, but this did not clearly affect the ultimate biogas yield [14, 32].

The mean methane content in biogas from digestion of wetland plants was lower compared to the analyzed mixes. The concentration of CO_2, O_2 and N_2O was similar, but H_2S and NH_3 contents in biogas from grasses were notably higher, what can inhibit the biogas production [23].

Area methane yield from maize silage was calculated to amount 4901 m^3 CH_4 ha^{-1} (Table 3). Maize due to its high aboveground biomass (in our study 11.9 Mg TS ha^{-1}) reached one of the highest area methane yields among crops. Obtained value was in the lower range given by Braun [33], who reported production between 3573 and 18540 m^3 CH_4 ha^{-1}. Measured crop yield of common reed was 8.5 Mg TS ha^{-1} and reed canary grass was only 4.6 Mg TS ha^{-1}. In relation to maize, the digestion of common reed and reed canary grass gave distinctly lower values of 1160 and 844 m^3 CH_4 ha^{-1}, respectively. The reed canary grass from wetlands exhibited also lower biogas production compared to *Phalaris*

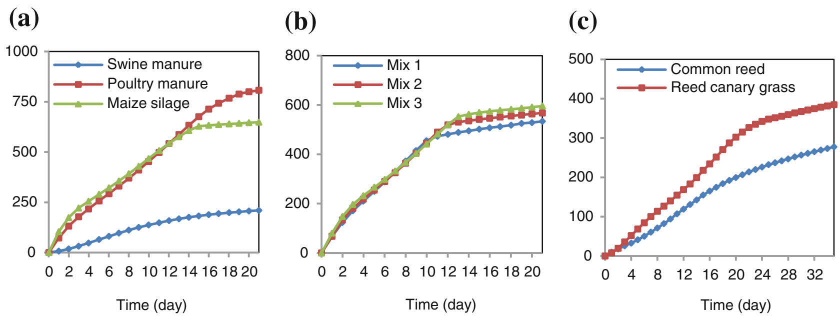


Fig. 1 Biogas yield in NL kg^{-1} VS of studied feedstocks: **a** swine manure, poultry manure and maize silage, **b** three mixes, **c** common reed and reed canary grass

Table 3 Mean values of crop yield, methane yield and gross energy yield of ensiled feedstocks

Crop	Crop yield ($Mg\ TS\ ha^{-1}$)	Methane yield ($m^3\ CH_4\ ha^{-1}$)	Gross energy yield ($MWh\ ha^{-1}$)
Maize	11.9	4901 (115)	48.7 (1.1)
Common reed	8.5	1160 (22)	11.5 (0.2)
Reed canary grass	4.6	844 (18)	8.4 (0.2)

Standard deviations in parenthesis

cultivated on intensive meadows, where area methane yield was reported to amount: 1700–4730 m^3 CH_4 ha^{-1} by Braun [33]; 3800–4200 m^3 CH_4 ha^{-1} by Lehtomäki et al. [29] and 910–1870 m^3 CH_4 ha^{-1} by Massé et al. [17]. Results similar to that obtained in our study showed Amon et al. [31] for extensive grassland in National Park Neusiedler See, Austria: 481–910 m^3 CH_4 ha^{-1}. Area methane yield of studied common reed is over two times lower than results from constructed wetland, Poland, reported by Gizińska-Górna et al. [34]: 2888 m^3 CH_4 ha^{-1}.

Gross energy yields of maize, common reed and reed canary grass estimated in this study were respectively 48.7, 11.5 and 8.4 MWh ha^{-1} (Table 3). Although the smaller SMY, the common reed had a 37% larger area methane yield and gross energy yield than reed canary grass. This was related to much higher crop yield. Compared to maize the common reed was characterized by three times lower methane productivity, but area methane yield and gross energy yield were over four times lower.

5 Conclusions

Due to notably smaller biogas and specific methane yields, reed canary grass and common reed from landscaping are unlikely to replace a maize silage in the normal wet digestion wholly. However, they can be acknowledged as interesting co-substrate, with methane productivity that is comparable to swine manure. Grasses as a substrate are relatively cheaper, as their production does not require fertilization and crop protection expenditure. Also, competitiveness of the use of grasses could be enhanced by EU agro-environmental payments for the protection of biodiversity of wetlands and abandoned meadows. To determine the economic and energetic viability of wetland biomass a life cycle assessment (LCA) for different substrates and digestion technologies (wet and dry) should be performed.

Particular attention attracts the common reed. Its vigorous spread together with high crop yield and low H_2S concentration in biogas suggests it to be a pretty good substrate for agricultural biogas plants.

Acknowledgements This work was financially supported by Ministry of Science and Higher Education as a part of the project S/WBiIŚ/1/17, Bialystok University of Technology, Bialystok, Poland.

References

1. Biogas sector statistics 2015/2016. http://www.biogas.org/edcom/webfvb.nsf/idDE_Branchenzahlen/$file/16–07-28_Biogas_Branchenzahlen-2015_Prognose-2016_engl_final.pdf. Last accessed 25 May 2017
2. URE. Mapa Odnawialnych Źródeł Energii, Urząd Regulacji Energii. http://www.ure.gov.pl/uremapoze/mapa.html. Last accessed 26 May 2017
3. Podkówka, Z., Podkówka, W.: Substraty dla biogazowni rolniczych. Agro Serwis Biznes-Press sp. z o.o., Warszawa (2010)
4. Register of energy companies producing agricultural biogas. http://www.arr.gov.pl/data/02004/rejestr_wytworcow_biogazu_rolniczego_17052017.pdf. Last accessed 26 May 2017
5. Fachagentur Nachwachsende Rohstoffe e.V. (FNR). Bioenergy in Germany facts and figures 2016. FNR 2017, 484, http://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Broschuere_Basisdaten_Bioenergie_englisch_2017.pdf. Last accessed 27 May 2017
6. Szlachta, J.: Ekspertyza—Możliwości pozyskania biogazu rolniczego jako odnawialnego źródła energii. Instytut Inżynierii Rolniczej UP, Wrocław (2009)
7. Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M.: The effect of bioenergy expansion: food, energy, and environment. Renew. Sust. Energ. Rev. **32**, 559–578 (2014)
8. Banaszuk, P., Wysocka-Czubaszek, A., Czubaszek, R., Roj-Rojewski, S.: Skutki energetycznego wykorzystania biomasy, Wieś i Rolnictwo, PAN. Instytut Rozwoju Wsi i Rolnictwa **4** (169), 13–152 (2015)
9. Schorling, M., Enders, C., Voigt, C.A.: Assessing the cultivation potential of the energy crop Miscanthus x giganteus for Germany. GCB Bioenergy **7**, 763–773 (2015)
10. Banaszuk, P., Kamocki, A.: Effects of climatic fluctuations and land-use changes on the hydrology of temperate fluviogenous mire. Ecol. Eng. **32**, 33–146 (2008)
11. Raposo, F., Fernández-Cegrí, V., de la Rubia, M.A., Borja, R., Béline, F., Cavinato, C., Demirer, G., Fernández, B., Fdz-Polanco, M., Frigon, J.C., Ganesh, R., Kaparaju, P., Koubova, J., Méndez, R., Menin, G., Peene, A., Scherer, P., Torrijos, M., Uellendahl, H., Wierinck, I., de Wilde, V.: Biochemicalmethane potential (BMP) of solid organic substrates: Evaluation of anaerobic biodegradability using data from an international interlaboratory study. J. Chem. Technol. Biotechnol. **86**(8), 1088–1098 (2011)
12. Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S., Janssen, R.: Biogas Handbook. University of Southern Denmark, Esbjerg (2008)
13. Seppälä, M., Paavola, T., Lehtomäki, A., Rintala, J.: Biogas production from boreal herbaceous grasses—specific methane yield and methane yield per hectare. Bioresour. Technol. **100**, 2952–2958 (2009)
14. Chynoweth, D.P., Turick, C.E., Owens, J.M., Jerger, D.E., Peck, M.W.: Biochemical methane potential of biomass and waste feedstock. Biomass Bioenergy **5**(1), 95–111 (1993)
15. Triolo, J.M., Sommer, S.G., Møller, H.B., Weisbjerg, M.R., Jiang, X.Y.: A new algorithm to characterize biodegradability of biomass during anaerobic digestion: influence of lignin concentration on methane production potential. Bioresour. Technol. **102**, 9395–9402 (2011)
16. Oleszek, M., Król, A., Tys, J., Matyka, M., Kulik, M.: Comparison of biogas production from wild and cultivated varieties of reed canary grass. Bioresour. Technol. **156**, 303–306 (2014)
17. Massé, D., Gilbert, Y., Savoie, P., Bélanger, G., Parent, G., Babineau, D.: Methane yield from switchgrass and reed canarygrass grown in Eastern Canada. Bioresour. Technol. **102**, 10286–10292 (2011)

18. APHA.: Standard Methods for the Examination of Water and Wastewater, 20th ed. American Public Health Association, Washington, DC (1998)
19. Weiland, P.: Biogas production: current state and perspectives. Appl. Microbiol. Biotechnol. **85**, 849–860 (2010)
20. Parkin, G.F., Owen, W.F.: Fundamentals of anaerobic-digestion of waste-water sludges. J. Environ. Eng. ASCE **112**(5), 867–920 (1986)
21. Weiland, P.: State of the art of solid-state digestion—recent developments. In: Rohstoffe, F.N. (ed.) Solid-State Digestion—State of the Art and Further R&D Requirements, vol. 24, pp. 22–38. Gulzower Fachgespräche, (2006)
22. Pang, Y.Z., Liu, Y.P., Li, X.J., Wang, K.S., Yuan, H.R.: Improving biodegradability and biogas production of corn stover through sodium hydroxide solid state pretreatment. Energ. Fuel **22**(4), 2761–2776 (2008)
23. Podkówka, W.: Biogaz rolniczy odnawialne źródło energii. Teoria i praktyczne zastosowanie. Powszechne Wydawnictwo Rolnicze i Leśne, Warszawa (2012)
24. Weiland, P.: Grundlagen der Methangärung-Biologie und substrate. In: Biogas als regenerative Energie-Stand und Perspektiven; Tagung. 19–20 Juni, Hanover (2001)
25. Effenberger, M., Lebuhn, M.: Methangärung—die Belastungsgrenzen erkennen. Mais Special. Biogas, pp. 4–7 (2008)
26. Fachagentur Nachwachsende Rohstoffe e.V (FNR). Handreichung Biogasgewinnung und—nutzung. Institut fur Energetik und Umwelt gGmbH. FNR 2006, Gülzow. http://www.big-east.eu/downloads/FNR_HR_Biogas.pdf. Last accessed 2017/06/05
27. Amon, T., Kryvoruchko, V., Amon, B., Moitzi, G., Buga, S., Fistarol Lyson, D., Hackl, E., Jeremic, D.: Biogas production from the energy crops maize and clover grass. Final Report No. 1249 GZ 24.002/59-IIA1/01 to the Austrian Federal Ministry of Agriculture and Environment. University of Natural Resources and Life Sciences, Vienna (2003)
28. Jagadabhi, P.S., Kaparaju, P., Rintala, J.: Two-stage anaerobicdigestion of tomato, cucumber, common reed and grass silage in leach-bed reactors and upflow anaerobic sludge blanket reactors. Bioresour. Technol. **102**, 4726–4733 (2011)
29. Lehtomäki, A., Viinikainen, T.A., Rintala, J.A.: Screening boreal energy crops and crop residues for methane biofuel production. Biomass Bioenergy **32**, 541–550 (2008)
30. Lemmer, A., Oechsner, H.: Einsatz von Mähgut landwirtschaftlich nicht genutzter Flächen als Kosubstrat in landwirtschaftlichen Biogasanlagen. Tagungsband zur 5. Internationalen Tagung Bau, Technik und Umwelt in der landwirtschaftlichen Nutztierhaltung. Hohenheim, 398–401 (2001)
31. Amon, T., Bodiroza, V., Kryvoruchko, V., Machmüller, A., Bauer, A.: Energetische Nutzung von Schilfgras von extensiven Naturschutzflächen des Nationalparks Neusiedler See und Makrophyten des Neusiedler Sees. Research Report, Vienna (2007)
32. Raposo, F., Banks, C.J., Siegert, I., Heaven, S., Borja, R.: Influence of inoculum to substrate ratio on the biochemical methane potential of maize in batch tests. Process Biochem. **41**, 1444–1450 (2006)
33. Braun, R.: Anaerobic digestion—a multi faceted process for energy, environmental management and rural development. In: Ranalli, P. (ed.) Improvement of Crop Plants for Industrial End Users. Springer, Berlin (2007)
34. Gizińska-Górna, M., Czekała, W., Józwiakowski, J., Lewicki, A., Dach, J., Marzec, M., Pytka, A., Janczak, D., Kowalczyk-Jusko, A., Listosz, A.: The possibility of using plants from hybrid constructed wetland wastewater treatment plant for energy purposes. Ecol. Eng. **95**, 534–541 (2016)

Analysis of the Potential of Methane Emission and Energy Power from Excrement of Livestock in Poland

Weronika Gracz, Wojciech Golimowski, Krystian Butlewski and Damian Marcinkowski

Abstract The emission of methane has a share of 12% of the total emission of greenhouse gases in Poland. In Poland, methane is primarily emitted by such industries as transport, agriculture and waste management. Agriculture, in particular excrement from the animal production, has a share of 31% of the total emission of methane in Poland. The key sources of the gas emission are livestock's enteric fermentation and the decomposition of animal excrement. Depending on the type of the livestock breeding system, its excrement may be classified into manure and liquid manure (bedding system) and slurry (non-bedding system). That excrement may be processed on an agricultural basis as manure according to the requirements of the Act on Fertilisers and Fertilisation. Manure permanently needs to be kept on sealed boards, whereas liquid manure needs to be stored in sealed tanks. One of the methods for restricting the emission of methane into the environment is to control the production and incinerate biogas that enables processing the animal excrement in a safe and energy effective manner. Therefore, the objective of the study is to analyse the potential of animal excrement and the potential of biogas energy power in Poland. For this purpose, the estimated quantity of electric energy and thermal energy that may be produced in biogas plants was calculated with respect to the potential of animal excrement. Research was conducted on the basis of the data obtained from the Chief Veterinary Inspectorate and from the Agency for the Restructuring and Modernisation of Agriculture. The livestock population (cattle, pigs and hens) was used for the calculations. The emission of methane from the animal excrement in Poland in the years 2013–2016 is stable and equals to

W. Gracz (✉) · W. Golimowski · K. Butlewski · D. Marcinkowski
Department of Biomass Processing Technologies, Institute of Technology and Life Sciences, 67 Biskupińska Str, 60-463 Poznań, Poland
e-mail: w.gracz@itp.edu.pl

W. Golimowski
e-mail: w.golimowski@itp.edu.pl

K. Butlewski
e-mail: k.butlewski@itp.edu.pl

D. Marcinkowski
e-mail: d.marcinkowski@itp.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_14

41,096 Mg per annum, whereas the energy power in 2016 was 37,625–85,180 MW of electric energy and 33,080–75,126 MW of thermal energy.

Keywords Emission of methane · Animal excrement · Power of biogas plant Biogas · Methane

1 Introduction

By ratifying the Kyoto Protocol, Poland committed itself to reduce the emission of greenhouse gases. The major greenhouse gases emitted into the environment are steam (H_2O) (36–72%), carbon dioxide (CO_2) (9–26%), methane (CH_4) (4–9%), and ozone (O_3) (3–7%). The global concentration of greenhouse gases in 2011 amounted to 391 ppm CO_2, 1803 ppb CH_4 and increased from the beginning of the industrial era by 40 and 150%, respectively [1–4].

The emission of CH_4 has a share of 12% of the total emission of greenhouse gases in Poland. In Poland, methane is primarily emitted by such industries as transport, agriculture and waste management. Agriculture emits 31% of the total methane emitted in Poland. In the animal production the major sources of the gas emission is the enteric fermentation and the decomposition of animal excrement. The enteric fermentation is a natural process and represents 88.3% of total methane emitted by animals, whereas the waste management sector emits 11.5%, including cattle that emits as many as 95% of methane [5].

The livestock bred in Poland comprises cattle, pigs, horses, sheep and poultry (chickens, geese, ducks and turkeys). The largest group consists of cattle, including dairy cows, pigs and hens. The livestock may be bred by using two systems: bedding and non-bedding. Depending on the system, its excrement may be classified into manure and liquid manure (bedding system) and slurry (non-bedding system) [6, 7].

That excrement may be processed agriculturally as manure according to the requirements of the Act on Fertilisers and Fertilisation [8]. This act provides for periods wherein excrement may be used to manure soils and a method of their storage until they are directly used. Manure permanently needs to be stored on sealed boards, whereas liquid manure needs to be stored in sealed tanks. The storage of animal excrement without a relevant protection may cause a threat to groundwater and surface water. One of the solutions to reduce the emission of methane into the environment is to process the animal excrement in the anaerobic fermentation process by agricultural biogas plants. Those systems minimise the adverse impact on the environment and enable the animal excrement to be processed in a safe and energy-effective way. Agricultural biogas plants may safely utilise any solid and liquid animal excrement. For the energy purposes there may be applied the surplus of natural manure not used in the agriculture. In Poland cattle's and pigs' manure is almost entirely used as organic manure, hence a potential substrate applied by the biogas plant is cattle and pigs slurry and poultry manure from the farms applying non-bedding and cage breeding systems [6, 7, 9].

2 Research Methodology

Research was carried out to estimate the level of CH_4 emission and the potential of energy power of the mono-substrate biogas plant supplied by excrement of cattle, dairy cows, pigs and hens for each Polish province.

The data on the population of cattle, dairy cows and pigs in the Polish provinces in the years 2013–2016 have been acquired from the Agency for the Restructuring and Modernisation of Agriculture that registers the livestock population in Poland. The calculations comprise all the farms breeding cattle and dairy cows and all those farms that keep over 100 pigs.

The data on the population of hens in the Polish provinces in 2016 have been received from the Chief Veterinary Inspectorate [10]. For hens, the barn and cage egg production systems were considered, without the free-cage egg production system.

2.1 Estimation of a Level of CH_4 Emission from the Production of Animal Excrement

The first stage was to calculate for cattle, dairy cows, pigs in the years 2013–2016 and hens in 2016, the quantity of livestock units (large livestock unit—LU) on the basis of the coefficients set forth in Table 1, which formed the basis for any further calculations.

Subsequently, the potential of methane E_{CH_4} was calculated for livestock on the basis of the Eq. 1:

$$E_{CH_4} = X_{DJP} \bullet EF_{DJP} \quad \left[kg\,CH_4\,LU^{-1}\,year^{-1}\right] \tag{1}$$

Table 1 LU conversion coefficient, CH_4 emission factor for units [EF] and for LU [EF_{DJP}] from livestock excrement [6, 11]

Animals	LU	EF kg CH_4 units^{-1} year^{-1}	EF_{DJP} kg CH_4 LU^{-1} year^{-1}
Cattle	0.63	2.15	1.35
Dairy cows	1.00	11.87	11.87
Pigs	0.11	1.99	0.22
Poultry	0.004	0.08	0.00032

Source Own data based on [6, 11]

where:

E_{CH_4} emission of CH_4 [kg CH_4 LU^{-1} $year^{-1}$];
X_{DJP} number of LU [–];
EF_{DJP} CH_4 emission factor for LU [kg CH_4 LU^{-1} $year^{-1}$];

The calculated value of the emission of CH_4 was converted into Mg $year^{-1}$.

2.2 Estimation of Energy Power from Animal Excrement Production

The biogas plant's energy power comprising power energy P_e and thermal power P_t of the plant was calculated by means of the Eqs. 2 and 3 [12].

Quantity of electric energy P_e produced by the biogas plant:

$$P_e = (W_b \bullet S_{CH_4} \bullet M \bullet W_{eCH_4} \bullet \eta_e) \bullet t^{-1}[MW] \quad (2)$$

where:

P_e quantity of electric energy produced by the cogeneration plant [MW];
W_b biogas efficiency of substrate [m^3 Mg^{-1}];
S_{CH_4} concentration of CH_4 in biogas [%];
M substrate mass [Mg];
W_{eCH_4} energy efficiency coefficient of methane—0.00917 [MWh m^{-3}];
η_e electrical efficiency of the cogeneration plant [–]; 0.36–0.44, for calculations the value of 0.4 was used;
t operation time of the cogeneration plant [h]; for calculations there was used the value of 8200 h of the cogeneration plan's operation time per year.

Quantity of thermal energy P_t produced by the biogas plant:

$$P_t = (W_b \bullet S_{CH_4} \bullet M \bullet W_{tCH_4} \bullet \eta_t) \bullet t^{-1}[MW] \quad (3)$$

where:

P_t quantity of thermal energy produced by the cogeneration plant [MW];
W_b biogas efficiency of substrate [m^3 Mg^{-1}];
S_{CH_4} concentration of CH_4 in biogas [%];
M substrate mass [Mg];
W_{eCH_4} energy efficiency coefficient of methane—0.00917 [MWh m^{-3}];
η_t thermal efficiency of the cogeneration plant [–]; 0.43–0.54, for calculations the value of 0.45 was used;
t operation time of the cogeneration plant [h]; for calculations there was used the value of 8200 h of the cogeneration plan's operation time per year.

Table 2 Factor for determining the annual average production of manure with respect to the livestock maintenance system [6]

Animals	Bedding-manure [Mg LU^{-1} $year^{-1}$]	Non-bedding-slurry [m^3 LU^{-1} $year^{-1}$]
Cattle	15	20
Dairy cows	15	20
Pigs	15	20
Poultry	15	20

Source Own data based on [6]

Table 3 Technological parameters of substrates [7]

Substrates	Dry mass [dm] % [fm]	Organic dry mass [odm] % [dm]	Biogas efficiency Ndm^3 kg dm^{-1}	Biogas efficiency Ndm^3 kg odm^{-1}	Methane share %
Cattle	8–11	75–82	20–30	200–500	50–55
Pigs	4–7	75–87	20–35	300–700	50–70
Hens	30–32	63–80	70-90	240–450	57–70

Source Own data based on [7]

The electric and thermal power was determined for minimum and maximum values of technological parameters of substrates of biogas plants (Tables 2 and 3).

3 Discussion of Results

In the group of the analysed livestock the largest quantity of CH_4 is emitted by dairy cows. This emission amounts to 38,826 $MgCH_4$, which is 94.01% of the total emission of CH_4 in 2016, whereas cattle, pigs and hens emit 5.33, 0.65, and 0.00013% $MgCH_4$, respectively. Figure 1 shows the emission of methane from excrement of cattle, dairy cows, pigs in the years 2013–2016 and hens in the year 2016 in Poland with a breakdown into provinces. For cattle and dairy cows the largest emission of CH_4 was observed in the Mazowieckie, Podlaskie and Wielkopolskie provinces, whereas the lowest emission was noted in the Lubuskie, Opolskie and Zachodniopomorskie provinces. As for pigs and hens by far the largest emission of CH_4 was recorded in the Wielkopolskie Province, whereas the lowest one in the Małopolskie Province.

In the group of the analysed livestock the largest potential of electric and thermal energy is observed for dairy cattle. This potential equals to 6765–20,339 MW of electric energy and 6013–18,079 MW of thermal energy, which equals to 47% of the total energy potential from excrement of livestock in 2016. The energy potential

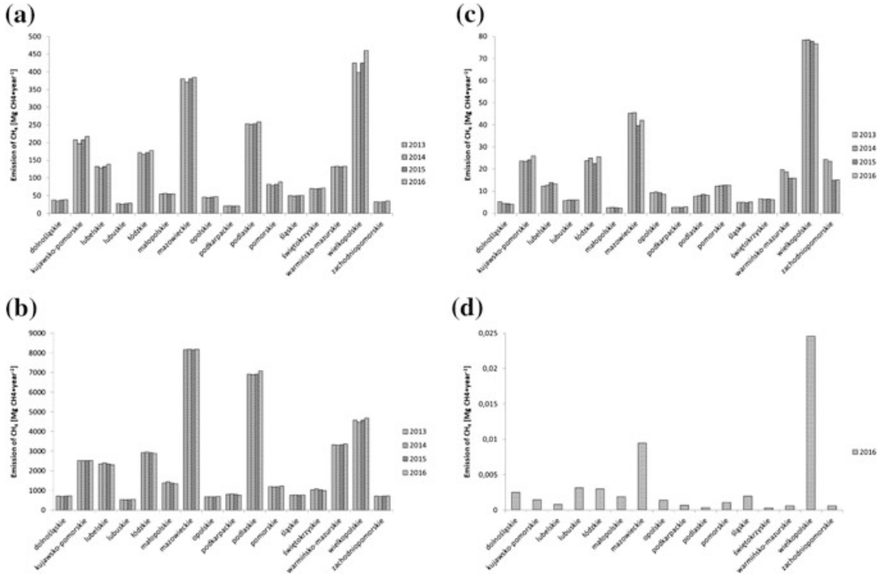


Fig. 1 Emission of CH_4 from excrement of **a** cattle, **b** dairy cows, **c** pigs in the years 2013–2016 and **d** hens in 2016 for Polish provinces

of cattle, pigs and hens is 23, 30, below 1%, respectively. The largest energy potential from excrement of dairy cows is recorded in Mazowieckie, Podlaskie and Wielkopolskie provinces (Fig. 3), whereas cattle, pigs and hens have the largest potential of electric and thermal energy in the Wielkopolskie and Mazowieckie provinces (Figs. 2, 4 and 5).

The greatest energy potential from the animal excrement in Poland is observed in the Wielkopolskie Province (19%) and the Mazowieckie Province (19%), whereas the lowest one is noted in the Podkarpackie Province (1%).

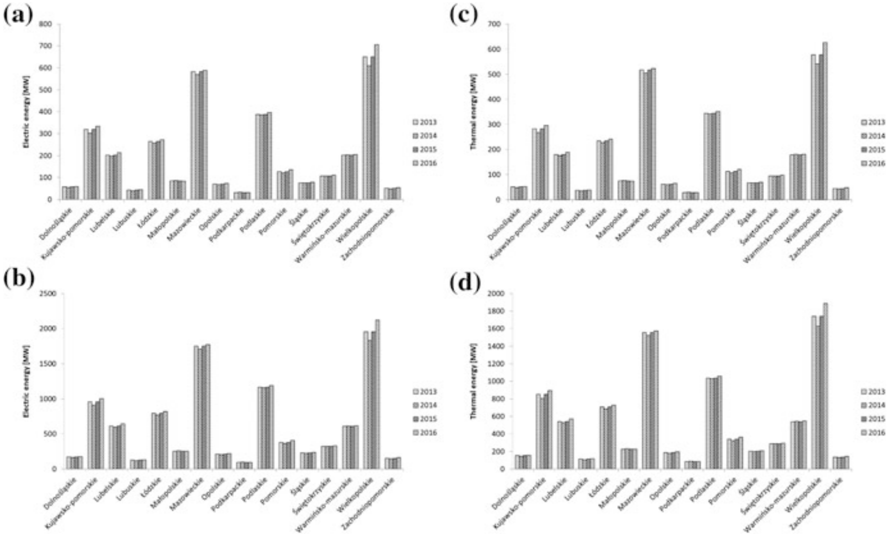


Fig. 2 **a** Minimum and **b** maximum electric power and **c** minimum and **d** maximum thermal power from cattle excrement in the years 2013–2016 for Polish provinces

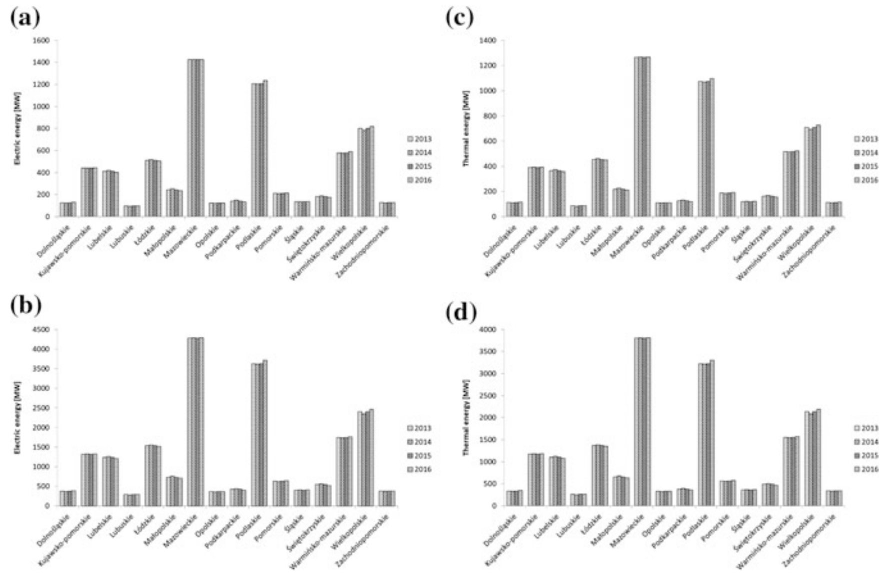


Fig. 3 **a** Minimum and **b** maximum electric power and **c** minimum and **d** maximum thermal power from excrement of dairy cows in the years 2013–2016 for Polish provinces

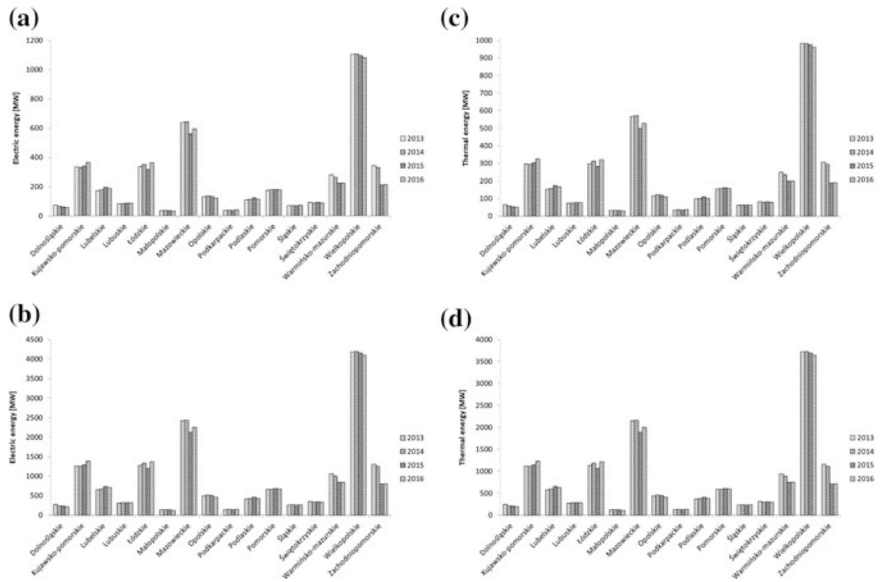


Fig. 4 **a** Minimum and **b** maximum electric power and **c** minimum and **d** maximum thermal power from excrement of pigs in the years 2013–2016 for Polish provinces

4 Conclusions

Excrement of the analysed livestock (cattle, dairy cows, pigs and hens) is the animal production waste that emits into the environment 41,096 Mg of methane per annum, but this excrement may be processed in a safe and energy-efficient way through the controlled production and incineration of biogas.

The methane emission from excrement of the analysed livestock in Poland in the years 2013–2016 was at a constant level and ranged from 41,012 Mg in 2014 to 41,297 Mg in 2016 (Fig. 6).

The energy power from the animal excrement in Poland in the years 2013–2016 was at a stable level and in 2016 Mg it amounted to 37,625–85,180 MW of electric energy and 33,080–75,126 MW of thermal energy (Fig. 7).

The largest share in the energy potential from the livestock excrement in Poland refers to dairy cows, which is 47%. Whereas, the energy potential of hens is below 1%.

The study was conducted within the Multiannual Programme for the period 2016–2020 according to Regulation No. 154/2016 dated 12 December 2016.

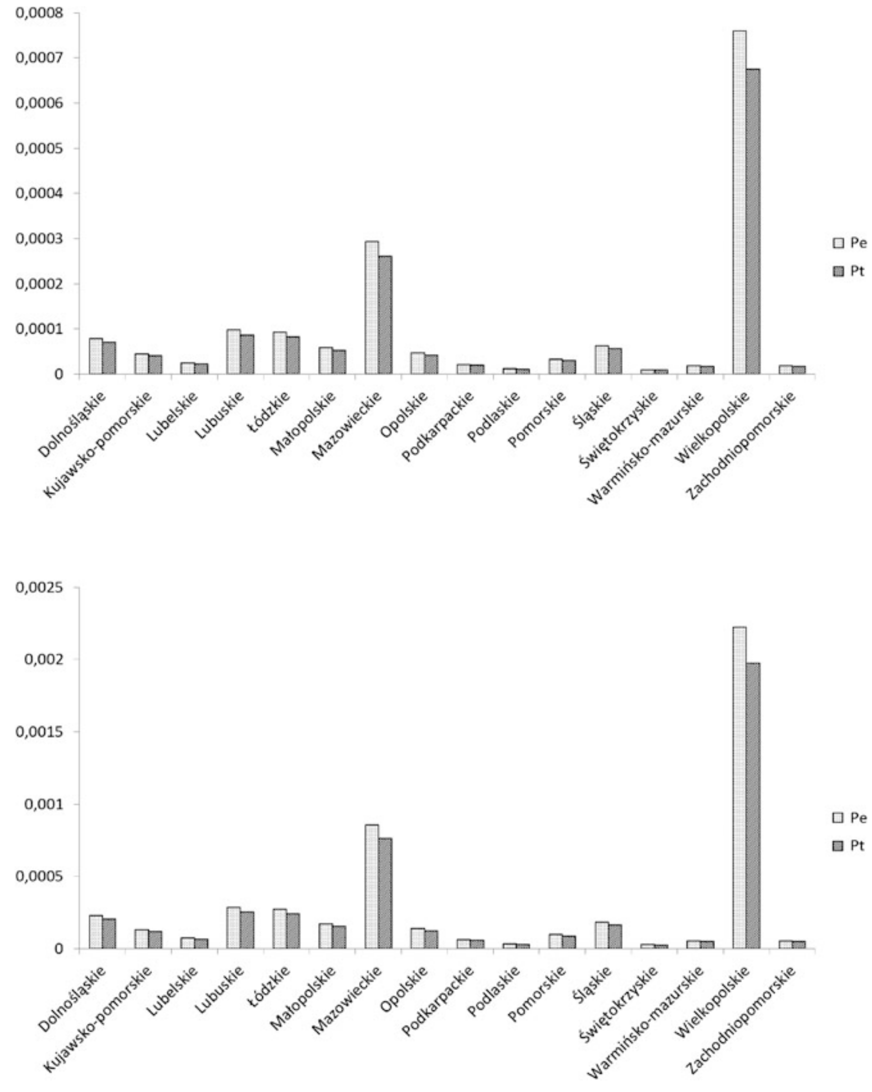


Fig. 5 **a** Minimum electric and thermal power and **b** maximum electric and thermal power from excrement of hens in 2016 for Polish provinces

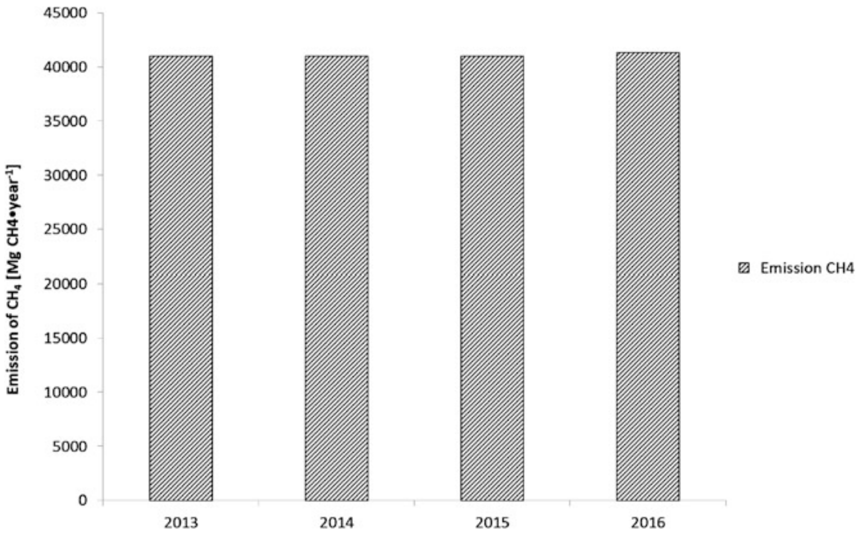


Fig. 6 Emission of CH_4 from excrement of cattle, dairy cows, pigs and hens in the years 2013–2016 in Poland

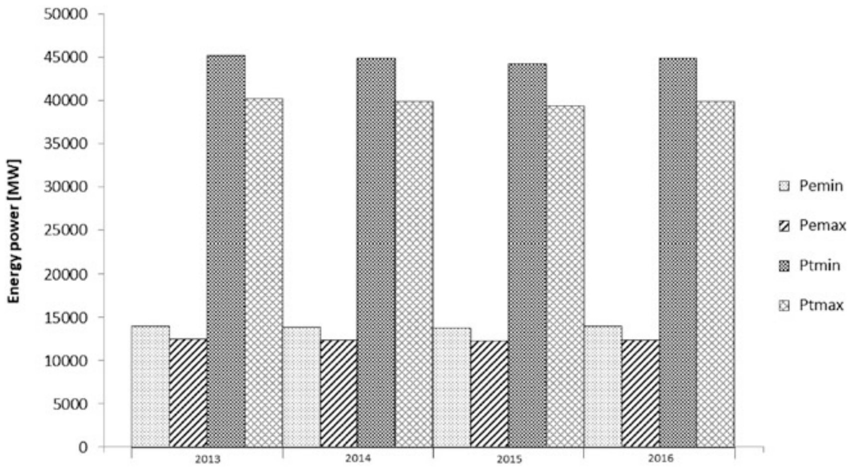


Fig. 7 Minimum electric and thermal power from excrement of cattle, dairy cows, pigs and hens in the years 2013–2016 in Poland

References

1. IPCC 2007: Zmiana klimatu 2007: Raport Syntetyczny. Wkład Grup roboczych I, II i III do Czwartego Raportu Oceniającego Międzynarodowego Zespołu ds. Zmian Klimatu [(red.) Główny zespół autorski, Pachauri R.K. i Reisinger A.]. Wyd. IOŚ, Warszawa, 2009
2. IPCC 2013: Podsumowanie dla Decydentów: Przyczynek I Grupy Roboczej do Piątego Raportu Oceny Zmiany Klimatu Międzyrządowego Zespołu ds. Zmiany Klimatu 2013: Fizyczne Podstawy Naukowe. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex i P.M. Midgley (red.)]. Cambridge University Press, Cambridge, Wielka Brytania i Nowy Jork, NY, USA
3. Kiehl, J.T., Trenberth K.E.: Earth's annual global mean energy budget. Bull. Am. Meteorol. Soc. **78,** 197–208 (2006)
4. Rees, R.M., Flack, S., Maxwell, K., Mistry, A.: Air: greenhouse gases from agriculture. Encyclopedia of Agriculture and Food Systems, pp. 293–304 (2014)
5. Krajowy Raport Inwentaryzacyjny 2017: Inwentaryzacja gazów cieplarnianych w Polsce 1988–2017, KOBiZE, Warszawa luty (2017)
6. Konieczny, R., Fedko, M., Łaska, B., Golimowski, W.: Nowe modele monitorowania zasobów biomasy oraz dostępne technologie jej konwersji w instalacjach OZE (na przykładzie gmin wiejskich województwa wielkopolskiego). Falenty-Poznań, pp. 26–42 (2015)
7. Myczko, A., Myczko, R., Kołodziejczyk, T., Golimowska, R., Lenarczyk, J., Janas, Z., Kliber, A., Karłowski, J., Dolska, M.: Budowa i eksploatacja biogazowni rolniczych. Poradnik dla inwestorów zainteresowanych budową biogazowni rolniczych. ITP Warszawa-Poznań, pp. 16–23 (2011)
8. Ustawa z dnia 10 lipca 2007 r. o nawozach i nawożeniu. Dz.U. z 2007 r. Nr 147 poz. 1033
9. Grzybek A., Pawlak J.: Potencjał i wykorzystanie odnawialnych źródeł energii w rolnictwie. Falenty pp. 11–40 (2015)
10. Główny Inspektorat Weterynarii: Lista ferm kur niosek zarejestrowanych zgodnie z dyrektywą 2002/4 [Dostęp 22.03.2017]. Dostępny w internecie. http://old.wetgiw.gov.pl/index.php?action=art&a_id=3098
11. Metodyka Oceny Poziomu Emisji Gazów Cieplarnianych w wybranych powiatach dla lat 2005, 2010 i 2010 z podziałem na sektory, Fundacja Instytut na rzecz Ekorozwoju, Warszawa (2015)
12. Szulc, R., Dach, J.: Kierunki rozwoju ekoenergetyki w polskim rolnictwie. Kraków: Polskie Towarzystwo Inżynierii Rolniczej, Kraków, pp. 72–86 (2014)

A Fuzzy Model of the Composting Process with Simultaneous Heat Recovery and Aeration Rate Control

Maciej Neugebauer, Tomasz Jakubowski, Piotr Sołowiej and Maciej Wesołowski

Abstract Composting is an effective method of managing biomass waste from agricultural crops and food processing. This exothermic reaction produces high-quality humus. Heat generated during composting can be evacuated from the compost pile and used effectively for other purposes. Effective methods are needed to control prism aeration and the evacuation of heat from the compost prism to maximize heat gain without compromising the composting process. A preliminary examination of fuzzy logic systems revealed that the terms of input and output variables and sharpening methods have to be adapted to specific compost materials. This approach also delivers immediate results without the need for lengthy research. The composting process lasts several weeks, therefore, models which illustrate the responses of control systems save time and support the selection of the optimal solutions for changing the aeration rate and heat consumption in feedstock. Fuzzy models of the control system developed in the LabVIEW programs are effective tools which can be directly implemented in a programmable logic controller (PLC).

Keywords Composting · Fuzzy logic · Heat reception

M. Neugebauer (✉) · P. Sołowiej · M. Wesołowski
University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: mak@uwm.edu.pl

P. Sołowiej
e-mail: pit@uwm.edu.pl

M. Wesołowski
e-mail: mwesolowski@uwm.edu.pl

T. Jakubowski
University of Agriculture in Krakow, Kraków, Poland
e-mail: tomasz.jakubowski@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_15

1 Introduction

Composting has long been used to manage biomass waste from agricultural crops and food processing. It is also an effective method of managing biological waste generated by households. According to Kollikkathara [1], in the bulk of household waste produced by large American cities in 2006, 0.17 kg per day per person was composted, whereas 0.26 kg per day per person was processed by incineration with energy recovery. Around 30% of waste generated by American cities is composted [1]. Composting is an exothermic reaction that produces high-quality humus. The temperature inside the compost heat is high, which promotes effective hygienisation of composted material [2–4]. The above was confirmed by laboratory tests of various materials, not only agricultural crops, but also wastes from the food industry, sewage treatment plants and others. These materials require hygienisation.

However, not all waste materials require hygienisation. Urban green waste, such as grass and leaves, do not require hygienisation. In this case, excess heat generated during composting is not required to sanitise the resulting compost and can be used for other purposes, such as soil heating in greenhouses. Heat cannot be evacuated from the compost prism in excessive quantities because the composting process is prolonged when the temperature inside the heap drops below 50 °C. For this reason, the heat recovery process should be controlled to maintain adequate composting temperature. According to the literature, the higher the temperature inside the prism, the greater the ammonia emissions [5]. Composted material should be aerated to reduce ammonia emissions [6]. Puyuelo [7], Kulcu and Yaldiz [8] and Sołowiej et al. [9] observed that aeration also decreases composting time, therefore, the rate of aeration has to be adjusted accordingly. Insufficient aeration lowers composting efficiency, whereas excessive aeration draws heat and moisture from the prism and slows down or, in extreme cases, terminates the composting process. It should also be noted that during composting, the rate of aeration and heat evacuation should change over time, although according to some authors [5], the aeration rate is constant during the composting process. The above implies that effective methods are needed to control heat evacuation and prism aeration to maximise heat gain without compromising the composting process and increasing ammonia emissions. This study proposes a model for determining the optimal aeration rate [10].

Experiments aiming to optimise the aeration rate were carried out at the University of Warmia and Mazury in Olsztyn [11]. The composting process and the evacuation and transport of heat have been resolved, but all the applied control systems were not highly effective. The use of fuzzy logic was proposed based on a review of the literature [12]. A fuzzy model of the composting process was presented in [13–15]. The general assumptions relating to fuzzy control systems have been described by numerous authors, including [16, 17].

A preliminary analysis of fuzzy logic systems yielded promising results, however, composting materials with different C/N ratios are composted at different rates [18], therefore, different terms of input and output variables and sharpening methods are required. The relevant modifications are also needed to produce direct results (total response area of the control system) and evaluate changes in the fuzzy control algorithm without the need for lengthy research. Nonlinear dynamic systems are modelled to verify the control system and the relevant assumptions [18–24] or to find the best process parameters [10]. The automation of composting and heat recovery requires a fully functional fuzzy model. Fuzzy models support rapid assessment of changes in the fuzzy control algorithm and the selection of the best solutions for various types of agricultural waste of different origin and with different chemical composition. Models that support quick acquisition of results and the selection of the most appropriate terms and sharpening methods for different materials shorten research time. The composting process lasts several weeks (around 60 days according to Wang et al. [25]), regardless of the additives that are applied to improve compost quality. According to Guo et al. [26], the composting process lasts around 40 days, and models illustrating control system responses save time and support the selection of the best solutions to change the rate of aeration and heat consumption for different types of feedstock. In this study, a fuzzy model was created in the LabVIEW program. LabVIEW software is intended mainly for the development of measurement and control applications. It can also be used to model various processes, such as diagnosing the condition of oil transformers [27]. Attempts were also made to apply fuzzy logic to control the composting process with simultaneous heat recovery [28, 29].

2 Assumptions for Fuzzy Model Design

As indicated in [28], the control input variables are:

- the temperature inside the compost prism,
- the amount of heat recovered from the compost prism,
- rate of aeration.

The output variables which influenced process control were:

- rate of heat recovery,
- rate of aeration.

A fuzzy model of the control system was developed in the following steps:

1. Determination of terms for input and output variables. A linguistic term for an input variable, temperature, is presented in Fig. 1.
2. Development of a database of rules based on previous experience and a review of literature. A total of 27 rules have to be developed for three input variables, where each variable can adopt three different states. A fragment of a database of rules presented in Fig. 2.
3. Selection of sharpening method—Fig. 2.

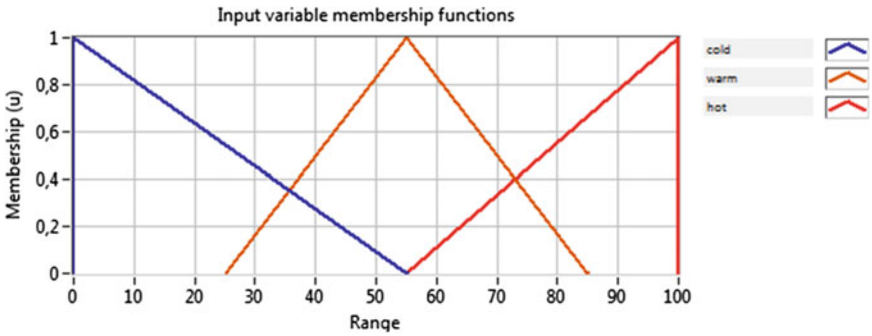


Fig. 1 Distribution of a linguistic variable—temperature

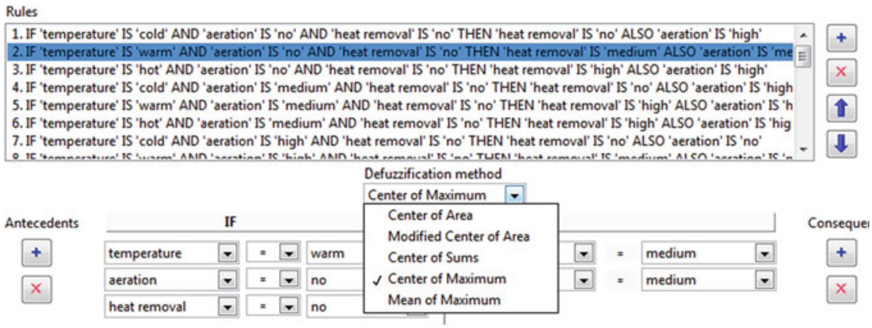


Fig. 2 A fragment of a database of rules and selection of a sharpening method (red arrow)

Table 1 Distribution of terms in the 3Δ model for temperature

Linguistic variable	Value		
Cold	0	0	55
Warm	25	55	85
Hot	55	100	100

4. Evaluation of the resulting fuzzy control system.

The example of distribution of terms of input and output variables is given in Table 1. The terms are described with three triangular numbers (Fig. 3) which denote the vertex coordinates of a triangle in the adopted axis system. The description of a trapezoid term is similar, where 4 numbers correspond to the vertex coordinates of a trapezoid in the adopted axis system. A preliminary model was verified, and the response surface is shown in Fig. 4. This model contains three linguistic variables with triangular distribution of input/output variables in the 3Δ preliminary model (3—number of linguistic variables, Δ—triangular distribution, T—trapezoidal distribution).

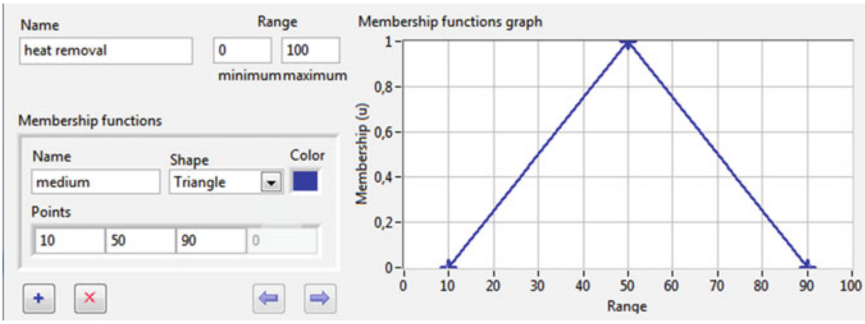
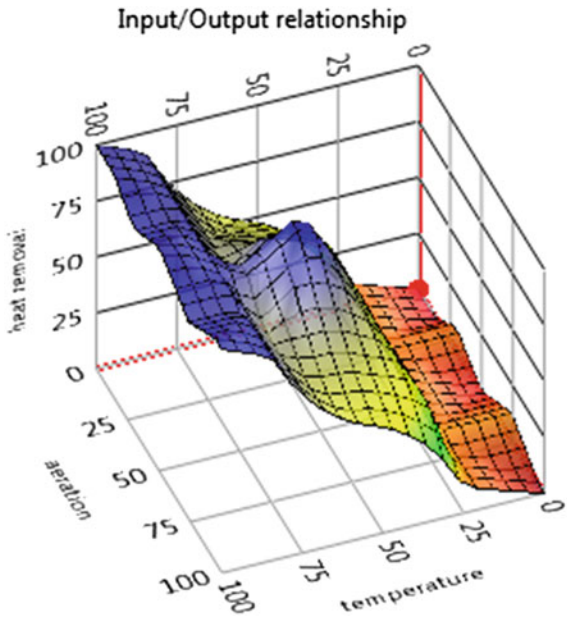


Fig. 3 Description of a triangular term

Fig. 4 Response surface in a fuzzy control model



Aeration and heat recovery variables are expressed in % of open flow control values (0–100%), where 100% aeration is equivalent to a water flow rate of 10 l/min, and 100% heat recovery is equivalent to a water flow rate of 4 l/min in the cooling system.

3 Testing the Fuzzy Model of Automatic Control

The following variables were selected for preliminary analysis:

- choice of sharpening method, and
- rate of aeration.

Other variables were not chosen because, according to preliminary studies and the literature, the optimal temperature inside the compost prism is 55 °C, and rate of heat recovery should be adjusted to the temperature inside the prism. All five sharpening methods in the program were tested, and the aeration rates described with the use of one, three and five linguistic variables for two types of terms—triangular and trapezoidal—are presented in Table 2. The other two variables did not change and their values were identical to those shown in the 3Δ model (Table 1).

For comparison, the control system was also tested for all variables in the decomposition of a rectangular term. This corresponds to the classical zero-one control design method (K model—for temperature) (Table 3).

The above procedure produced a total of 35 possible results [seven models: K, 1Δ, 3Δ, 5Δ, 1T, 3T and 5T, multiplied by five sharpening methods: Centre of Area (CA), Modified Centre of Area (MCA), Centre of Sums (CS), Centre of Maximum (CM) and Mean of Maximum (MM)]. The resulting response surfaces are shown in Fig. 5.

Table 2 Distribution of terms for the aeration variable in the tested models

Model	Linguistic variable	Value			
1Δ	Medium	0	50	100	X
3Δ	None	0	0	50	X
	Medium	0	50	100	X
	High	50	100	100	X
5Δ	None	0	0	25	X
	Low	0	25	50	X
	Medium	25	50	75	X
	Medium-high	50	75	100	X
	High	75	100	100	X
1T	Medium	0	25	75	100
3T	None	0	0	25	50
	Medium	0	25	75	100
	High	50	75	100	100
5T	None	0	0	12.5	25
	Low	0	12.5	37.5	50
	Medium	12.5	37.5	62.5	75
	Medium-high	50	62.5	87.5	100
	High	75	87.5	100	100

Table 3 Distribution of terms in the 3K model for temperature

Linguistic variable	Value			
Cold	0	0	54	54
Warm	54	54	56	56
Hot	56	56	100	100

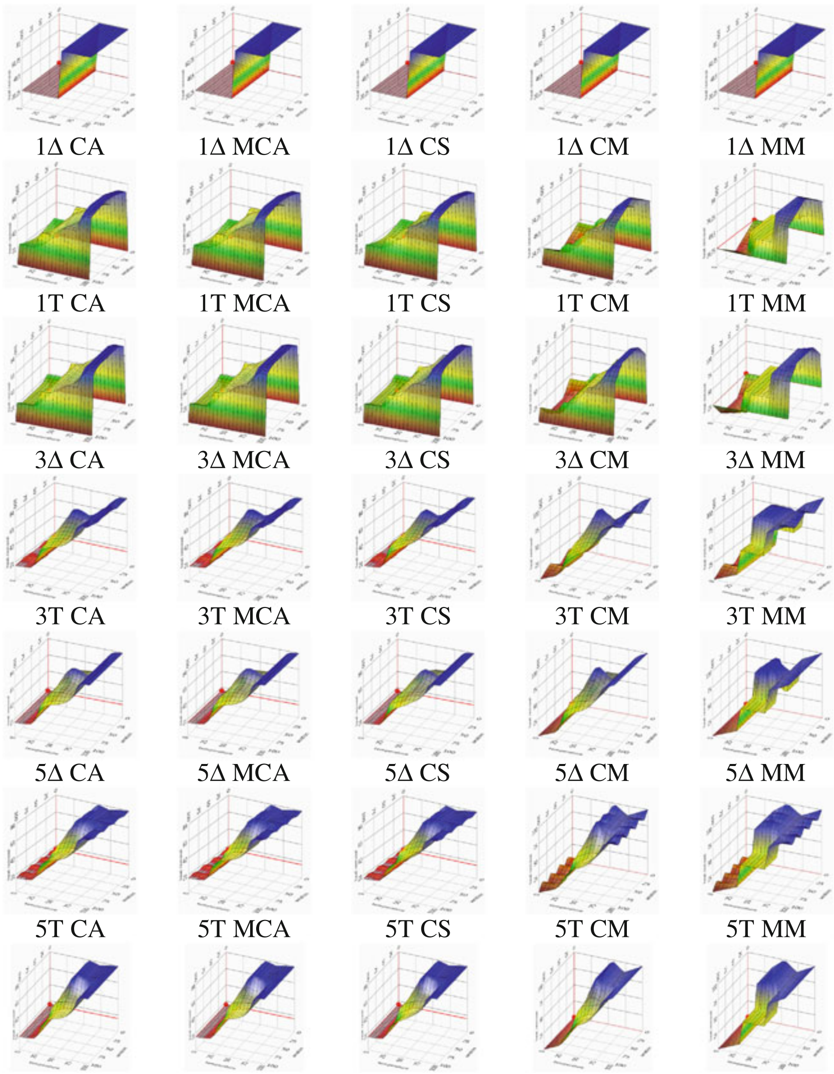


Fig. 5 Response surfaces for all analysed variants

4 Summary and Conclusions

The results of the performed simulations support the formulation of the following conclusions:

- Only minor differences are noted between models with triangular and trapezoidal terms, which can be attributed mainly to the smoother edges of models with trapezoidal terms;
- The choice of sharpening method does not significantly influence the results. Minor differences are observed, but most of them are not statistically significant;
- The shape of the response surface (and quality control) has the greatest impact on the number of linguistic variables that describe each input/output variable;
- The higher the number of linguistic variables for each variable, the more rules have to be created. Nine rules were created for 1X models, 27 rules for 3X models, and 45 rules for 5X models;
- Heat recovery is highest in the classical model (zero-one) when the temperature inside the compost prism exceeds 56 °C, which is not appropriate for complex systems and biological processes. Fuzzy control algorithms offer a better solution;
- The classical model of the control system can be expanded to obtain more response surfaces, as shown in Fig. 6.

To conclude, a fuzzy control system should be modelled before it is applied in practice, and the LabView program offers an excellent modelling environment.

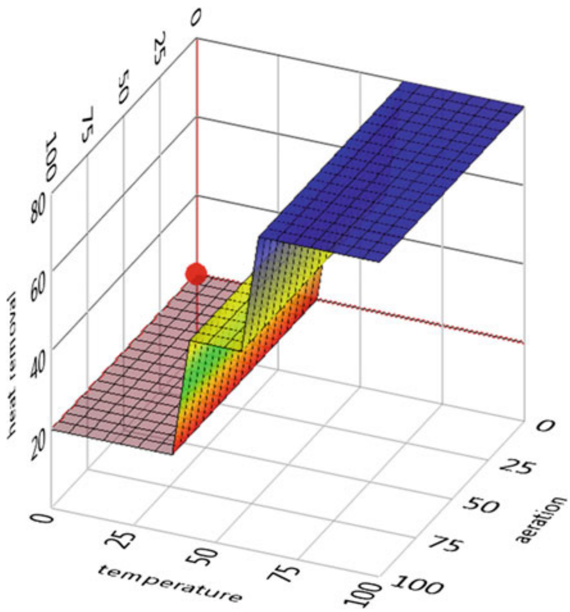


Fig. 6 Response surface in an expanded classical model

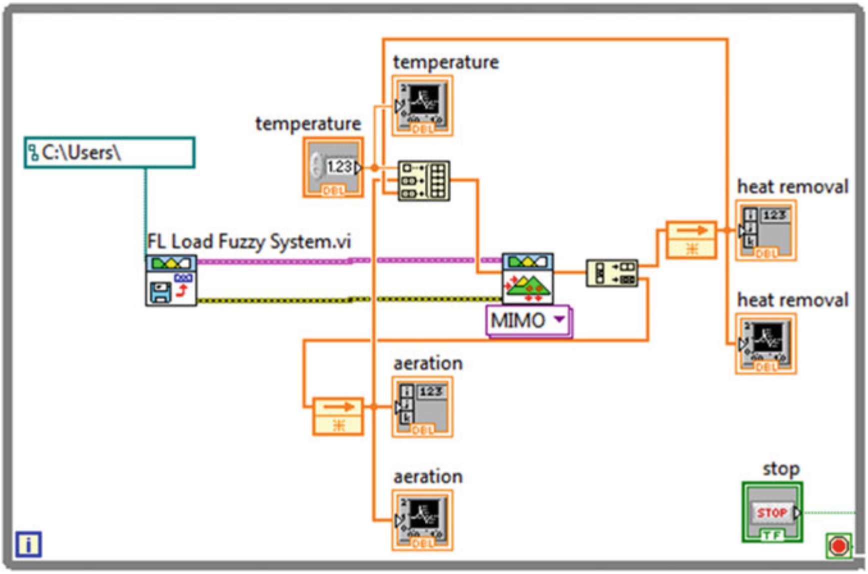


Fig. 7 An application developed in LabVIEW for controlling the composting process and heat recovery with the use of fuzzy logic

A fuzzy control system modelled in LabVIEW can be directly implemented to control a process automation system. A simple and ready-to-use BlockPanel application designed in LabVIEW is shown in Fig. 7.

References

1. Kollikkathara, N., Feng, H., Stern, E.: A purview of waste management evolution: special emphasis on USA. Waste Manage. **29**, 974–985 (2009)
2. Jakubowski, T., Sołowiej, P.: Dynamics of temperature changes in thermophille phase of composting process in the aspect of sanitary condition of obtained material. Agric. Eng. **20**(4), 207–217 (2016)
3. Lashermes, G., Barriuso, E., Le Villio-Poitrenaud, M., Houot, S.: Composting in small laboratory pilots: performance and reproducibility. Waste Manage. **32**, 271–277 (2012)
4. Raj, D., Antil, R.S.: Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. Biores. Technol. **102**, 2868–2873 (2011)
5. Pagans, E., Barrena, R., Font, X., Sánchez, A.: Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere **62**, 1534–1542 (2006)
6. Yang, F., Li, G.X., Yang, Q.Y., Luo, W.H.: Effect of bulking agents on maturity and gaseous emissions during kitchen waste composting. Chemosphere **93**, 1393–1399 (2013)
7. Puyuelo, B., Gea, T., Sánchez, A.: A new control strategy for the composting process based on the oxygen uptake rate. Chem. Eng. J. **165**, 161–169 (2010)

8. Kulcu, R., Yaldiz, O.: Determination of aeration rate and kinetics of composting some agricultural wastes. Biores. Technol. **93**, 49–57 (2004)
9. Sołowiej, P., Piechocki, J., Neugebauer, M.: The impact of bed aeration on the progress of first composting process phase. Inżynieria Rolnicza **3**(121), 193–198 (2010)
10. Bari, Q.H., Koenig, A.: Application of a simplified mathematical model to estimate the effect of forced aeration on composting in a closed system. Waste Manage. **32**, 2037–2045 (2012)
11. Neugebauer, M., Sołowiej, P.: Using self-learning algorithms to control composting process for biomass of agricultural origin. Inżynieria Rolnicza **8**(117), 147–153 (2009)
12. Castelli, L. Ferrari, R.: Fuzzy logic control applied to in-vessel composting. In: US Composting Council 2007 Conference, Orlando, Florida. Available at: http://nebula.wsimg.com/6091ca06b369e24d1d6a82361f42fd6f?AccessKeyId=1A23BDC9F081DE6ACE22&disposition=0
13. Giusti, E., Marsili-Libelli, S.: Fuzzy modelling of the composting process. Environ. Model Softw. **25**, 641–647 (2010)
14. Jiang, X., Qin, X., Xi, B., Huang, G., Liu, H., Liang, Z., Christine, W.C.: Fuzzy approach for dynamic simulation of composting process under uncertainty. Civ. Eng. Res. (2012)
15. Qin, X., Huang, G., Zeng, G., Chakma, A., Xi, B.: A fuzzy composting process model. J. Air Waste Manag. Assoc. **57**(5), 535–550 (2007)
16. Gerla, G.: Fuzzy logic programming and fuzzy control. Stud. Logic. **79**, 231–254 (2005)
17. Mamdani, E.: Application of fuzzy logic to approximate reasoning using linguistic systems. Fuzzy Sets Syst. **26**, 1182–1191 (1977)
18. Guo, T., Liu, G.: Aadaptive fuzzy control for unknown nonlinear time-delay systems with virtual control functions. Int. J. Control Autom. Syst. **9**(6), 1227–1234 (2011)
19. Сиротюк, В., Гальчак, В., Сиротюк, С.: Fuzzy logic контроллер солнечной системы горячего водоснабжения. Motrol **16**(4), 32–37 (2014)
20. Сиротюк, С., Сиротюк, В., Гальчак, В.: Fuzzy-logic контроллер управления режимами работы ветроэлектрической установки. Motrol **17**(4), 39–46 (2015)
21. Du, Z., Qu, Z.: Improved adaptive fuzzy control for MIMO nonlinear time-delay systems. J. Control Theory Appl. **9**(2), 278–282 (2011)
22. Işik, H., Saraçoğlu, E.: The design of thermoelectric footwear heating system via fuzzy logic. J. Med. Syst. **31**, 521–527 (2007)
23. Luo, X., Sun, Z., Sun, F.: A new approach to fuzzy modeling and control for nonlinear dynamic systems: neuro-fuzzy dynamic characteristic modeling and adaptive control mechanism. Int. J. Control Autom. Syst. **7**(1), 123–132 (2009)
24. Niittymäki, J., Turunen, E.: Traffic signal control on similarity logic reasoning. Fuzzy Sets Syst. **133**, 109–131 (2003)
25. Wang, X., Selvam, A., Chan, M., Wong, J.: Nitrogen conservation and acidity control during food wastes composting through struvite formation. Biores. Technol. **147**, 17–22 (2013)
26. Guo, R., Li, G., Jiang, T., Schuchardt, F., Chen, T., Zhao, Y., Shen, Y.: Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost. Biores. Technol. **112**, 171–178 (2012)
27. Muhamad, N.A., Sam, A.: LabVIEW with fuzzy logic controller simulation panel for condition monitoring of oil and dry type transformer. Int. J. Appl. Math. Comput. Sci. 213–219 (2005). 1; 4 © www.waset.org
28. Neugebauer, M., Sołowiej, P., Piechocki, J.: Fuzzy control for the process of heat removal during the composting of agricultural waste. J. Mater. Cycles Waste Manage. **16**(2), 87–93 (2013)
29. Neugebauer, M., Sołowiej, P.: The concept of using fuzzy logic to control composting process for biomass of agricultural origin with simultaneous heat reception. Inżynieria Rolnicza **8** (117), 139–145 (2009)

Variability of Soil Temperatures During 5 Years of a Horizontal Heat Exchanger Operation Co-operating with a Heat Pump in a Single-Family House

Joanna Piotrowska-Woroniak and Wiesław Załuska

Abstract The paper presents the results of measurements of the temperature distribution of the ground source heat with the brine-water heat pump and a horizontal ground heat exchanger. The research was carried out for a period of 5 years. The horizontal ground heat exchanger is a ground source for a heat pump with the measured average heating output of 9.53 kW and cooling capacity of 7.8 kW, installed in a single-family house located in the north-eastern part of Poland. A heat exchanger with the area of 253 m^2 is located at a depth of 1.9 m in the groundwater layer being in hydraulic contact with the waters of Lake Elk. During the first four years, each year it can be observed that soil of the ground heat source is chilling at a depth of 1.9 m, due to working heat pump. Between January and April heat pump was working with the ground source frozen, where the temperature ranged from −0.6 to −2.1 °C. Subsidence and cooling of the soil was caused by a relatively small active area of ground source of heat which was 253 m^2 with the dimensions of 11 m × 23 m, as well as inadequate spacing between sections of the spiral heat exchanger amounting to 0.1 m. After operational testing of the heat pump and the ground source of heat, the "microBMS" a control and optimization system, working independently from the heat pump control was introduced into the building in January 2014. Its introduction has significantly increased that lower minimum flow temperature of the heat exchanger to +0.3–0.9 °C. There was also an increase of the minimum temperature of the ground source heat exchanger by the value of +1.3–3.0 °C and decrease in cooling of the soil in August—an increase of temperature by about 0.7 °C. Operational tests of heat pump system working with an unusual and original application of horizontal spiral heat exchanger have shown that in the first period introduction of an additional heat exchanger was considered. In subsequent years of heat pump operation and after the introduction of its independent monitoring and optimization, the study showed good properties of ground source and its complete recovery in the summer. Ground source, chilled properly to a temperature

J. Piotrowska-Woroniak (✉) · W. Załuska
Department of HVAC Engineering, Faculty of Civil Engineering and Environmental Engineering, Bialystok University of Technology, Wiejska 45E, 15-351 Bialystok, Poland
e-mail: j.piotrowska@pb.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_16

of about 0 °C became a very good cooling reservoir during periods of spring and summer heat. The use of the Earth's heat helps to improve the environment, while in some way it violates the natural thermal and agrophysical condition of the ground. Operation of ground source heat pump affects the periodic changes of agro-thermal parameters of soil. The delay of the vegetation period above the horizontal heat exchanger of heat pump is about 13 days and is caused by postponed thawing of ground observed at 0.05 m.

Keywords Temperature distribution · Horizontal ground heat exchanger
Ground · Heat pump

1 Introduction

Horizontal ground heat exchanger is one of the simplest forms of energy stored in soil.

The ground temperature varies with depth, intensive change can be observed in the subsurface layers, where the accumulation of solar heat, and the temperature variation depends on the season. The temperature in these layers is influenced by weather factors, i.e.: precipitation, solar radiation, air humidity and velocity, atmospheric pressure, and the type of ground cover [1]. Temperature fluctuations associated with the change of seasons decline beneath the depth of frost penetration. In agrotechnics, the area used for cultivation is the ground area of the soil which is characterized by intense temperature fluctuations.

Temperature changes of subsurface layers related to climate change have a significant impact on the amount of heat flow [2], and the depth and structure of soil affects the volume of obtained heat.

The researches on soil temperature were carried out, among others, in Montana [2], Japan [3], the UK [4], New Zealand [5] or Cyprus [6] Predicting the ground temperature is an important element for the analysis of the assessment of energy resources. Huining and Spitler [2] studied the effects of moisture, residual layer of snow, freezing and thawing of soil temperature changes in the soil at different depths and times of the year.

Heating systems based on heat pumps with horizontal ground heat exchangers use the heat stored in soil and water environment. In case recommended minimum spacing between the horizontal coils or vertical ground exchangers is not maintained, installations can locally affect the environment by lowering the temperature of the soil–water source, from which heat is collected [7, 8].

This can cause a shift in the vegetation period of plants. The soil temperature has a major impact on plant growth, at a temperature below 0 °C root system is not able to draw water and thereby to develop. Plants for the passage of a full cycle of growth and development not only require a certain amount of heat, but also the appropriate exposure time of thermal conditions. Ground heat exchangers intensively exploited may affect the growing period of some plants.

The greatest temperature changes are noticeable in shallow layers, where the frost penetrates the ground, which is related to the rapid reaction of the subsurface area to daily and short-term weather changes [1].

The vegetation period of the plants, which is calculated on the basis of the number of days in a year in which the average temperature is at least 50, ranges from 185 to 225 days in Poland, the longest one is in the Odra valley and in the Tarnów area (220 days) and the shortest one is in Masuria Lake District (less than 200 days) and in the mountains (less than 190 days).

At present, very often the issue of analytical or numerical optimization of horizontal ground heat exchangers, as ground source energy for heat pumps is addressed in scientific literature [9–16]. Experimental investigation of spiral ground heat exchanger running in British climate have been carried out, among others, by Wu et al. [15].

One of the advantages of using low-temperature geothermal systems on a global scale is that it contributes to reducing greenhouse gas emissions to the atmosphere and allows restrictions and more economical use of fossil fuels.

The paper presents results of temperature distribution in the soil to a depth of 1.9 m with a spiral ground heat exchanger during heat pump operation and temperature measurement of soil to a depth of 1.5 m unencumbered with work of horizontal ground heat exchanger. It also shows the results of studies carried out over five years on spiral ground heat exchanger, experimentally arrangement at intervals of 0.1 m from each other, which resulted in a design of an innovative, almost no-cost, heat and cold container.

2 Object of the Study

A horizontal ground heat exchanger subjected to tests is a ground source of heat for brine-water heat pump, with heating output of 9.53 and 7.8 kW of cooling capacity. Is made with polyethylene pipes with a diameter of 25 mm. It was laid at a depth of 1.9 m below the freezing zone. The heat exchanger was made in the form of 10 spiral collectors with a width of 1 m and length of 100 m each. Spacing between heat exchangers amounted to 0.1 m. The design also included a collection sump with 10-pipe manifold joining all loops.

Experimentally reduced distance between spiral heat exchangers was due to residues of groundwater remaining in hydraulic contact with the waters of Lake at this depth. Possible freezing of land and shift of the vegetation season were expected. Introduction of supplementary horizontal heat exchanger or vertical probes placed in the ground as an additional ground source of heat for the heat pump was considered in case of insufficient output of the ground source or drop in temperature of the heating medium below the critical value for the heat pump. The design recommended distance between the horizontal spiral ground heat exchanger should be at least 4 m [17].

Active area of an exchanger is 11 m × 23 m, F = 253 m^2. Ground heat exchanger due to the high groundwater level occurring in this area was arranged in a layer of water. Ground heat exchanger is located about 200 m away from Lake. View of ground heat exchanger location near Lake is shown in Fig. 1.

The heat pump was installed in February 2010 and it operates in a monovalent system providing heat for central heating and hot water for domestic use.

The method of laying of the exchanger is shown in Fig. 2.

Figure 3 presents the area that is taken by a horizontal spiral ground heat exchanger, along with the location of measuring probes.

The ground heat exchanger research was conducted over a period of 5 years.

For measuring the soil temperature above the ground source exchanger at depths: 0.05, 0.5 and 1.8 m and in an inspection hole at depths 0.05, 0.5 and 1.5 m temperature sensors DS18B20 type by Dallas were used.

The applied temperature sensors type DS18B20 provide a temperature measurement with a resolution set in a range from 9 to 12 bits. Temperature range is from −55 to +125 °C. For the measurement of the temperature, sensors were calibrated in the temperature range with an accuracy of ±0.1 °C. Calibration of sensors allowed to avoid errors occurring due to overlapping of deviations in the final reading. Placing sensors in a relatively thermally stable environment (ground) and using measuring system with simultaneous statistical processing of temperature signals sampled every minute, resulted in an additional and surprising possibility to

Fig. 1 Location of a ground exchanger nearby Lake (photo by authors)

Fig. 2 Laying the ground source heat pump system at a depth of 1.9 m, 10 loops 100 m each, active area of the exchanger is 11 m × 23 m (photo by authors)

increase the sensitivity of the dynamics of the processes of registration to the value of ±0.01 °C.

Figure 4 shows an exemplary recorded dynamics of the heat exchanger work with its gradual cooling from 9 March to 16 March with an accuracy of ±0.01 °C.

3 Results of the Studies and Analysis

From 2010 to 2015 year, soil temperature measurements were carried out over the ground heat exchanger at depths: 0.05, 0.5 and 1.8 m, as well as temperature measurements of ground undisturbed by work of heat exchanger at depths of 0.05, 0.5 and 1.5 m in a control hole and operation of the heat pump was monitored. The heat pump provides heat for central heating and hot water for domestic use.

Changes of temperature of ground source of heat within five heating seasons and running time of the heat pump in each month is shown in Fig. 5.

Fig. 3 A view of the area taken by a ground source heat exchanger (photo by authors)

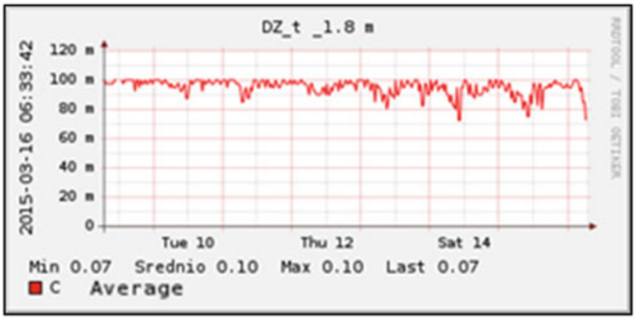


Fig. 4 A graph representing dynamics of temperature changes of the ground source registered at a depth of 1.8 m from 9 until 16 March 2015

During several years of operation of ground heat exchanger (Fig. 5) its cyclical character can be noticed. Four clear periods of work can be noticed: (1) cooling period September–January, (2) period of work with the ground source frozen January–April (approximately 64–107 days), (3) ground source recovery period May–August, (4) re-cooling of the ground, starting with the beginning of the heating season from the second half of September.

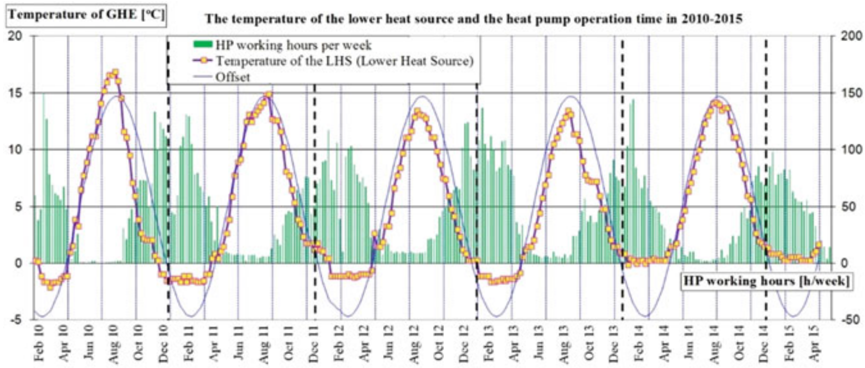


Fig. 5 Comparison of seasonal temperature distributions during the ground heat exchanger operation and the number of the heat pump operating hours

During the first four years, each year it can be observed that soil of the ground heat source is chilling at a depth of 1.9 m, due to working heat pump. Between January and April heat pump was working with the ground source frozen, where the temperature ranged from −0.6 to −2.1 °C. Subsidence and cooling of the soil was caused by a relatively small active area of ground source of heat which was 253 m^2 with the dimensions of 11 m × 23 m, as well as inadequate spacing between sections of the spiral heat exchanger amounting to 0.1 m.

Figure 6 shows the work of ground source of heat in 2013 and running time of the heat pump. The freezing of soil in 2013 to approximately −1.6 °C took place in mid-February, and in March the temperature remained at −1.5 °C to drop in April to −0.8 °C. Working time of ground source at freezing temperatures was 99 days.

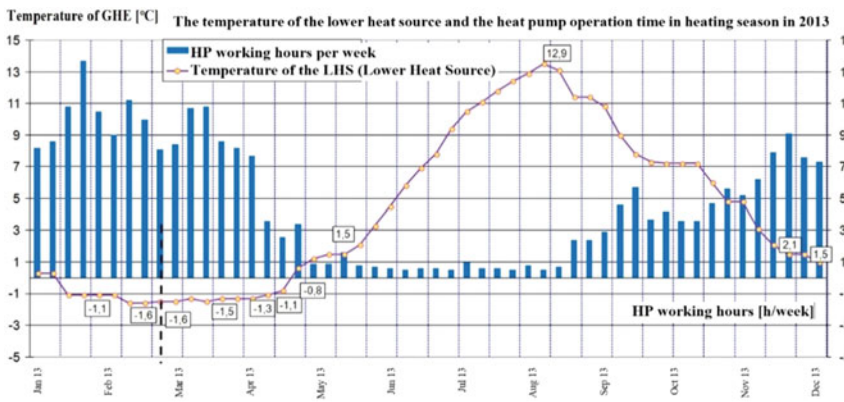


Fig. 6 Changes of temperature of ground source of heat from and running time of the heat pump in 2013

The temperature above zero was not recorded in 2013 until 5 May and amounted to +0.6 °C. In earlier years ground source was also working in freezing temperatures.

In 2010 the lowest temperature occurred on March 21 and was −2.1 °C, which indicated intense operation of the ground source. Subzero temperature of the ground source remained from 28 February to 2 May and ranged from −1.1 to −2.1 °C (64 days). There were finishing works of the building in progress at that time so more energy was consumed for heating and removal of the so-called technological moisture which resulted in grater exploitation of the ground source. The heat pump should only be switched on after the building has been dried thoroughly. The temperature above zero at a depth of 1.9 m was not recorded until 9 May and it was +1.0 °C.

In 2011, the lowest temperature of ground source occurred in February and amounted to −1.6 °C. The first temperature above zero was only recorded on 24 April and amounted to +5 °C. The subzero temperature of the ground source sustained from 1 January to 17 April and ranged from −0.90 to −1.60 °C (107 days).

In 2012, the lowest temperature of the ground source was registered on 18 March and amounted to −1.2 °C, the temperature above zero was first recorded on 6 May and it amounted to +2.7 °C. The temperature of the ground source remained below zero from 2 February to 29 April, and ranged from −0.6 to −1.2 °C (88 days).

Despite intense cooling of the ground, or even freezing (−0.6 to −2.1 °C) for a period of nearly three months, ground source remained fully sufficient to supply a residential building with a usable area of 135 m^2 and an outbuilding of 75 m^2. Temperature maintained in the residential part amounted to +23 °C. Additionally run full monitoring of the heat pump helped to define the parameters of the heat pump and its Seasonal Performance Factor (SPF), which in 2014 amounted to 3.26.

The temperature of the ground source would probably be much lower during the heat pump operation, were it not that the heat exchanger was arranged in a layer of groundwater being in hydraulic contact with waters of Lake. The incoming water from the lake probably caused a rise in ground temperature. Horizontal ground heat exchanger is located about 200 m from the lake's shoreline (Fig. 3), hence the emphasis of a very large impact on ground heat exchanger work made by the waters of Lake.

Additionally, during the soil freezing, the ice cover on the spiral heat exchanger could increase its heat exchange surface. On the heat pump market appeared a solution using, as the ground source for heat pumps working on brine–water, instead of horizontal heat exchanger or vertical probes the energy storage device, called the ice tank [18] which allows to collect heat from the cooled water near 0 °C using the phase transformation of water–ice. This solution has already been used in heat pumps systems ACES (Annual Cycle Energy Systems) [19].

In this case, alongside using the original solution of spiral horizontal heat exchanger arranged with very small gaps in an aquifer it was possible to construct an almost cost-free, eco-friendly heating and cooling tank, thus increasing the efficiency of horizontal ground heat exchanger. A large amount of energy obtained

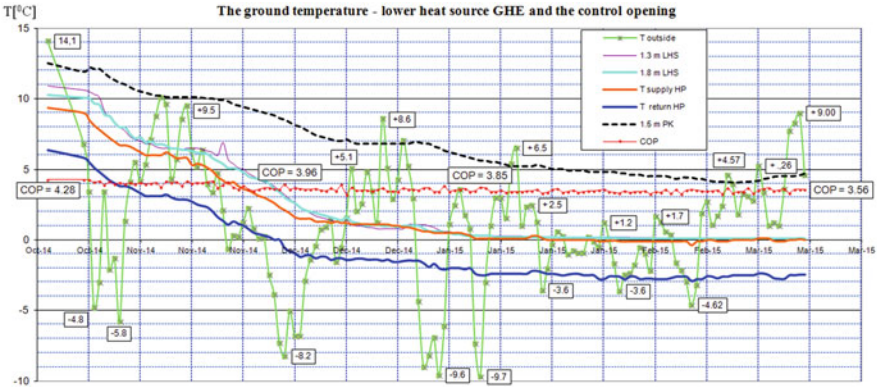


Fig. 7 Temperatures at different depths in the ground exchanger and the undisturbed soil in the period from October 2015 to April 2015, acronyms of term associated with temp. measurement: LHS—Lower Heat Source, supply HP—brine temperature at the entrance to the heat pump, return HP—brine temperature at the return from heat pump, PK—control measurement of soil

at a constant temperature close to zero corresponds to the cooling occurring at the phase change water–ice. It seems that the influx of underground waters being with permanent hydraulic contact with the waters of Lake acts as the auxiliary heat source used to melt unnecessary ice or its excessive quantities. In case of ice tanks, the additional source can be e.g. solar collectors.

Cyclical changes shown in Fig. 5, are very close to the theoretical sinusoid of annual changes of the temperature area on the test soil depth determined, among others by Baggs [20], Popiel et al. [21]. By introducing disturbance to the natural soil temperature area with the use of a horizontal ground heat exchanger, occurrence of different temperature areas can be noticed. Also, the amplitude of sinusoidal changes of ground source temperature has increased along with the rapid collapse at −2.1 to −1.6 °C. During the first four years of research the ground heat exchanger cooled down to below −1.6 °C.

Comparison of soil temperatures at different depths undisturbed by the heat exchanger and soil temperatures above the ground heat exchanger is shown in Fig. 7. According to the graph there was a reduction of soil temperature with the ground heat exchanger in relation to the ground in the undisturbed state. The undisturbed ground temperature is higher than the temperature of the ground with the ground heat exchanger.

After operational testing of the heat pump and the ground source of heat, the "microBMS" a control and optimization system, working independently from the heat pump control was introduced into the building in January 2014. Its introduction has significantly increased that lower minimum flow temperature of the heat exchanger to +0.3–0.9 °C. There was also an increase of the minimum temperature of the ground source heat exchanger by the value of +1.3–3.0 °C and decrease in cooling of the soil in August—an increase of temperature by about 0.7 °C.

The lowest temperature of the ground source of heat in 2014 was recorded on 19 January and it was −0.1 °C. In the period from February to April, where in previous years 2010–2013, the ground source was working in sub-zero temperatures, the measured temperature ranged from 0.0 to +0.9 °C. A graph of changes of temperature of the ground source in 2014 and the heat pump running time are shown in Fig. 8.

In 2015, the lowest measured temperature of the ground source was +0.3 °C and maintained from 8 February to 12 April 2015, as it is shown on Fig. 9.

The introduction of an independent optimization of the heat pump and the heat exchanger caused a decrease in the number of hours the heat pump running in winter and summer, which had impact on electricity consumption by the heat pump and the cost of its purchase. BMS system and optimization also contributed to the stabilization of the temperature in the building and thermal comfort.

The electricity consumption of the heat pump depends on its runtime and number of activation/deactivation times. The only noticed problem with exploitation resulting from gradual cooling and heating of the ground, was the need to periodically adjust the heating curve settings for the heat pump. From several years of operating experience it has been established that for the object in question it is effective to set the heating curve at 0.2–0.3 and the raising or lowering of the curve between 0° and 7° during the cooling of the ground source and a further reduction in the curve to 0° during the Spring. The need for raising the heating curve originates from a gradual decrease in the set temperature in the building by about 1 °C which is usually evident within about two weeks. Figure 10 shows a graph of correlation between the ground source temperature and heat pump operation time in the years 2010–2015.

Directly around a horizontal ground heat exchanger, the ground was periodically frozen in the second half of the heating season (February–April) which did not adversely affect the work of the heating system, whereas prolonging period of frozen soil affected only a shift in vegetation season. Freezing of the soil was

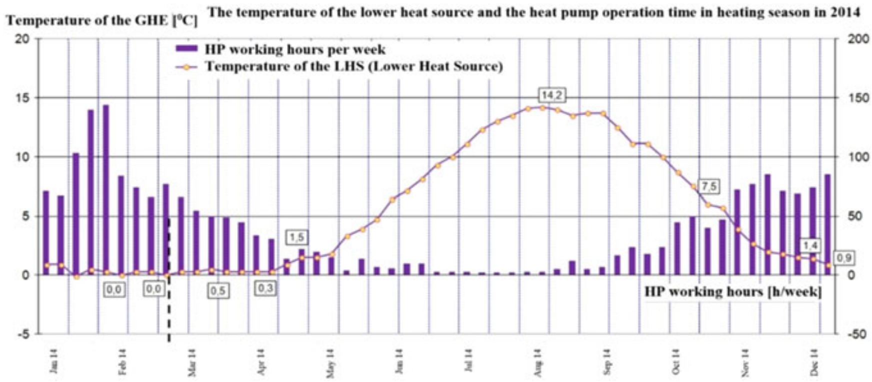


Fig. 8 Changes of temperature of the ground source and the heat pump running time in 2014

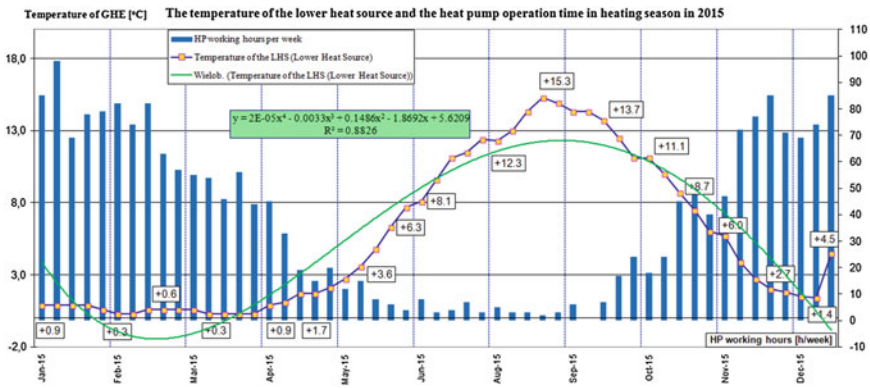


Fig. 9 Changes of temperature of the ground source and the heat pump running time in 2015

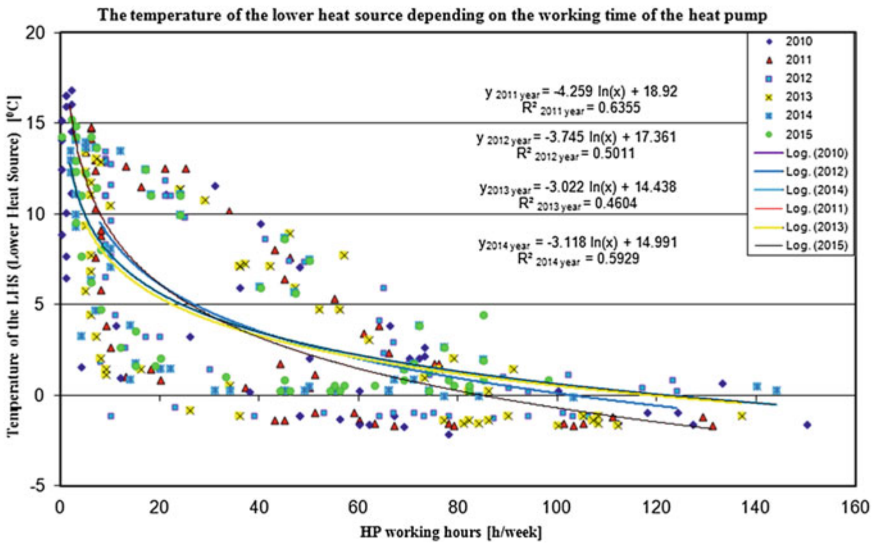


Fig. 10 Correlation between the ground source temperature and heat pump operation time within a week

affected by a too small area planned for the ground heat exchanger and too small gaps between the coils. This happens in the case of heat pumps extracting heat from the ground using horizontal ground heat exchangers which operate under full load. Overload on the heat exchanger caused a long-term decrease in temperature.

Figure 11 presents a graph of ground temperature changes for probes located above the horizontal exchanger at depths of 0.05, 0.5 and 1.8 m and in inspection hole at depths of 0.05, 0.5, 1.5 m from 11 February, 2015 to 11 March 2015.

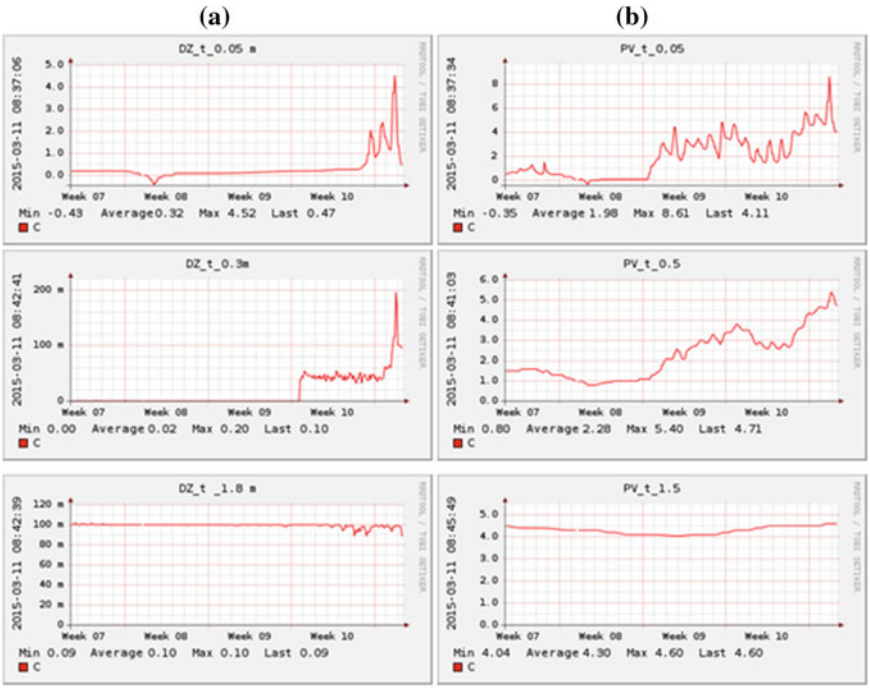


Fig. 11 Comparing of ground temperature measured: **a** above the ground source exchanger at depths: (DZ) 0.05, 0.5 and 1.8 m **b** in an inspection hole at depths: (*PV*) 0.05 m, *PV* 0.5 m and *PV* 1.5 m

While comparing the temperature changes it was noticed that a considerable increase in temperature for the inspection hole at a depth of 0.05 m occurred on 23 February, in the case of a probe above the heat exchanger thawing of the soil at a depth of 0.05 m took place on 7 March. The delay period for the soil temperature increase at a depth of 0.05 m, including the vegetation, was estimated for 13 days. Ground at a depth of 0.3 m—thawing noted earlier—on 2 March—the impact of heat from the ground while temperature drops to a depth of 1.8 m—cooling of the heat exchanger.

Figure 12 shows a thermal camera image of the area occupied by ground heat exchanger. It is visible that the temperature is clearly reduced in comparison to the surface area of the plot without the heat exchanger, which directly affects the delay of vegetation in this area.

The delay period of temperature increase and vegetation in the case of another type of ground where there were no groundwater in hydraulic connection with Lake, would probably be more than 13 days.

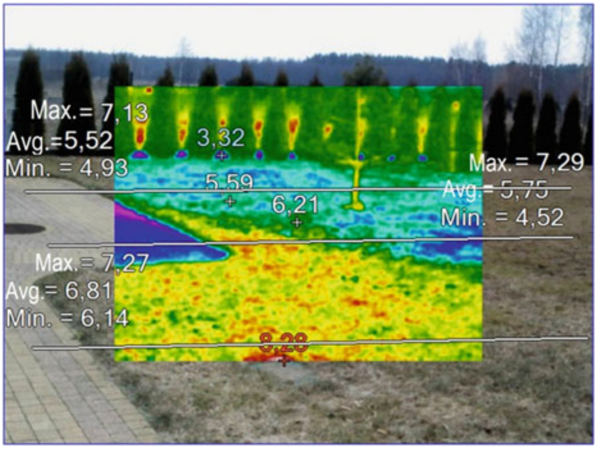


Fig. 12 A thermal camera image showing a lawn with a visible area occupied by the ground heat exchanger (photo by authors)

4 Summary

- Shift of seasonal cyclical changes of ground temperature areas were observed, caused by thermal distortion of operating horizontal exchanger of heat pump. For this particular case there was about a two-week shift in cyclical annual temperatures measured at a depth of 1.9 m.
- Operation of ground source heat pump affects the periodic changes of agro-thermal parameters of soil. The delay of the vegetation period above the horizontal heat exchanger of heat pump is about 13 days and is caused by postponed thawing of ground observed at 0.05 m.
- The soil at a depth of about 1.9 m of the exchanger is cooled to ca. 4.0 °C compared to control measurements and maintains until about mid-April. For the first four years of operation of ground heat exchanger with the ground source frozen working period lasted from January to April (approximately 64–107 days).
- The way of adjusting the heat curve and optimization of heat pump operation time influences to a great extent dynamic properties of ground source. Precise optimization of the heat pump allowed it to increase the minimum flow temperature of the ground source from −2.1 to 0.6 °C (2.7 °C increase).
- Operational tests of heat pump system working with an unusual and original application of horizontal spiral heat exchanger have shown that in the first

period introduction of an additional heat exchanger was considered. In subsequent years of heat pump operation and after the introduction of its independent monitoring and optimization, the study showed good properties of ground source and its complete recovery in the summer. Ground source, chilled properly to a temperature of about 0 °C became a very good cooling reservoir during periods of spring and summer heat.

Acknowledgements The study has been implemented from the resources of the S/WBiIŚ/4/14 statutory work financed by the Ministry of Science and Higher Education in Poland.

References

1. Zheng, T., Shao, H., Schelenz, S., Hein, P., Vienken, T., Pang, Z., Kolditz, O., Nagel, T.: Efficiency and economic analysis of utilizing latent heat from groundwater freezing in the context of borehole heat exchanger coupled ground source heat pump systems. Appl. Therm. Eng. **105**, 314–326 (2015). https://doi.org/10.1016/j.applthermaleng.2016.05.158
2. Huining, X., Spitler, J.D.: The relative importance of moisture transfer, soil freezing and snow cover on ground temperature predictions. Renew. Energy **72**, 1–11 (2014). https://doi.org/10.1016/j.renene.2014.06.044
3. Tarnawski, V.R., Leong, W.H., Momose, T., Hamada, Y.: Analysis of ground source heat pumps with horizontal ground heat exchangers for northern Japan. Renew. Energy **34**, 127–134 (2009). https://doi.org/10.1016/j.renene.2008.03.026
4. Gonzalez, R.A., Verhoef, A., Vidale, P., Main, B., Gan, G., Wu, Y.: Interactions between the physical soil environment and a horizontal ground coupled heat pump, for a domestic site in the UK. Renew. Energy **44**, 141–153 (2012). https://doi.org/10.1016/j.renene.2012.01.080
5. van Manen, S.M., Wallin, E.: Ground temperature profiles and thermal rock properties at Wairakei, New Zealand. Renew. Energy **43**, 313–321 (2012). https://doi.org/10.1016/j.renene.2011.11.032
6. Florides, G.A., Pouloupatis, P.D., Kalogirou, S., Messaritis, V., Panayides, I., Zomeni, Z., Partasides, G., Lizides, A., Sophocleous, E., Koutsoumpas, K.: The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus. Energy **36**, 5027–5036 (2011). https://doi.org/10.1016/j.energy.2011.05.048
7. Congedo, P.M., Colangelo, G., Starace, G.: CFD simulations of horizontal ground heat exchangers: a comparison among different configuration. Appl. Therm. Eng. **33–34**, 24–32 (2012). https://doi.org/10.1016/j.applthermaleng.2011.09.005
8. Vietel, M., Rouabhi, M., Tijani, M., Guerin, F.: Modeling heat transfer between a freeze pipe and the surrounding ground during artificial ground freezing activities. Comput. Geotech. **63**, 99–111 (2015). https://doi.org/10.1016/j.compgeo.2014.08.004
9. Fujii, H., Nishi, K., Komaniwa, Y., Chou, N.: Numerical modeling of slinky-coil horizontal ground heat exchangers. Geothermics **41**, 55–62 (2012). https://doi.org/10.1016/j.geothermics.2011.09.002
10. Kim, J., Lee, Y., Yoon, W.S., Jeon, J.S., Koo, M.-H., Keehm, Y.: Numerical modeling of aquifer thermal energy storage system. Energy **35**, 4955–4965 (2010). https://doi.org/10.1016/j.energy.2010.08.029
11. Fontaine, P.O., Marcotte, D., Pasquier, P., Thibodeau, D.: Modeling of horizontal geoexchange systems for building heating and permafrost stabilization. Geothermics **40**, 211–220 (2011). https://doi.org/10.1016/j.geothermics.2011.07.002

12. Al-Hinti, I., Al-Muhtady, A., Al-Kouz, W.: Measurement and modelling of the ground temperature profile in Zarqa, Jordan for geothermal heat pump applications. Appl. Therm. Eng. **123**, 131–137 (2017). https://doi.org/10.1016/j.applthermaleng.2017.05.107
13. Adamovsky, D., Neuberger, P., Adamovsky, P.: Changes in energy and temperature in the ground mass with horizontal heat exchangers—The energy source for heat pumps. Energy Build. **92**, 107–115 (2015). https://doi.org/10.1016/j.enbuild.2015.01.052
14. Qi, D., Pu, L., Sun, F., Li, Y.: Numerical investigation on thermal performance of ground heat exchangers using phase change materials as grout for ground source heat pump system. Appl. Therm. Eng. **106**, 1023–1032 (2016). https://doi.org/10.1016/j.applthermaleng.2016.06.048
15. Wu, Y., Gan, G., Verhoef, A., Vidale, P.L., Gonzalez, R.G.: Experimental measurement and numerical simulation of horizontal-coupled slinky ground source heat exchangers. Appl. Therm. Eng. **30**, 2574–2583 (2010). https://doi.org/10.1016/j.applthermaleng.2010.07.008
16. Dehghan, B.: Experimental and computational investigation of the spiral ground heat exchangers for ground source heat pump applications. Appl. Therm. Eng. **121**, 908–921 (2017). https://doi.org/10.1016/j.applthermaleng.2017.05.002
17. Lachman, P. (eds.): Guidelines for design, construction and commissioning of heat pump installations, part 1. Lower Heat Source Sources. Polish Organization for the Development of Heat Pump Technology, Cracow (2013) (in Polish)
18. Zheng, T., Shao, H., Schelenz, S., Hein, P., Vienken, T., Pang, Z., Kolditz, O., Nagel, T.: Efficiency and economic analysis of utilizing latent heat from groundwater freezing in the context of borehole heat exchanger coupled ground source heat pump system. Appl. Therm. Eng. **105**, 314–326 (2016). https://doi.org/10.1016/j.applthermaleng.2016.05.158
19. Hsiao, M.J., Kuo, Y.F., Shen, Ch., Cheng, Ch.: Performance enhancement of a heat pump system with ice storage subcooler. Int. J. Refrig. **33**(2), 251–258 (2010). https://doi.org/10.1016/j.ijrefrig.2009.11.002
20. Baggs, S.A.: Remote prediction of ground temperature in Australian soils and mapping its distribution. Sol. Energy **30**(4), 351–366 (1983). https://doi.org/10.1016/0038-092X(83)90189-5
21. Popiel, C.O., Wojtkowiak, J., Prętka, I.: Effect of surface cover on ground temperature season's fluctuations. Found. Civil Environ. Eng. **1**(2), 151–164 (2002). bwmeta1.element.baztech-article-BPP1-0042-0084

Examination of the Solar Air Heater Operating Parameters Equipped with the Swirlers

Miroslaw Zukowski, Grzegorz Woroniak and Andrzej Perkowski

Abstract The aim of the solar air heater collector investigations was to conduct its operating parameters. The article shows the solution of its installation and presents the results of the analysis in real conditions. This type of device is equipped with the swirlers to increase the heat exchange and finally to gain more energy from the sun. This type of support elements are more and more popular in such devices. The air flow through the exchanger is forced by high flow ventilators. The test stand consists of inlet and outlet temperature data recorder and anemometer to control the air flow through the collector. The meteorological data such solar radiation, wind parameters, atmospheric pressure and the ambient temperature is obtain from Davies Vantage Pro2 weather station. The weather station was placed near the test stand. The analysis of the installation work was performed on the basis of monitoring of operating parameters conducted in time interval from April to September 2016. The results of energy analysis show the validity of such installation. It also helps to promote the other forms of energy generation and to reduce greenhouse gas emissions.

Keywords Solar air heater · Swirlers · Renewable energy sources
Operating parameters

1 Introduction

Energy is one of the fundamental resources that our society depends on. Energy is the most important part of modern civilization, and it is mostly used in the form of electrical and thermal energy. The energy is generated by means of fossil fuels like coal, crude oil, nuclear etc., which are exhaustive in nature. In this regard, researches are working to develop new renewable energies and technologies to utilize them in efficient way. Among many forms of renewable energy, solar energy

M. Zukowski · G. Woroniak (✉) · A. Perkowski
Department of HVAC Engineering, Bialystok University of Technology, Bialystok, Poland
e-mail: g.woroniak@pb.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_17

is the most widely available and has the largest potential to fulfill energy demands without polluting the environment. Conversion of solar radiation into thermal energy is achieved by solar collector devices like solar air heaters (SAHs) and solar water heaters (SWHs) which contain most frequently flat plates and flat plate is energized by insolation to increase thermal energy of an air and water, respectively. The design of a SWH is more difficult than that of SAH because of e.g. corrosion. In the case of SAH, design is less complex, less expensive, and easier to fabricate. SAH heat an air at a moderate temperature for various applications, such as space heating, building heating, crop drying, and various industrial heating processes. SAH can also be used as an integrated system with the existing conventional dryer system such as bin drier, conveyer drier, tunnel drier and fluidized bed dryers (FBDs) to save the fuel consumption [1]. The SAHs are becoming increasingly popular in agriculture, and particularly in the residential buildings sector. A general review of the construction of solar energy conversion devices is presented in [2, 3] where both the advantages and disadvantages of glazed, unglazed, parallel-pass, double-pass and transpired solar air panels are characterized. It is generally believed that air is not the most effective working fluid when considering the optimization of heat exchangers. For the reason that air has the low value of thermal conductivity and specific heat, various technical solutions can be applied to improve the thermal performance of such equipment [3]. Solar air heaters (SAHs) are devices for converting the solar energy to thermal energy. Solar air heater is a simple type of heat exchanger in the form of rectangular duct. This device can be fabricated with woods, which is available in plenty. It has various applications like space heating for residential and commercial purpose, drying of laundry, agricultural crops (i.e. tea, corn, and coffee) and seasoning of wood.

In order to enhance the performance, a passive technique of introducing ribs on the absorber plate is the most common practice. These ribs create turbulence inside the duct, which significantly increases the heat transfer rate, in addition to the frictional losses, which require high pumping power. Therefore, to avoid higher pumping power needs, turbulence is created only near to the absorber plate in the laminar sub layer zone. Lots of research is going on experimentally as well as numerically, to predict the performance of a solar air heater with rib turbulators on the absorber plate. Sharma and Kalamkar [4]. Some numerical studies researchers have summarized it in their review articles like Yadav and Bhagoria [5], Sharma and Kalamkar [6]. These authors reveal that the heat transfer and fluid flow characteristics depend on the geometrical parameters like the relative roughness pitch (P/e), relative roughness height (e/Dh), angle of attack (a) along with Reynolds number (Re) and duct aspect ratio (W/H), associated with ribbed solar air heater duct.

Solar energy is the type of energy source that is freely available and possible to be endlessly used. The solar air heater is one of the most popular thermal devices because it is easy to use and maintain. However, its energy saving parameters are quite low due to the low convective heat transfer coefficient for smooth surface or the flat plate of the solar air heater. They can be improved by the application of passive techniques in the form of artificial roughness on the absorber plate of the

SAH. A fin, groove, baffle, rib, wing and winglet are often introduced to the design of the solar air heater in order to increase the convective heat transfer rate which leads to more compact heat exchangers and to increased thermal performance. A turbulent promoter (called 'vortex generator', VG) in the form of a wing-type vortex generator (WVG) is often used to help increase the heat transfer coefficient through fast fluid mixing between the core and the near-surface and to reduce thermal boundary layer in the absorber plate [7–9].

The use of artificial roughness or turbulence promoters, on a heated surface, is an effective technique to increase the heat transfer rate to a convective fluid [10, 11]. In particular, rib-roughened channels with repeated rib turbulators along the main flow direction have been recommended for heat transfer augmentation in several engineering systems [12, 13]. Investigations of the efficiency of SAHs with obstacles and double-flow passages have been performed in [14, 15]. The application of wires or ribs fixed on the absorber plate has been widely studied and recommended by several investigators [16–22]. The implementation of artificial roughness elements (e.g. ribs), is useful to break the laminar sublayer and create local wall turbulence due to flow separation and reattachment between the ribs, thus greatly enhancing the cooling effect. However, this is typically accompanied by an increase in frictional losses which leads to the fan requiring more power. Thus, the design of the roughness elements should take into account both the convective heat transfer enhancement and the corresponding increase in friction losses [13]. Despite the transient nature of the SAH performance under real working conditions, these studies were conducted in the steady-state due to the complexity of the analysis and the large number of variables involved.

Flat plate SAHs are the universal services for interception solar heat at low temperature, and had been utilized widely for applications of air heating. It could be noted that in all previous reviews, the main aim was to augment the thermal efficiency of the SAHs. However, for large scale utilize of SAHs, like in drying applications, it is desired to have cheap SAHs as well [23]. The effect of plastic SAH covers shape on the thermal performance efficiency of SAH is not well studied. The effect of changing SAH's cover shape is studied experimentally by Abdullah et al. [23].

The environmental impact of different types of solar panels are presented by Aman et al. [24]. Negative and positive environmental implications associated with the use of solar energy techniques are reported by Tsoutsos et al. [25]. The reduction of greenhouse gases (GHG) emissions and the prevention of emission of toxic gases has been listed by Zukowski [26] as the main environmental advantages.

The SAH can be an element of building ventilation system. It can act as an air direct heater or as a preheater. Figure 1 present SAH acting as a direct heating device.

A solar air heater is never going to generate the volume of heat of central heating system it can only act as a support system. Figure 2 shows that SAH can also be part of the ventilation system of a residential building and can be incorporated into a

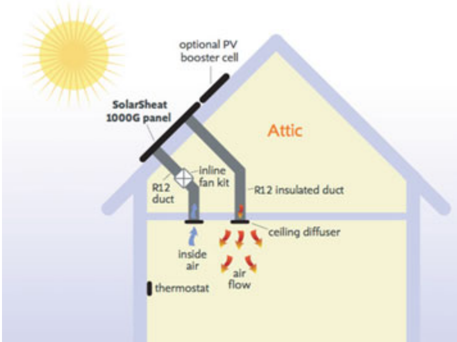


Fig. 1 SAH as a direct heater in the building (http://organicmechanic.com)

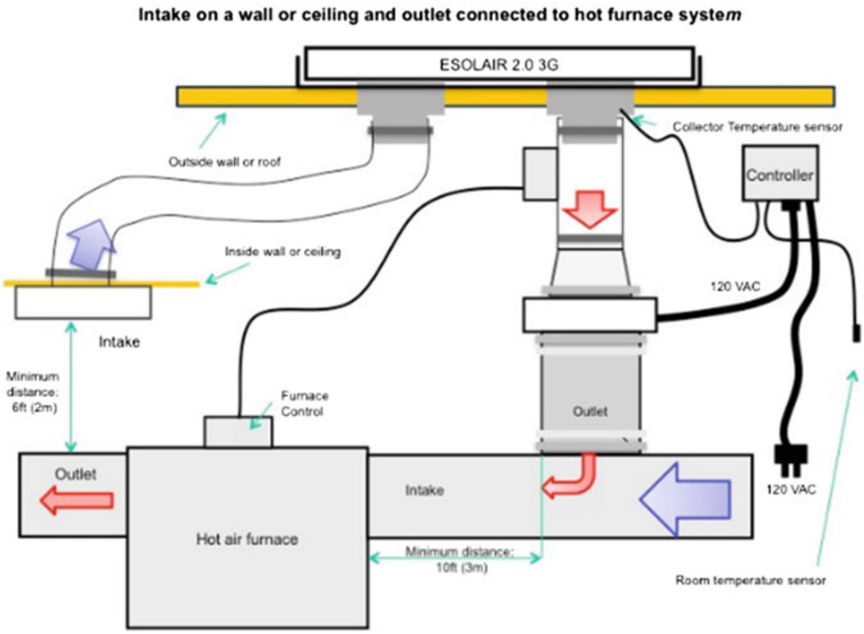


Fig. 2 SAH as a part of the ventilation system (http://www.ecosolaris.ca)

mechanical ventilation system, which will significantly reduce the need for heat for ventilation purposes.

The installation of solar air heaters is generally done on the south facing façade of a building. It's most popular application is the direct heating of a defined space like a basement, garage, living room, kitchen etc. It is also possible to attach it to the existing ventilation system, forced air or heat exchanger. As can be seen on

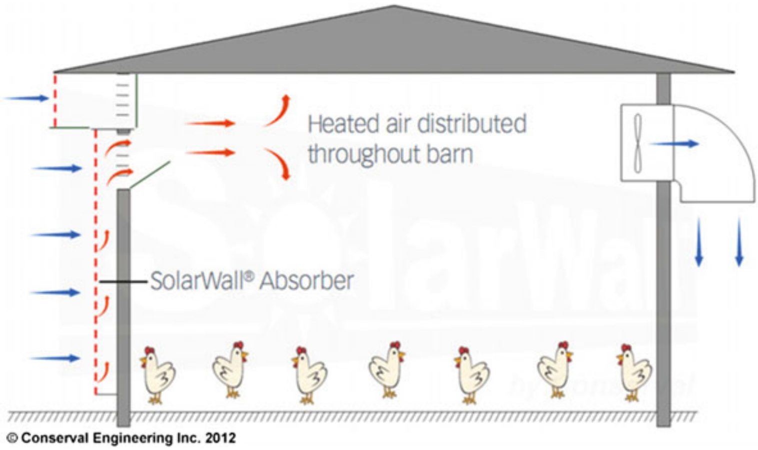


Fig. 3 Application of SAH in agricultural holdings (http://solarwall.com)

Fig. 3, SAH is also suitable for Agricultural Applications. Agricultural and agro-food operators consume tremendous quantities of energy which represent a sizable proportion of their total input costs. Rising energy prices has been putting downward pressure on agricultural incomes, which is why solar energy represents a tremendous opportunity for the agricultural sector.

2 Description of the Solar Air Heater and the Test Apparatus

The prototype solar air heater under the test, is made of an aluminum casing of the following dimensions: length—2000 mm, height—850 mm, depth—190 mm. The top cover of the SAH is a solar glass with the thickness of 3.2 mm. Thermal insulation is made of mineral wool (thickness—40 mm, thermal conductivity $\lambda = 0.039$ W/m/K). The most important part of the collector—the absorber—is made of aluminum sheet covered with a special coating to ensure higher absorption of solar radiation (emissivity = 0.97). The SAH was equipped with the swirlers, which were patented in 2016.

The main dimensions of the solar heater were as follows:

Gross area (calculated as the height multiplied by the length)—1.7 m^2,

Aperture area (calculated as the area of the glazing exposed to the Sun's radiation)—1.53 m^2.

As is shown in Fig. 4, the SAH is installed on the roof of the building of Faculty of Civil Engineering and Environmental Engineering—Bialystok University of Technology (Poland).

Fig. 4 SAH tested experimentally in normal operating conditions (left) and the weather station view (right), the solar irradiation sensor inclination was set just like the SAH one

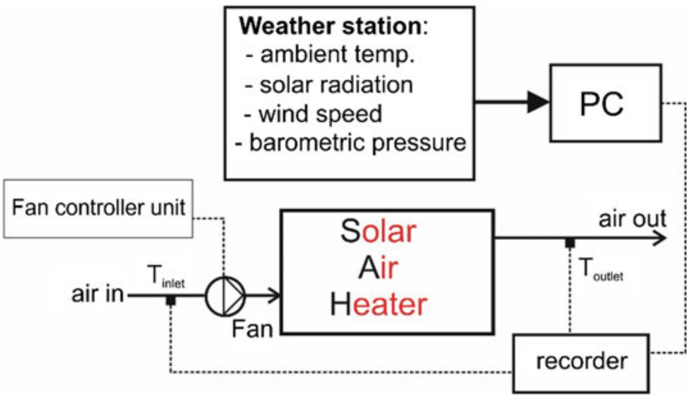


Fig. 5 Diagram showing the measurement stand

The test stand is presented in Fig. 5. The external air was sucked from the back shaded side of the collector by two fans. The flow rate could be adjusted from 50 to 120 m^3/h. The air temperature at the SAH inlet and outlet is measured by PT1000 resistance temperature sensors. A data recorder is used to collect the results of the investigations with one-minute time intervals. Meteorological parameters are collected by an automatic weather station integrated with a data logger that is located inside the building. The station allows to measure such environmental parameters as outside air temperature, wind speed and direction, atmospheric pressure and solar radiation. The sampling frequency of the weather conditions was set to one minute.

3 Results of the Experiments and Discussion

The main goal of this project was to determine the operating parameters of the new type of the air solar heater. The project was conducted as two series of experiments with different air flow rates, the first was 109 m^3/h (the study lasted from April 27 to May 5, 2016), and the second was 79 m^3/h, (it was lasted from May 11 to 19, 2016).

The sample data of the weather conditions, showing how values are changed during the course of study, are shown in Fig. 6. A wide range of variation of both irradiance and air temperature occurred during the experiment periods while wind speed remained light and moderate.

Results of the measurements are presented below. In the case of solar air heaters, an important parameter is the temperature rise ΔT_{SAH} (Eq. 1) inside the device.

$$\Delta T_{SAH} = T_{out} - T_{in} \quad (1)$$

where:

T_{out} is the temperature of the air leaving the SAH,
T_{in} is the temperature of the air entering the SAH.

The increase in the temperature of air passing through the solar panel as the function of solar radiation flux is shown in Fig. 7. In both cases, the sets of data have a quite linear correlation. Thus, the results of the experiment were approximated with the use of the linear regression method. As can be observed, with lower air flow rate—79 m^3/h, the maximum temperature rise exceeds 40 °C.

Knowing the value of air temperature increase resulting from the flow through the panel, we can estimate the power output of the solar collector, based on the following relation:

$$q_{SAH} = V_a \cdot \rho_a \cdot c_a \cdot \Delta T_{SAH}, \quad (2)$$

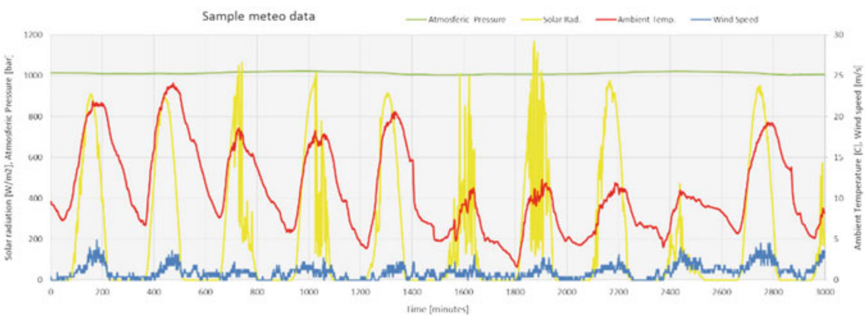


Fig. 6 Sample meteorological data received from the weather station used for SAH Parameters calculation, time 0 means the beginning of the month at midnight

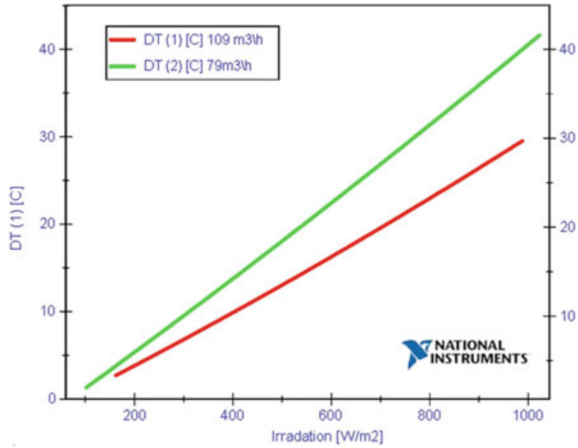


Fig. 7 Comparison of temperature increase in SAH for two different airflow rates

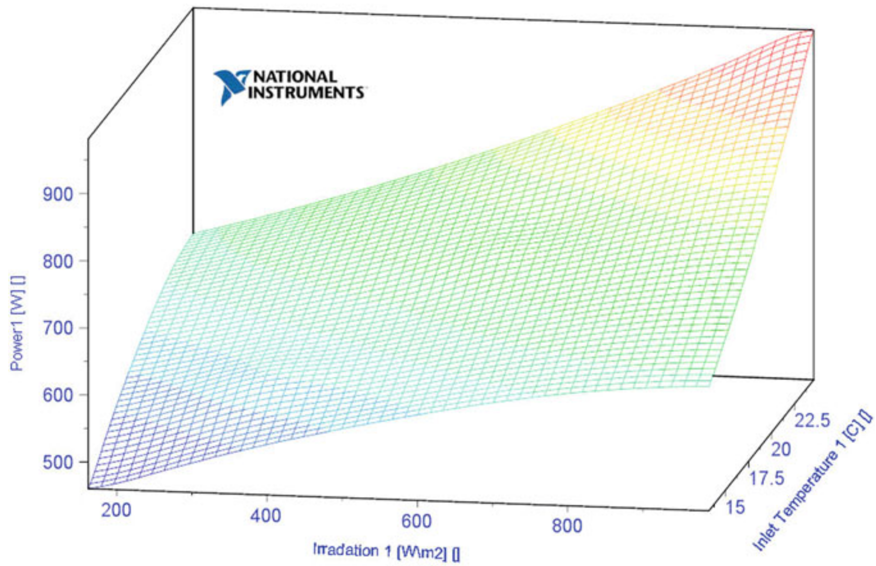


Fig. 8 Power q_{SAH} obtained in SAH depending on irradiation and inlet air temperature for flow 109 m^3/h

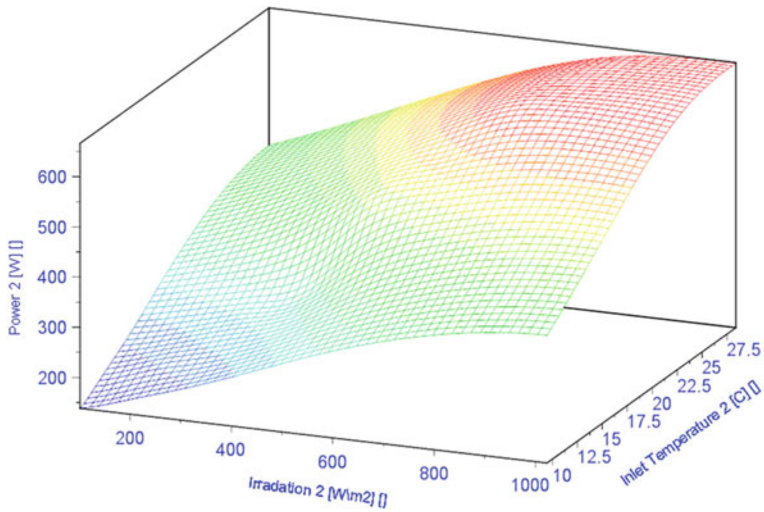


Fig. 9 Power q_{SAH} obtained in SAH depending on irradiation and inlet air temperature for flow 79 m^3/h

where:

V_a volume air-flow rate [m^3/s],
ρ_a air density [kg/m^3],
c_p heat capacity of air [J/kg/K],
ΔT_{SAH} temperature rise in SAH [°C].

Figure 8 shows the dependence of actual useful power extracted from the SAH on the intensity of solar radiation and inlet air temperature for air flow 109 m^3/h, and Fig. 9 shows the same values but for air flow 79 m^3/h.

An important parameter of the thermal performance is the efficiency of the solar collector ηA. This value is defined as useful energy, obtained through the conversion of solar radiation into heat energy, to the total radiation falling on the absorber. Instantaneous efficiency based on absorber area A_A can be obtained from Eq. (3).

$$\eta_A = \frac{V_a \cdot \rho_a \cdot c_a \cdot \Delta T_{SAH}}{I \cdot A_A}, \tag{3}$$

where:

V_a volume air-flow rate [m^3/s],
ρ_a air density [kg/m^3],
c_p heat capacity of air [J/kg/K],
A_A aperture area [m^2].

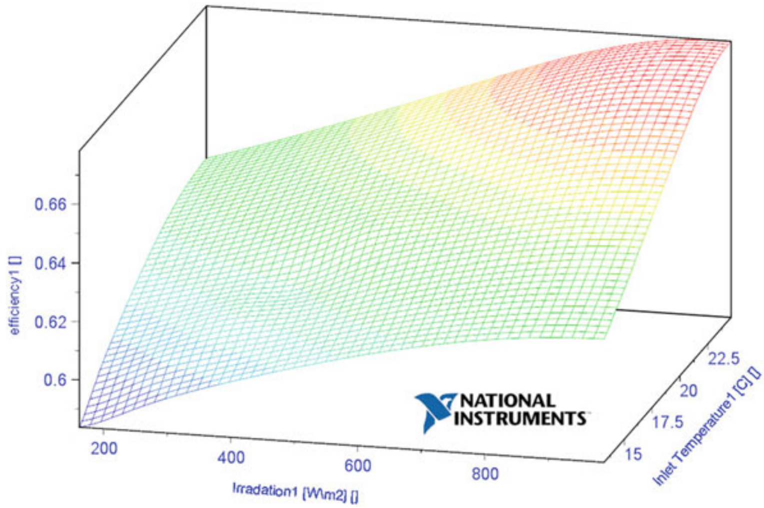


Fig. 10 Thermal efficiency of the SAH as the function of solar radiation and inlet air temperature for air flow 109 m^3/h

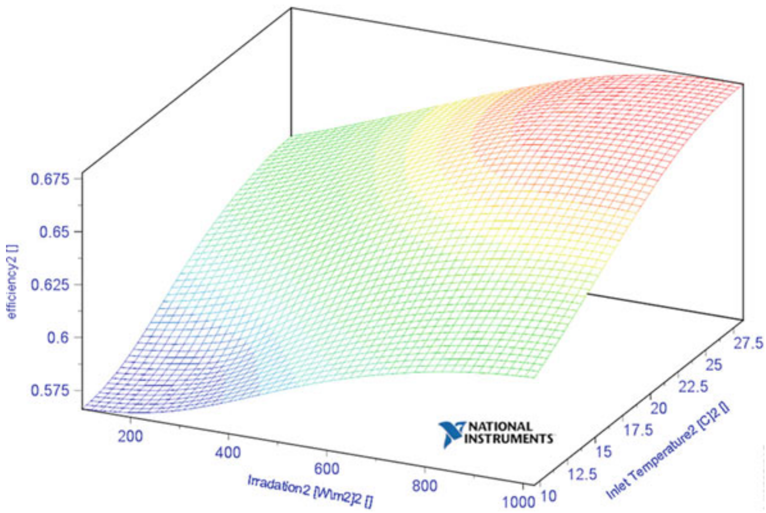


Fig. 11 Thermal efficiency of the SAH as the function of solar radiation and inlet air temperature for air flow 79 m^3/h

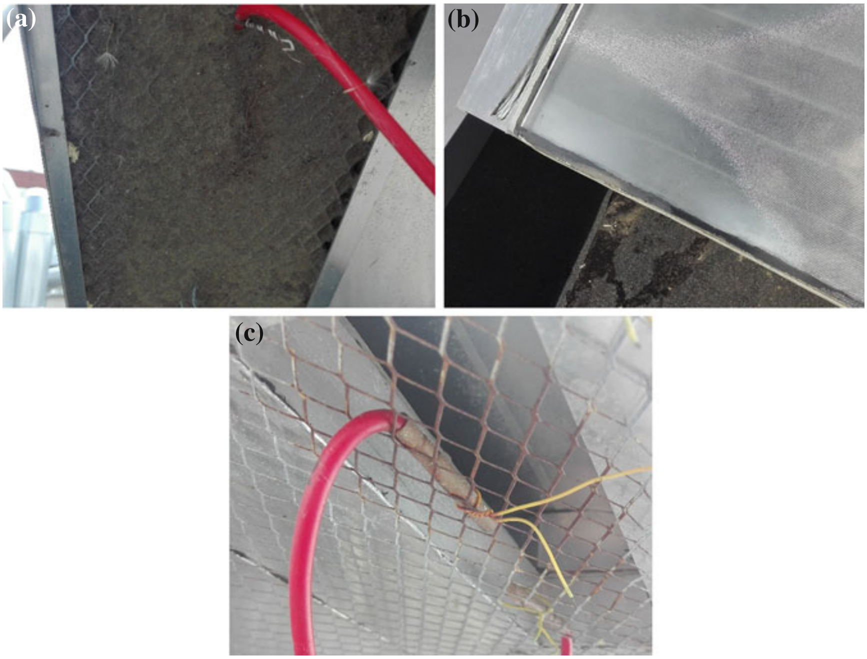


Fig. 12 View of SAH after one year working in external conditions: **a** inlet air filter, **b** part of the absorber glass, **c** outlet air grille with visible PT1000 temperature sensor

The results of the calculations performed on the basis of the collected measurement data are presented in Figs. 10 and 11. The analysis of these graphs shows that the efficiency of the device is within the range 50–70%. The energy efficiency of the tested system increases with the intensity of solar radiation. The swirlers have a positive impact on the intensification of heat exchange, even at lower air flow rates.

The quality of the experimental runs was estimated on the basis of the root-sum-square method [27]. The maximum uncertainty in the thermal performance was 3.89% and the relative error did not exceed 0.058.

4 Conclusions

The widespread use of renewable energy sources are an effective way to increase energy security at the local level, as well as to improve ambient air quality. The main goal of the present analysis has been to determine the thermal performance of the solar air collector for the purpose of preheating ventilation air in cold climates. The device is equipped with the swirlers for the intensity of heat transfer.

Tested SAH is a prototype device, its commercial version should be better suited for outdoor weather conditions. As you can see in Fig. 17.12, the device after a year of working in external conditions shows some imperfections. The first thing that comes to mind is the filter of intake air, it is completely worn out—it was originally white, SAH in winter and full summer did not work, because during these periods either there is not enough sunlight or there is no need for warm air. The second issue is the outlet grille, which shows signs of corrosion. In the prototype device did not withstand the sealing of the absorber glass, insulation tape does not withstand external conditions, and these issues require immediate improvement, which is usually done in the case of commercial equipment. Figure 12 shows the components that need to be improved as soon as possible.

The taken measurements have allowed to determine that the maximum temperature rise inside the tested SAH exceeds 40 and 27.5 °C for air flow rate equal to 80 and 110 m^3/h, respectively. It can be regarded as a good result.

The thermal efficiency of the SAH was related to the intensity of solar radiation. The highest efficiency (70%) appeared at the maximum insolation.

In conclusion, it should be noted that the use of the swirlers can be regarded as a good technical solution, which allows the tested SAH to compete with the best commercially available ones. SAH is also suitable for heating air in buildings such as greenhouses which, during spring and autumn, should help to reduce the heat consumption from fossil fuels in these facilities.

The tested SAH is a device of high efficiency as for air exchanger, it should be considered as a successful construction.

Acknowledgements The study has been implemented from the resources of the S/WBiIŚ/4/14 statutory work financed by the Ministry of Science and Higher Education in Poland.

References

1. Tabish, A., Man-Hoe, K.: Performance improvement of double-pass solar air heater—a state of art of review. Renew. Sustain. Energy Rev. **79**, 779–793 (2017)
2. Varun, S.A., El-Sebaii, A.A.: A thermodynamic review of solar air heaters. Renew. Sustain. Energy Rev. **43**, 863–890 (2015)
3. Zukowski, M.: Identification of heat transport processes in solar air collectors. In: Pawlowski, L. (ed.) Environmental Engineering IV, pp. 451–455. CRC Press—Taylor & Francis Group, London (2013)
4. Sharma, S.K., Kalamkar, V.R.: Experimental and numerical investigation of forced convective heat transfer in solar air heater with thin ribs. Sol. Energy **147**, 277–291 (2017)
5. Yadav, A.S., Bhagoria, J.L.: A CFD (computational fluid dynamics) based heat transfer and fluid flow analysis of a solar air heater provided with circular transverse wire rib roughness on the absorber plate. Energy **55**, 1127–1142 (2013)
6. Sharma, S.K., Kalamkar, V.R.: Computational fluid dynamics approach in thermo-hydraulic analysis of flow in ducts with rib roughened walls—a review. Renew. Sustain. Energy Rev. **55**, 756–788 (2016)

7. Aris, M.S., McGlen, R., Owen, I., Sutcliffe, C.J.: An experimental investigation into the deployment of 3-D, finned wing and shape memory alloy vortex generators in a forced air convection heat pipe fin stack. Appl. Therm. Eng. **31**, 2230–2240 (2011)
8. Skullong, S., Promvonge, P., Thianpong, C., Pimsarn, M.: Thermal performance in solar air heater channel with combined wavy-groove and perforated-delta wing vortex generators. Appl. Therm. Eng. **100**, 611–620 (2016)
9. Tamna, S., Skullong, S., Thianpong, C., Promvonge, P.: Heat transfer behaviors in a solar air heater channel with multiple V-baffle vortex generators. Sol. Energy **110**, 720–735 (2014)
10. Han, J.C., Glicksman, L.R., Rohsenow, W.M.: An investigation of heat transfer and friction for rib-roughened surfaces. Int. J. Heat Mass Transf. **21**, 1143–1156 (1978)
11. Webb, R.L., Eckert, E.R.G., Goldstein, R.J.: Heat transfer and friction in tubes with repeated-rib roughness. Int. J. Heat Mass Transf. **14**, 601–617 (1971)
12. Han, J.C., Dutta, S., Ekkad, S.V.: Gas turbine heat transfer and cooling technology. Taylor & Francis, New York (2000)
13. Tanda, G.: Performance of solar air heater ducts with different types of ribs on the absorber plate. Energy **36**, 6651–6660 (2011)
14. Esen, H.: Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates. Build. Environ. **43**, 1046–1054 (2008)
15. Ozgen, F., Esen, M., Esen, H.: Experimental investigation of thermal performance of a double-flow solar air heater having aluminium cans. Renew. Energy **34**, 2391–2398 (2009)
16. Bhagoria, J.L., Saini, J.S., Solanki, S.C.: Heat transfer coefficient and friction factor correlations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate. Renew. Energy **25**, 341–369 (2002)
17. Momin, E., Saini, J.S., Solanki, S.C.: Heat transfer and friction in a solar air heater duct with V-shaped rib roughness on absorber plate. Int. J. Heat Mass Transf. **45**, 3383–3396 (2002)
18. Aharwal, K.R., Gandhi, B.K., Saini, J.S.: Heat transfer and friction characteristics of solar air heater ducts having integral discrete ribs on absorber plate. Int. J. Heat Mass Transf. **52**, 5970–5977 (2009)
19. Kumar, A., Bhagoria, J.L., Sarviya, R.M.: Heat transfer and friction correlations for artificially roughened solar air heater duct with discrete W-shaped ribs. Energy Convers. Manage. **50**, 2106–2117 (2009)
20. Layek, A., Saini, J.S., Solanki, S.C.: Second law optimization of a solar air heater having chamfered rib-groove roughness on absorber plate. Renew. Energy **32**, 1967–1980 (2007)
21. Mittal, M.K., Varun, G., Saini, P.P., Singal, S.K.: Effective efficiency of solar air heaters having different types of roughness elements on the absorber plate. Energy **32**, 739–745 (2007)
22. Sahu, M.M., Bhagoria, J.L.: Augmentation of heat transfer coefficient using 90 broken transverse ribs on absorber plate of solar air heater. Renew. Energy **30**, 2057–2073 (2005)
23. Abdullah, A.S., El-Samadony, Y.A.F., Omara, Z.M.: Performance evaluation of plastic solar air heater with different cross sectional configuration. Appl. Therm. Eng. **121**, 218–223 (2017)
24. Aman, M.M., Solangi, K.H., Hossain, M.S., Badarudin, A., Jasmon, G.B., Mokhlis, H., Bakar, A.H.A., Kazi, S.N.: A review of Safety, Health and Environmental (SHE) issues of solar energy system. Renew. Sustain. Energy Rev. **41**, 1190–1204 (2015)
25. Tsoutsos, T., Frantzeskaki, N., Gekas, V.: Environmental impacts from the solar energy technologies. Energy Policy **33**, 289–296 (2005)
26. Zukowski, M.: Assessing the environmental impacts of using solar air heaters. J. Int. Sci. Publ. **10**, 76–84 (2016)
27. Mathioulakis, E., Panaras, G., Belessiotis, V.: Uncertainty in estimating the performance of solar thermal systems. Sol. Energy **86**(11), 3450–3459 (2012)
28. Eco Solaris. http://www.ecosolaris.ca. Last access 14 June 2017
29. Organic Mechanic. http://organicmechanic.com. Last access 14 June 2017
30. Solar Wall. http://solarwall.com. Last access 14 June 2017

Bio-fertilizers and Soil Health—An Approach Based on Balance of Elements in the Vegetable Cropping Sequence

Katarzyna Przygocka-Cyna, Agnieszka Andrzejewska and Witold Grzebisz

Abstract It has been assumed that bio-fertilizers based on biomass ash and biogas leads to a depletion of soil macronutrients. This hypothesis was experimentally validated. Vegetables were grown in a cropping sequence of radish-green bean-radish grown on light soil and treated with two bio-fertilizers. They were both based on bio-ash and digestate (BAD) composed in contrasting ratio of 2.2:1 (FE1) and 1:2.2 (FE2) and phosphoric rock (15%). The BAD rates were as follows: 0, 20, 40, 80, 160, 320 g m^{-2}. The total yield of crops was limited by an uptake of K, Mg, and Cu. The decisive role of these three elements can be explained based on the course of their balance with respect to the type and rate of BAD. The absolute value of a particular element balance increased progressively with BAD rates. As a rule, low BAD rates led to depletion, while high rates resulted in the enrichment of soil resources for most elements, including heavy metals. The only exception was Fe and Mn, which soil resources increased along all of the applied BAD rates. The K balance pattern indicates that its supply within BAD, irrespective of the rate, was too low to prevent the exhaustion of its soil reserves. The strong depletion of soil resources at low BAD rate, but element specific, were recorded not only for Ca and Mg, but also for Zn, Cu, Pb and Cd. It can be concluded that soil amendments based on bio-ash and digestate applied in low rates should be enriched with the nutrients, which are crucial for an intensive and healthy production of vegetables.

Keywords Bio-ash · Digestate · Nutrients · Heavy metals · Balance

---

K. Przygocka-Cyna (✉) · A. Andrzejewska · W. Grzebisz
Poznan University of Life Sciences, Wojska Polskiego 71F, 60-625 Poznań, Poland
e-mail: kasiac@up.poznan.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_18

1 Introduction—Problematic Areas of Bio-fertilizers Application

The key pillars of sustainable agriculture are the increase of (i) food production and fiber, and recently fuel, and (ii) effective use of non-renewable resources [1]. The latter objective can be, at least partly, fulfilled by a wise use of non-agricultural residues, like biomass ash (BA) or biogas digestate (D). The key reason is the *climate package*, which obligates the EU member countries to increase the proportion of renewable-energy sources up to 20% of the total energy consumption by 2020. In Poland, this target value was fixed at 15% by 2020. The renewable-energy sources in 2020 are biomass (78.9%), including energy crops (27.9%), biofuels (12.2%), biogas (20.2%), and others (18.6%) [2]. In general, BA is considered both as an excellent liming material, leading to soil pH increase, accelerating, in turn, activity of soil organisms [3]. The biogas digestate, as a product of anaerobic digestion of different organic residues, including manures or maize silage, is a good source of nutrients, however their concentration is low and highly variable [4, 5]. The condensate of raw slurry into solids can be used solely or as a substrate for bio-fertilizer manufacturing [6]. The raw bio-wastes or their processed products may contain, depending on the source, different concentration levels of heavy metals (HMs). Therefore, all bio-fertilizers undergo the legalization procedure in order to minimize their negative impact on both soil and consumable crop quality [7, 8]. The most sensitive to the excess of HMs in arable soils are leafy and root vegetables [9, 10]. The maximum levels of harmful metals acceptable in the edible parts of vegetables are based on strictly defined norms, which should be used to evaluate bio-fertilizers as soil amendments [11]. The bio-ash (BA) and biogas digestate (D) physically unified in a conglomerate can exert a big, yet highly diversified impact on both soil agrochemical properties and activity of soil microorganisms. The basis for this hypothesis is: (i) high liming potential of BA, (ii) narrow C:N ratio in D, (iii) low concentration of nutrient, (iv) potential threat of soil enrichment with HMs. Based on these assumptions few issues arise concerning the effect of this type of conglomerate (termed as BAD) on the health condition of soil and consumable crops. The most problematic one is to evaluate the optimum rate of BAD in accordance with growing crop needs and the protection of its edible parts, as a prerequisite of human health.

The objective of this paper is to evaluate the impact of the two bio-fertilizers based on the contrasted ratio of bio-ash and digestate on a balance of nutrients and heavy metals in the radish-green bean-radish cropping sequence. This study should indicate the problematic areas of the bio-fertilizer use on soil and its consequent effects on human health.

2 Materials and Methods

The assumed objectives were validated based on data obtained from the micro-plot experiment with vegetables grown in a cropping sequence: radish-green bean-radish. The test was carried out on a light, slightly acid soil with moderate content of available nutrients [for details: 12]. The two-factorial experiment was arranged as follows:

1. The first factor: two types of BAD fertilizers composed of biomass ash (BA) + a solid residue of biogas digestate (D) + phosphoric rock (PR) + elemental sulfur (S^0). The tested BAD differed in a contribution of the principal two components:
   a. FE1: BA-55% + BDs-25% + PR-15% + S^0-5%;
   b. FE2: BA-25% + BDs-55% + PR-15% + S^0-5%;
2. The second factor: five rates of BAD: 0; 20; 40; 80; 160; 320 g m^{-2}.

Mineral nitrogen in the form of ammonia nitrate in the rate of 4 g N m^{-2} was applied to all plots. There were fertilized only radish crops.

The operational view of a particular element management in the cropping sequence requires a recognition and a definition of its input (**I**) and output (**O**) components. The **Input** components were calculated based on the BAD rate for its type and a specific element content as presented in Table 1. The **Output** components were directly measured for consecutive plants based on dry main yield (root, pods) and byproducts (tops—radish; leaves, stems—green bean) and concentration of the particular element. The **net balance** (**B_n**) formula was as follows:

$$B_n = I - O \tag{1}$$

The calculated data were subjected to the conventional analysis of variance using computer programs STATISTICA 12®. The differences between treatments were evaluated with the Tukey's test. In tables, figures, and equation's *F* test results (***, **, * indicate significance at the $P < 0.1$, 1, and 5%, respectively), are given.

Table 1 Content of elements introduced into soil with BAD soil amendments

Macronutrients	FE1	FE2	Trace elements	FE1	FE2
	g kg^{-1} DM			mg kg^{-1} DM	
Nitrogen, N	26.5	37.0	Iron, Fe	13,586	6906.7
Phosphorus, P	36.8	36.4	Manganese, Mn	1392.4	682.7
Potassium, K	31.1	19.7	Zinc, Zn	205.1	181.0
Calcium, Ca	57.4	40.4	Copper, Cu	58.3	49.0
Magnesium, Mg	9.1	5.2	Lead, Pb	21.8	14.1
Sulfur, S	48.0	48.0	Cadmium, Cd	3.6	2.1

3 Results and Discussion

3.1 Biomass Production

The quantity of any element incorporated into the soil was in accordance with the experimentally fixed rates. The BAD was the key carrier of most elements, excluding phosphorus (P), and nitrogen (N). The first was added to the BAD conglomerate in the form of phosphoric rock (Pc) (Table 1). The second was applied to both radish crops as ammonium nitrate at the seedling stage.

The total crop biomass (TY) is a measure of a particular element accumulation. The patterns of TY response to the type and rates of BAD, which increased in the geometrical order, was significant (Fig. 1a). The total biomass of crops grown on plots treated with FE1 was below the N control up to its rate of 80 g m^{-2}. The rates of FE1 above 80 g m^{-2} resulted again in biomass yield depression. The pattern of biomass production by plants on plots amended with FE2 was quite different. Its maximum was achieved on the plot with 20 g m^{-2}. The next rates resulted in the significant step by step yield decrease, but without depression. The observed difference can be partly explained by the specific impact of crops grown in this cropping sequence. The patterns presented in Fig. 1a were driven by green bean. The highest yield of bean pods was just harvested from the plot fertilized with 20 g m^{-2} of FE2 (131 vs. 118 g m^{-2} on) the N-control. Only the 1st radish significantly affected the total biomass (data not shown but available by authors; for details see [13]).

Only five from 12 studied elements significantly responded to the BAD, clearly stressing the advantage of FE2 over FE1 (data not shown, but available by Authors, [12]). The effect of FE2 was observed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and copper (Cu). The observed response indicates that digestate incorporated into the soil affects a series of processes, thus increasing the pool of plant available nutrients [14]. The stepwise regression procedure showed that the TY was governed by three nutrients:

$$\mathrm{TY} = 47.6 + 0.02\mathrm{K} + 0.07\mathrm{Mg} + 0.05\mathrm{Cu}\ \text{for}\ \mathrm{R}^2 = 0.94, \mathrm{n} = 72, \text{and}\ P \leq 0.001 \quad (2)$$

The supply of these three nutrients to plants was too low, limiting the dry matter production by crops grown in the sequence: radish → green bean → radish.

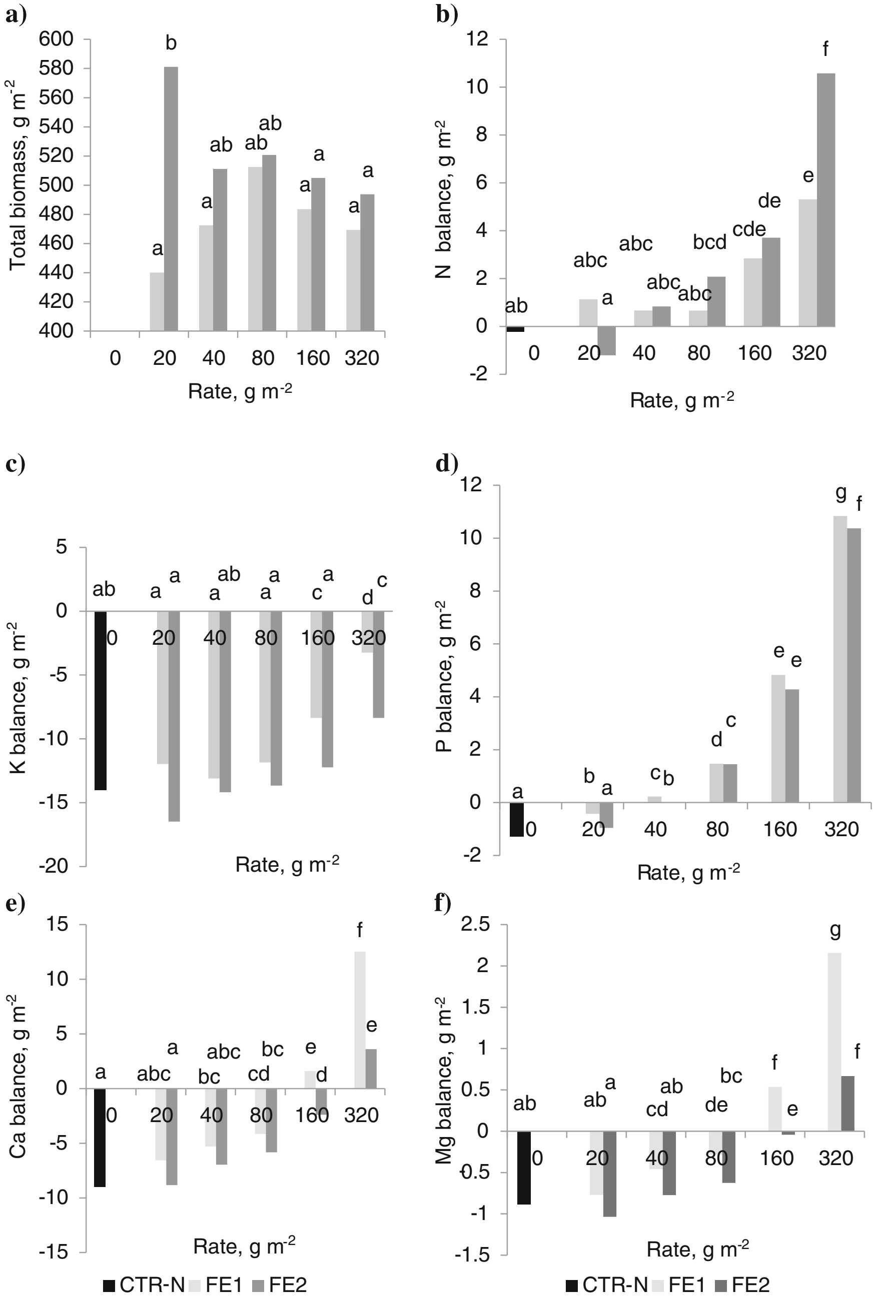


Fig. 1 Dry yield of total biomass of vegetables grown in radish-green bean-radish rotation and balance of macronutrients

3.2 Balance of Elements

The observed controversies with respect to the type and rate of BAD can be explained by the balance analysis of nutrients and heavy metals (Table 2). The total biomass of grown crops, as results from the stepwise regression model was governed by the net balance of five elements:

$$TY = 33.7 + 40P_b - 28K_b - 61.9Mg_b + 0.14Fe_b - 32.2Cu_b \text{ for } R^2 = 0.91, \text{ and } n = 72 \quad (3)$$

This equation follows, to a considerable degree, the model presented by the Eq. (2). The negative signs for K, Mg, and Cu indicate the depletion of their soil resources. It means that supply of these three nutrients was too low with respect to requirements of the grown crops. The detailed balance trends are explained in the following three groups (i) macronutrients, (ii) micronutrients, (iii) heavy metals.

3.2.1 Macronutrients

For the first group, the positive balance was recorded for N and P. On average, N_b for FE2 was higher by 51% compared to FE1 (Fig. 1b). A detailed analysis, as presented in Fig. 1b, clearly shows a slight N mining on the N-control plot. It means that the 80 g m^{-2} of N fertilizer applied to the studied crops was entirely exploited. The negative N_b was also recorded for the plot with 20 g m^{-2} of FE2, where the highest yield of green bean pods was harvested [13]. The lack of this type of response for the respective FE1 plot indicates another reason for yield depression than N supply. For all other treatments, N_b was positive, increasing exponentially with the amount of N fertilizer. This trend indicates a surplus of nitrogen in the soil-plant system, being in part responsible for yield drop on plots treated with the highest rates of BAD.

The K_b was negative along with BAD rates, reaching on average, much lower values for plots fertilized with FE2 (Fig. 1c). The obtained results clearly indicate that K was a critical nutrient for crops growing in sequence: radish-green bean-radish. The K negative balance was a result of high needs of radish plants for K [15]. The deepest K mining was not an attribute of the N-control, but it was an attribute of the plot with 20 g FE2 m^{-2}. The K exhaustion gap decreased in accordance with the increasing BAD rate. This pattern coincides with the pattern of the total biomass production of the studied crops (Fig. 1a). The K_b alone explains 84% of the TY variability:

$$TY = 32.19K_b + 31 \text{ for } R^2 = 0.84, n = 72, \text{ and } P \leq 0.001 \quad (4)$$

Table 2 Effect of BAD bio-fertilizers on nutrients and heavy metals budgeting in intensive cropping sequence with radish-green bean-radish

Factors	Level of factors	Macronutrients (g m^{-2})					Micronutrients (mg m^{-2})					
		N	P	K	Ca	Mg	Fe	Mn	Zn	Cu	Pb	Cd
BAD	FE1	1.73^{a}	2.61^{b}	-10.4^{b}	-1.82^{b}	0.05^{b}	1319^{b}	131.9	8.82	4.01^{b}	1.08^{b}	0.29^{b}
	FE2	2.62^{b}	2.31^{a}	-13.2^{a}	-4.90^{a}	-0.45^{a}	626^{a}	56.1	4.54	2.86^{a}	0.25^{a}	0.13^{a}
F test		8.91**	38.7***	67.7***	100.3***	217***	499***	1324***	10.0**	179***	500***	405***
Rate (R) (g m^{-2})	0	-0.25^{a}	-1.30^{a}	-14.0^{a}	−9.00	−0.88	−84	−13.6	−13.0	−2.19	−1.16	−0.09
	20	-0.04^{ab}	-0.69^{b}	-14.2^{a}	−7.70	−0.90	113	5.53	−10.1	−1.19	−0.86	−0.03
	40	0.75^{ab}	0.12^{c}	-13.6^{a}	−6.13	−0.62	326	27.5	−6.99	0.12	−0.47	0.03
	80	1.37^{b}	1.46^{d}	-12.8^{a}	−4.99	−0.45	728	69.6	1.19	2.03	0.17	0.14
	160	3.28^{c}	4.55^{e}	-10.3^{b}	−0.40	0.25	1553	152.0	17.3	6.58	1.72	0.37
	320	7.94^{d}	10.60^{f}	-5.8^{c}	8.07	1.41	3203	319.8	51.7	15.3	4.59	0.83
F test		72.0***	573***	64.0***	281***	465***	1058***	2489***	22.0***	391***	229***	127***
F for the interaction												
BAD × Rate		11.8***	4.36**	6.28***	17.2***	39.3***	1100***	277***	14.0**	25.6***	91.5***	85.5***

[a–f]Numbers marked with the same letter are not significantly different; ***, **, * significance at $P < 0.001$; 0.01; 0.05, respectively

The P balance (P_b) was positive, but the impact of the BAD type was low, showing a slightly higher P balance in soil fertilized with FE1 (Fig. 1d). It was negative on the control N plot and fertilized with 20 g BAD m^{-2}.

The calcium balance (Ca_b) was on average much more negative in soil fertilized with FE2 (Fig. 1e). The negative Ca_b was recorded for most plots receiving less than 80 g m^{-2} of FE1 and 160 g m^{-2} of FE2 BAD. As in the case of K, the supply of Ca in the applied BAD was too small to cover the requirements of the tested crops. It is well recognized that green bean exerts high requirements for Ca [16]. This opinion was corroborated in this study, because the fresh yield of green pods (PY_{FW}) responded significantly to Ca_b, but only in the FE1 treatment:

$$PY_{FW} = 3.9Ca_b^2 + 15.9Ca_b + 1541 \text{ for } R^2 = 0.46, \text{and } n = 36 \quad (5)$$

The critical Ca_b for the maximum yield of pods, equal to 1557 g m^{-2}, was −2.03 g m^{-2}. The obtained regression model clearly informs that plots fertilized with FE1 revealed both a significant shortage, as well as an excess of Ca over K, which could be the reason for the disturbance of green bean growth and yield [16].

The magnesium balance (Mg_b), averaged over BAD rates, was positive for FE1 at its rate of 160 g m^{-2}, whereas it was only positive for FE2, when its rate doubled (Fig. 1f). Only the yield of bean grown on the FE1 plot showed a significant response to Mg_b:

$$PF_{FW} = 207.5Mg_b^2 + 263.3Mg_b + 1511 \text{ for } R^2 = 0.51, \text{and } n = 36 \quad (6)$$

The critical Mg_b for the maximum yield of pods, equal to 1594 g m^{-2}, was −0.63 g m^{-2}. The presented results for Ca, and Mg with respect to the total biomass produced by crops in the sequence: radish-green bean-radish, implicitly indicate the shortage of both nutrients applied in rates below 160 g m^{-2} for FE1, and 320 g m^{-2} for FE2. A strong relationship between both indices (R^2 = 0.99) points at bio-ash as the key source of their supply to plants.

3.2.2 Micronutrients

The second group comprises of four micronutrients which can be divided into two sub-groups. In general, Fe and Mn showed a net positive balance over the entire set of tested BAD rates (Fig. 2a, b). The relationship between both indices was ideal (R^2 = 1.0). Both elements showed high relationship with Ca_b (R^2 = 0.98), indicating bio-ash as their key source. The patterns of the Zn, and Cu responses to BAD rates were quite different (Fig. 2c, d). The Zn_b followed the same patterns as observed for Ca_b and Mg_b (Fig. 2c, d). For Zn its soil accumulation started from the rate of 80 g m^{-2} for FE1 and 160 g m^{-2} for FE2. For Cu_b this trend was revealed earlier. Both indices correlated with each other (R^2 = 0.99) and with P_b, indirectly indicating the phosphoric rock as an important source for plants (Zn_b = 0.97; Cu_b = 0.99).

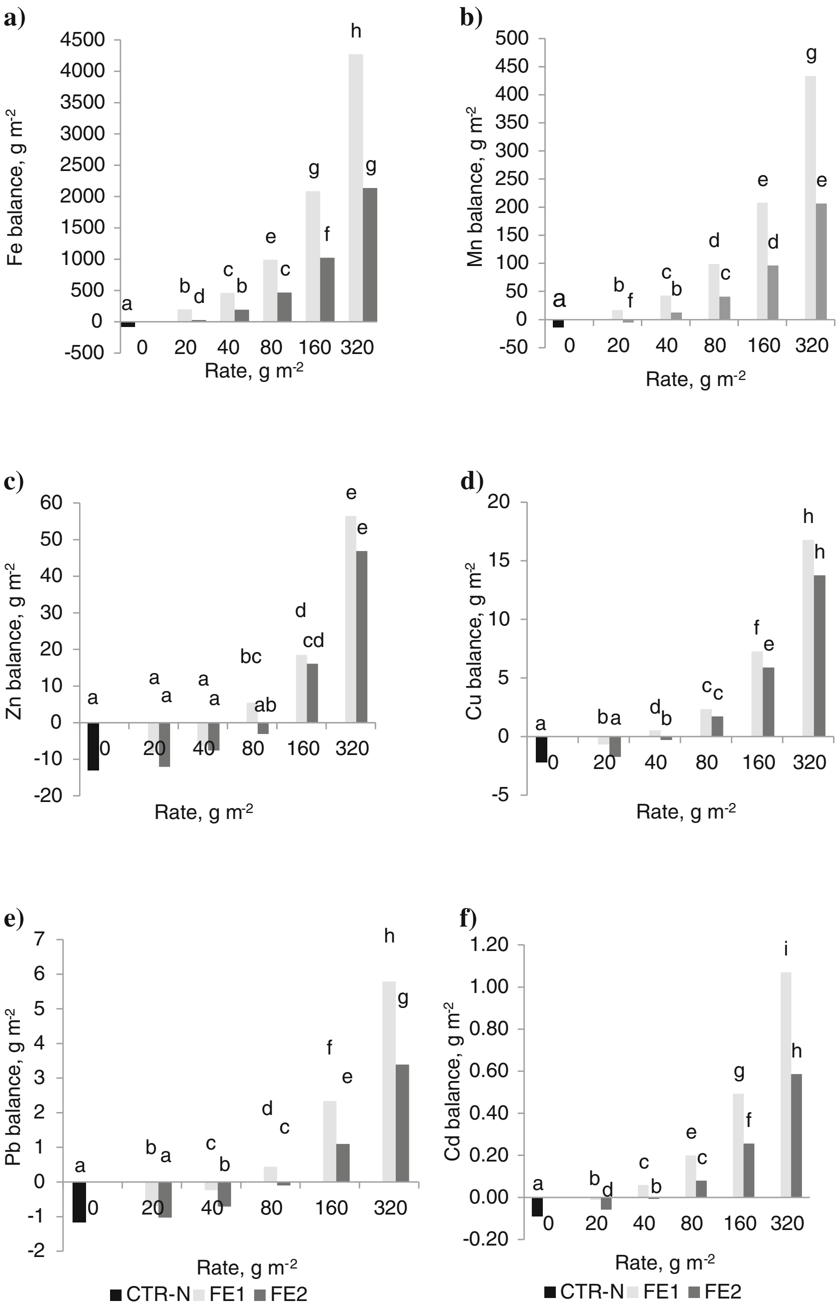


Fig. 2 Balance of micronutrients and heavy metals in cropping sequence of radish-green bean-radish

3.2.3 Heavy Metals

The content of heavy metals in bio-fertilizers is considered with special care [6, 8, 11]. The Pb balance (Pb_b) in response to BAD rates showed the same pattern as noticed for Zn_b (Fig. 2e). Its value was driven by balances of other elements:

$$Pb_b = -0.29 + 0.18P_b + 0.63Mg_b + 0.001Fe \text{ for } R^2 = 0.99, n = 72 \quad (7)$$

This model indicates two different sources of lead, i.e. bio-ash as the main one (Mg, Fe) and phosphoric rock as the secondary one. The pattern of cadmium balance (Cd_b) as shown in Fig. 2f is very similar to the one recorded for Zn (Fig. 2c). Its indices were governed by the following set of elements:

$$Cd_b = -0.007 - 0.003N_b + 0.0002Fe_b + 0.01Cu_b + 0.039Pb_b \text{ for } R^2 = 0.99, n = 72 \quad (8)$$

This set of elements clearly informs about the complex processes responsible for Cd_b in the bio-fertilizer → soil → plant system. The Pb_b relationships with Pb and Fe clearly point at bio-ash as the key lead source. This conclusion was fully corroborated by Cyna and Grzebisz [13], who showed an elevated concentration of Pb in radish root on plots fertilized with BAD rate of 80 g m^{-2}. The higher BAD rates resulted in exponential increase of Pb concentration in this radish part. In general, it coincides with Pb net balance.

4 Conclusions

The type of BAD bio-fertilizer significantly affected the pattern of biomass response to its rates. In general, the supply of K, Mg, and Cu to plants grown in the sequence: radish → green bean → radish was too low, limiting the dry matter production. On plots fertilized with the highest BAD rates, the Ca/K antagonism was probably one of the main reasons for yield depression. In addition, they resulted in high accumulation of heavy metals in soil, creating a real threat to the health of grown vegetables. Six groups of element balances were distinguished. The first, represented by N and P was, in general, positive following a particular fertilizer composition for FE2 or yield for FE1. The second one represented by K was negative, clearly indicating the exhaustion of its soil resources. This process resulted in yield depression on plots with BAD rates below 80 g m^{-2}. The third one, comprising of Ca and Mg, followed the experimental design, indicating soil resource depletion on plots with low BAD rates and accumulation on plots with high BAD rates. It showed much stronger imbalance on plots treated with BAD rich in digestate, indicating its impact on the available pool of soil resources of both nutrients. The fourth one composed of Zn and Cu followed the general pattern of response to the type and rate of BAD, but both elements showed significant relationships with P_b, indicating an influence of phosphoric rock on their balance. Patterns of Pb and Cd balance were significantly correlated with each other and with Fe_b and Mn_b, pointing at bio-ash as their main source.

References

1. Woods, J., Williams, A., Hughes, J.K., Black, M., Murphy, R.: Energy and the food system. Phil. Trans. R. Soc. B. **365**, 2991–3006 (2013)
2. Baum, R., Wajszczuk, K., Pepliński, B., Wawrzynowicz, J.: Potential for agricultural biomass production for Energy purposes in Poland: a review. Vizja Press & IT **7**(1), 63–74 (2013)
3. Ohno, T., Erich, M.S.: Effect of wood ash application on soil pH and soil test nutrient levels. Agric. Ecosyst. Environ. **32**, 223–239 (1990)
4. Arthurson, V.: Closing the global energy and nutrient cycles through application of biogas residue to agricultural land—potential benefits and drawbacks. Energies **2**, 226–242 (2009)
5. Diacono, M., Montemurro, F.: Long-term effects of organic amendments on soil fertility. A review. Agron. Sustain. Dev. **30**(2), 401–422 (2010)
6. Chen, S., Chen, B., Song, D.: Life-cycle energy production and emissions mitigation by comprehensive biogas-digestate utilization. Biores. Techn. **114**, 357–364 (2012)
7. Castro, E., Mañas, P., De las Heras, J.: A comparison of the application of different waste products to a lettuce crop: effects on plant and soil properties. Sci. Hortic. **123** 148–155 (2009)
8. Koupaie, E.H., Eskicioglu, C.: Health risk assessment of heavy metals through the consumption of food crops fertilized by biosolids: a probabilistic-based analysis. J. Hazard. Mater. **300**, 855–865 (2015)
9. Pandey, N., Sharma, C.P.: Effect of heavy metals Co^{2+}, Ni^{2+}, and Cd^{2+}, on growth and metabolism of cabbage. Plant Sci. **163**, 753–758 (2002)
10. Singh, S., Zacharis, M., Kalpana, S., Mishra, S.: Heavy metals accumulation and distribution pattern in different vegetable crops. J. Environ. Chem. Ecotoxicol. **4**(10), 170–177 (2012)
11. Commission Regulation (EU) No 420/2011 of 29 April, 2011 amending Regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs (2011)
12. Przygocka-Cyna, K., Grzebisz, W.: The effect of bio-fertilizer amendments on nutrient accumulation by vegetables grown in short cropping sequence. J. Elem. (in press) (2018a)
13. Przygocka-Cyna K., Grzebisz W. The effect of bio-fertilizer amendments on elements concentration in edible parts of radish and green bean grown in a cropping sequence. J. Elem. (in press) (2018b)
14. De La Fuente, C., Alburqueque, J.A., Clemente, R., Bernal, M.P.: Soil C and N mineralization and agricultural value of the products of an anaerobic digestion system. Biol. Fertil. Soil **49**, 313–322 (2013)
15. Srinivas, K., Naik, L.B.: Growth and yield of radish (*Raphanus sativus* L.) in relation to nitrogen and potash fertilization. Indian J. Hortic. **47**, 114–119 (1990)
16. Da Silva Domingues, L., Dalfollo Ribeiro, N., Andriollo, J.L., Della Flora Possobom, M.T., Mezzomo Zemolin, A.E.: Growth, grain yield and calcium, potassium, and magnesium accumulation in common bean as related to calcium nutrition. Acta Sci. Agron. **38**(2), 207–217 (2016)

Use of Solar Installations as a Way to Reduce Low Emissions

Tomasz Wyleciał, Robert Starczyk, Henryk Otwinowski and Dariusz Urbaniak

Abstract The paper presents the application of solar heating installation as an element contributing to the production of heat in a traditional coal heating plant. To reduce emissions from furnaces of individual households, it is advisable to opt out of this type of heating and, where possible, to connect to a central heating system fed from a heating plant. In this way, the fragmented heat generation, where control of the combustion process is ineffective, will be replaced by central heat generation where the local community's nuisance is limited and the combustion process is controlled. In addition, the use of solar installations reduces the amount of coal burned and thus reduces harmful emissions. Renewable energy sources are characterized by the randomness of their use. It is often the case that potential uses (wind, sun) do not coincide with the time of energy demand. A solar installation working as a auxiliary element of coal boilers seems to be a good way to address the above mentioned deficiency of renewable energy.

Keywords Heating plant · Solar installations · Coal boilers · Emission of pollution · Renewable energy sources

T. Wyleciał (✉)
Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, Armii Krajowej 19, 42-200 Czestochowa, Poland
e-mail: wylecial@wip.pcz.pl

R. Starczyk
Czestochowa University of Technology, Armii Krajowej 21, 42-200 Czestochowa, Poland

H. Otwinowski · D. Urbaniak
Faculty of Mechanical Engineering and Computer Science, Czestochowa University of Technology, Armii Krajowej 21, 42-200 Czestochowa, Poland
e-mail: otwinowski@imc.pcz.pl

D. Urbaniak
e-mail: urbaniak@imc.pcz.czest.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_19

1 Introduction

The growing awareness of human and economic development, causing an increase in the wealth of society, have led to increasing debate on the protection of the environment. These discussions are increasingly leading to the implementation of such activities, which significantly contribute to the improvement of air, water and soil quality.

One of the essential human activities, contributing to the pollution of the environment are coal combustion processes. In Poland, coal was and is the main source of meeting the needs of energy and district heating [1, 2]. Therefore, the state of the environment until the mid-nineties of the last century was not satisfactory.

Since the mid-nineties of the twentieth century, a lot of activities have been implemented in the field of energy, which have contributed to the significant improvement of the quality of nature. Exhaust gas desulphurization technologies have been introduced, with efficiencies of more than 90%, which significantly reduced sulphur oxide emissions to the atmosphere, thus significantly reducing the negative impact of this sector on the environment. Activities aimed at limiting the formation of nitrogen oxides have been introduced, this reduced the emission of these compounds into the atmosphere by about a half. Currently, the implementation of selective and non-selective catalytic methods for the capture of nitrogen oxides from flue gas is being carried out, which further reduces emissions. For a long time, the emission of dust into the atmosphere has been eliminated. The use of high efficiency electrostatic precipitators (over 99%) eliminates almost all this kind of pollution.

In the field of district heating similar trends are observed. The actions taken to reduce the harmful emissions are present to a lesser extent, but the situation is not the worst. The operation of the heating plant is covered by legislation regulating and controlling emissions.

The worst situation is in the area of family holdings. Wallet of the average inhabitant of the poor areas of the country is such that the heat generation is realized by combustion in outdated furnaces and boilers. Replacing these units on modern boilers with closed combustion chamber exceeds the financial capacity of most of these people. Outdated boiler units are incapable of controlling combustion. Such an implementation of this process, generates the emission of products of incomplete combustion. These units are characterized by low efficiency, which forces, in order to achieve the assumed amount of heat, greater amounts of badly burned fuel.

Low prosperity often involves the burning of the “cheapest” fuel, whose questionable quality is due to poor quality of combustion, and thus increased pollutant emissions.

Emissions in single-family holdings are particularly dangerous because they emit to the atmosphere from low chimneys. Heat generation happens frequently when the humidity is high. This is the reason for the persistence of pollutants in the area where people live every day. In effect the people are poisoning themselves.

2 Low Emissions

The environment is the air, soil, water. So talking about the pollution of nature, we need to analyze each of these elements. However, it seems that air pollution is of crucial importance in the process of polluting the entire ecosystem. Atmospheric pollutants affect other elements of the environment—soil and water. Among the pollutants of the atmosphere stands out:

- carbon dioxide (CO_2);
- carbon monoxide (CO);
- oxides of nitrogen (NO_x);
- sulphur dioxide (SO_2);
- hydrogen chloride (HCl);
- hydrogen fluoride (HF);
- persistent organic compounds (POPs), which include polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDDs and PCDFs), polychlorinated biphenyls;
- volatile organic compounds (VOCs);
- heavy metals, especially mercury (Hg) and its compounds, cadmium and thallium (Cd, Tl) and their compounds, antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni), vanadium (V);
- total dust (TSP) and its fractions PM10, PM2.5.

All these pollutants are extremely important from a human point of view, because in a relatively short time they cause a deterioration in human health, and in many cases even death.

In Poland, the main sources of pollution are considered the power industry, communal-living sector and road transport [3]—Fig. 1. According to the KOBiZE [3] report, professional power industry leads the field of emissions of sulfur dioxide and nitrogen oxides. The emission of sulphur oxides, suspended dust, non-methane volatile organic compounds, and nitric oxide from communal-living sector are not insignificant. Road transport, which is growing year by year, mainly produces nitrogen oxides and non-methane volatile organic compounds (NMLZO).

For the average person, the last two emission sources are of particular importance. They are responsible for so-called low emission (emission from sources with emitters not exceeding 40 m). Low emissions are particularly dangerous in the heating season in areas where people meet their living needs by burning the fuel of varying quality in outdated boilers or furnaces. It generates the emission of very dangerous toxic compounds, resulting from incomplete combustion.

Furthermore, low emission is extremely dangerous in large urban agglomerations where the influence of the factors mentioned above is enhanced by the impact of road transport. In large urban agglomerations are moving every day, growing from year to year, a significant number of cars, which operate in an urban environment is not ecological. A large number of traffic lights and car plugs cause

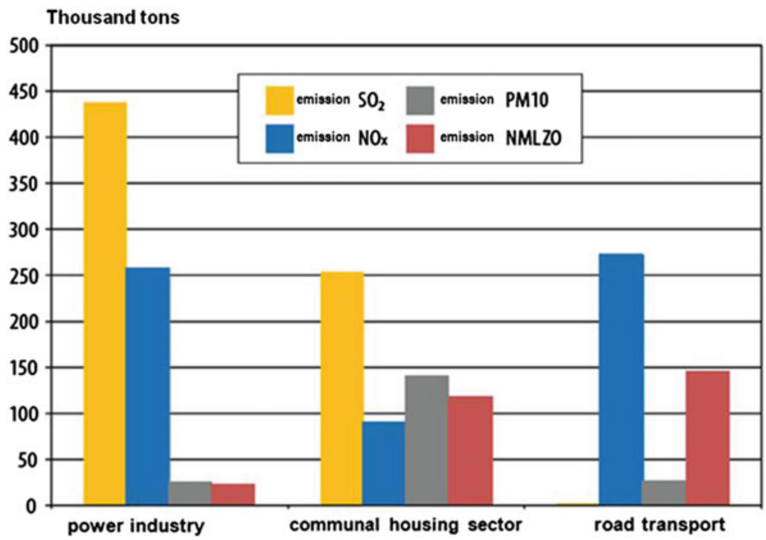


Fig. 1 The structure of emissions of main air pollutants in Poland in the year 2012 [3]

improper work of car engines. This is the cause of significant emissions of harmful gases, the concentration of which is very high and is maintained at this level for a long time. Often buildings in large urban areas make it difficult or even impossible natural ventilation of these areas.

High emission of pollutants in the communal-living sector (due to the low height of the chimneys—usually not exceeding 10 m) and road transport cause high concentration of air pollution at the ground level. This is very dangerous due to direct inhalation of contaminated air and consumption of contaminated food. Study of carcinogenicity "smoke" from the combustion of coal has shown that it is comparable to the emission of coke oven battery, and higher than cigarette smoke [4, 5]. Emissions of dioxins, one of the biggest poisons, have risen more than 100 times, if plastics, rubber or even inappropriately wood are burned with solid fuel at home [4, 5].

Among the pollutants emitted in the residential sector to particularly dangerous are dust, especially its sub fractions PM10 and PM2.5. They contain heavy metals and pollutants such as polycyclic aromatic hydrocarbons, dioxins and furans. As a result, PM10, PM2.5 are responsible for respiratory and cardiovascular diseases, various allergies, and as a consequence of population mortality in areas with high immittance ratios.

Particular attention is required to combustion of wood. Wood is considered one of the main components of biomass, which is particularly recommended by various EU documents [6, 7]. While the improper burning of wood can be much more dangerous than burning of coal. It has been shown that there is a correlation between exposures to wood burning smoke and chronic and acute respiratory diseases. It is noticeable especially among children or older people [4, 5]. Studies conducted among Mexican women have shown that cooking in wood-fired kitchens causes heavier pulmonary diseases than nicotine addiction [5].

3 Modern Coal Heating Plant Assisted by Solar System

For a long time, also in Poland, renewable sources of energy enjoy great interest [6–9]. Relatively low operating costs and environmental savings are their main advantages. The use of these sources of energy allows to reduce the emission of pollutants into the atmosphere resulting from the combustion of traditional fuels. Nevertheless, these sources are characterized by the randomness of occurrence and the need to store energy. The increased share of renewable energy sources in the entire power system of the country would also require a highly developed intelligent control and distribution system, which would have an impact on operating costs and would reduce the overall system security.

In addition, a rapid reduction in the share of conventional fuels in heat and power generation would lead to large changes in the employment structure, which could be a serious social problem—unemployment, employment restructuring, etc.

It seems that a good idea to solve the problem of poor air quality (low emission) is to combine the use of conventional and renewable sources in larger power generation units such as heating plants. Indeed, one of the recommended ways of reducing low emissions is, where possible, the abandonment of domestic boilers and the use of district heating systems.

Using renewable sources in heating plants would reduce the consumption of conventional fuels and save the environment, and the randomness of renewable sources could be correlated with the use of conventional fuels.

The advantage of solar energy is its beneficial effect on the environment, particularly as a result of the reduction of pollutant emissions into the atmosphere resulting from the process of generating energy from coal combustion. Reduction of CO2 emissions through solar thermal energy, according to forecasts, will amount to almost 2.8 million tons/year in 2020 and 4.8 million tons/year in 2030 [3].

The paper presents the interaction of these two types of energy sources on the example of a modern academic heating plant. The primary fuel burned in the heating plant is hard coal. Heating plant produces and provides heat for central heating (central heating) and preparation of domestic hot water (dhw) [10]. There are three water boilers with mechanical grate in the heating plant. All boilers are modern computer-controlled units.

Scheme water boiler is shown in Fig. 2.

In the heating plant solar heaters are also used, which are used to prepare the dhw—solar energy is used for pre-heating of network water, but the basic heating is carried out by the coal boiler. Such solution allows partial replacement of coal with solar energy, while the possibility of producing hot water is independent of the

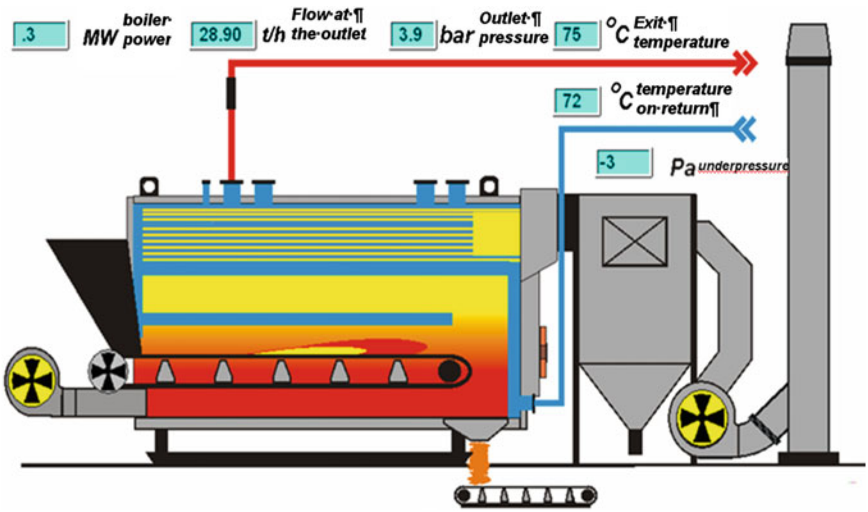


Fig. 2 Scheme of water boiler of type KRm-1,1; company SEFAKO S.A. [10]

randomness of solar energy. Limiting the amount of coal burned reduces emissions and reduces the cost of heat producing.

The solar installation, shown in Fig. 3, consists of 117 solar collectors. The number of collectors has been determined by the available surface of mounting and the specificity of everyday life of the heat consumer, which is an academic campus. The installation is divided into two sets. Technical data of the collector installed in the heating plant are presented in Table 1.

The power of a single solar collector is 910 W/m^2 [10]. The total absorption surface is 249.21 m^2, which, assuming 60% efficiency of the entire system, allows

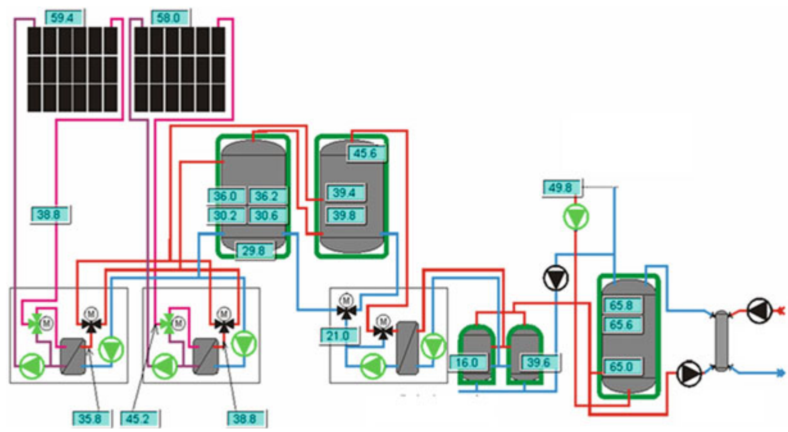


Fig. 3 Solar system installed in the analyzed heating plant [10]

Table 1 Technical data collector [10]

The dimensions of the collector	2036 × 1138 × 79 mm
The surface of the collector	2.32 m^2
The weight of the collector	46.9 kg
The nominal thermal output	910 W/m^2
The absorber surface	2.13 m^2
The absorber surface	2.13 m^2

for a maximum heat output of about 136.07 kW [10]. The total capacity of the trays of hot water in the solar system is 12,000 dm^3 [10].

4 Effects of Work of the Academic Heating Plant and Their Analysis

As mentioned at the outset, low emissions are complex phenomenon, which generally involves the excessive emissions of a large number of pollutants. Coal combustion, which is not always of a good quality, has a strong influence on its occurrence.

The paper presents the possibility of limiting the phenomenon of low emission by replacing in the process of energy production the process of burning coal using the solar system. Solar installation permits replace the specified amount of coal and thus does not emit pollutants.

The total amount of generated heat from a solar installation in individual months of 2014, 2015 and 2016 is shown in Fig. 4.

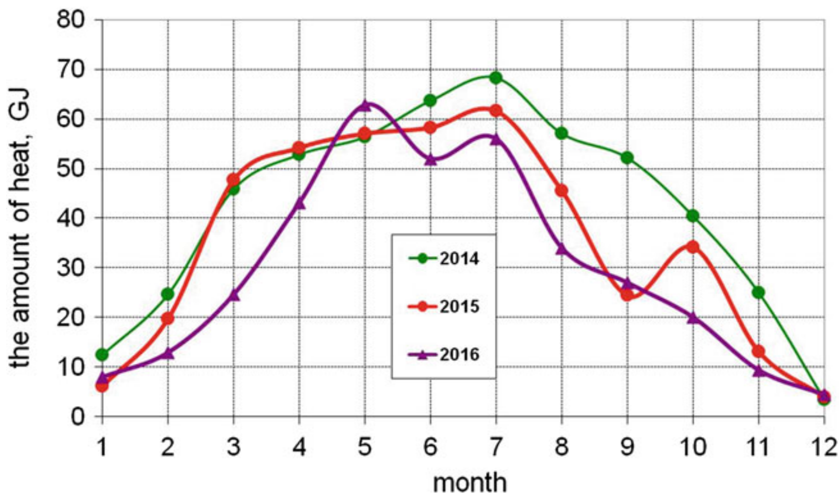


Fig. 4 The amount of heat absorbed by the solar installation in 2014, 2015 and 2016

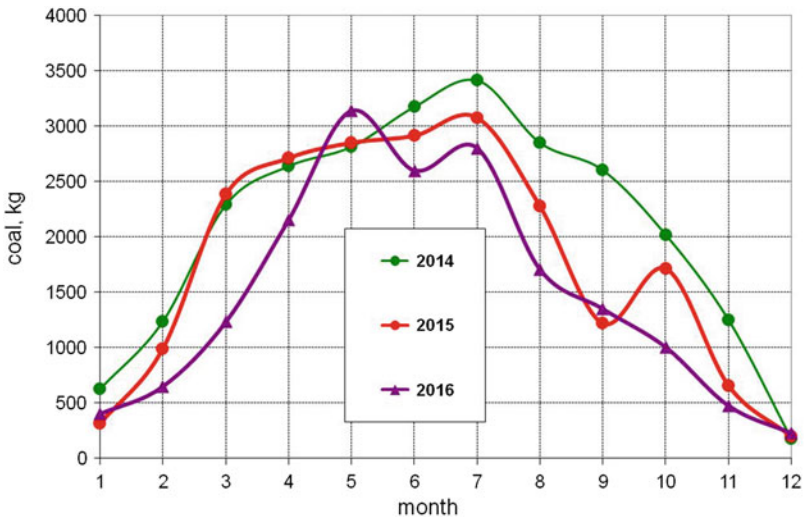


Fig. 5 The mass of unburned coal as a result of work of solar installation

It may be noted that the most effective solar installation work is the summer months—May, June and July. While in the winter months—October, November, December, January, February—solar installations are characterized by negligible amounts of produced heat. This is of course related to the geographical conditions of Poland.

If we assume that the calorific value of the average quality of coal is 20,000 kJ/kg, then the amount of generated heat by the solar system can be converted into the amount of unburned and thus saved coal. The calculation results are shown in the Fig. 5.

It is obvious that the nature of the curves in Fig. 5 above is identical to Fig. 4. The greatest amount of coal can be saved in the summer, which is not, unfortunately, the happiest observation. Low emissions are particularly vexatious in winter during the heating season. According to Fig. 5, solar installations are not the best alternative to coal in this period. However, it should be stressed that the operating costs of solar systems are negligible and thus the current costs of heat generation in the summer are reduced accordingly.

One of the pollutants of combustion of coal is CO_2. It is excessive amounts in the atmosphere are perceived negatively. Therefore, the amount of unburned coal was converted into the quantity not emitted CO_2. The results are shown in Fig. 6.

It can be seen that in this case the nature of curvature variations in particular months of the year is similar as before. The solar system is most beneficial for the environment in summer. In the winter its advantages are heavily restricted.

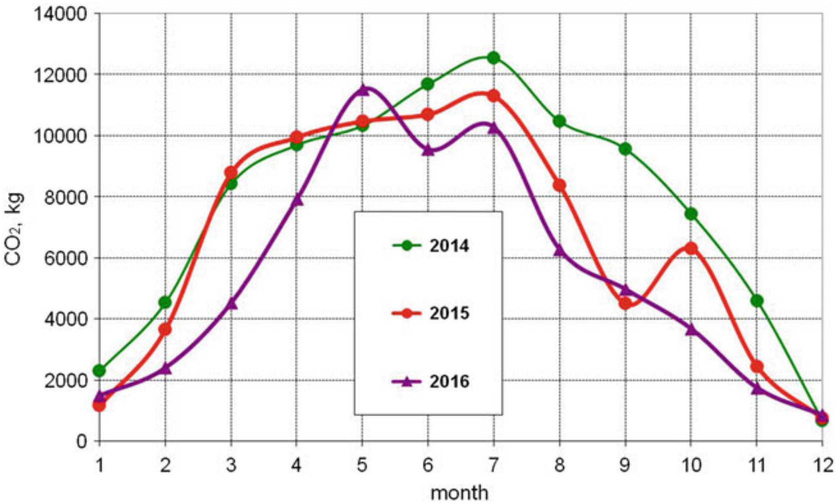


Fig. 6 The mass of CO_2 not emitted by working of the solar system

5 Conclusions

The cost of generating heat from hard coal is growing year by year. Therefore any amount of spared unburned coal is valuable. Unburned coal is a concern for the environment—it means less emissions of toxic pollutants. This is especially important for heavily urbanized areas, where compact housing hampers the natural ventilation of these areas and often causes low emissions.

Effective work of solar collectors depends on the time of the year. In the case of Poland, higher amounts of heat are consumed in winter, and then the efficiency of solar radiation is, unfortunately, the lowest. During summer the heat consumption decreases, accompanied by intense solar radiation. In the case of improper selection of solar power in relation to the amount of received heat, it can lead to excessive heating of installation, which in turn may result in its failure.

It must be remembered that a very important aspect of the potential use of solar collectors is the cost of installation, which in many cases is subsidized by environmental programs. This type of activity has a beneficial effect for the area, because it improves the environmental conditions, thus improving the health of inhabitants. If potentially saved money for public health improvements would be included in the total economic cost of solar installations, then perhaps these investments have become more profitable.

References

1. Kubica, K.: Efektywne i przyjazne środowisku źródła ciepła – ograniczenie niskiej emisji, POLSKI KLUB EKOLOGICZNY OKRĘG GÓRNOŚLĄSKI, Katowice (2007)
2. Lewandowski, W.M.: Proekologiczne odnawialne źródła energii. Wydawnictwa Naukowo-Techniczne, Warszawa (2006)
3. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (KOBiZE).: Krajowy bilans emisji SO_2, NO_x, CO, NH_3, NMLZO, pyłów, metali ciężkich i TZO za lata 2011–2012 w układzie klasyfikacji SNAP. Raport Syntetyczny, Warszawa (2014)
4. Koenig, J.Q., Hanley, Q.S., Rebolledo, V., Dumler, K., Larson, K., Ang, S.W., Checkoway, H., Van Belle, G., Pierson, W.E.: Lung function changes in young children associated with particulate matter from wood smoke. Am. Rev. Respir. Dis. **139**, A425 (1990)
5. Sandoval, J.: Pulmonary arterial hypertension and cor pulmonale associated with chronic domestic woodsmoke inhalation. Chest **103**, 12–20 (1993)
6. Gałusza, M., Paruch, J.: Odnawialne i niekonwencjonalne źródła energii. Poradnik. Tarbonus, Kraków -Tarnobrzeg (2008)
7. Krawiec, F.: Odnawialne źródła energii w świetle globalnego kryzysu energetycznego Wybrane problemy, Wyd. Difin, Warszawa (2010)
8. Kuciński, K.: Energia w czasach kryzysu. Centrum Doradztwa i Informacji Dyfin, Warszawa (2006)
9. Tutak, W., Jamrozik, A., Pyrc, M., Sobiepański, M.: Investigation on combustion process and emissions characteristic in direct injection diesel engine powered by wet ethanol using blend mode. Fuel Process. Technol. **149**, 86–95 (2016)
10. Bera, D.: Porównanie działania kotłowni Politechniki Częstochowskiej, przed i po modernizacji. Praca dyplomowa, Częstochowa (2007)

Influence of Solar Installation on the Change of Fuel Structure of the Heating Plant

Dariusz Urbaniak, Tomasz Wyleciał and Robert Starczyk

Abstract Poland as a member of the European Community is obliged to change its fuel structure on the energy market. This is a consequence of the accepted international obligations and concern for the environment. Changing the fuel mix should be aimed at reducing the share of coal, while increasing the share of renewable energy sources. Coal combustion is a source of harmful pollutants, while increasing use of renewable energy sources contributes to the improvement of the environment. The paper presents the use of a solar collector system as a supporting element of the process of heat production in traditional coal heating plants. The efficiency of the work of heating plant in particular months of the year is discussed. The impact of the solar installation on the change in the fuel structure of the heating plant has been assessed.

Keywords Heating plant · Solar installations · Coal boilers
The structure of fuel · Renewable energy sources

D. Urbaniak (✉)
Faculty of Mechanical Engineering and Computer Science,
Czestochowa University of Technology,
Armii Krajowej 21, 42-200 Czestochowa, Poland
e-mail: urbaniak@imc.pcz.czest.pl

T. Wyleciał
Faculty of Production Engineering and Materials Technology,
Czestochowa University of Technology,
Armii Krajowej 19, 42-200 Czestochowa, Poland
e-mail: wylecial@wip.pcz.pl

R. Starczyk
Czestochowa University of Technology,
Armii Krajowej 21, 42-200 Czestochowa, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_20

1 Introduction

The development of each country is determined, among others, opportunities to meet energy needs. This development should be seen not only in terms of economic, but also in terms of social, population etc. Energy independence is today one of the basic elements of the security and sovereignty of the state. Thus, the need to ensure adequate amounts of energy seems to be one of the key challenges the authorities of the state.

In Poland, coal and lignite use as primary energy fuel. This is the result of a specific structure of the natural resources present in our country, as well as the huge investment made in the mining industry in the previous socio-political period.

However, coal is a fuel whose resources decline each year and the cost of extraction, especially in the case of hard coal, is rising [1]. In addition, the cost of energy production from coal are becoming increasingly inter alia, due to the increasingly stringent EU regulations [2].

One way to change a specific structure of the energy generation is to introduce alternative energy sources [3–8]. This solution is especially recommended by the European Union [2]. However, the introduction of this type of source involves a change not only the structure of energy production, but also changes in the other components of the power system of the country. Renewable energy sources are characterized by random occurrences. Often the possibility of energy production temporarily does not coincide with its potential reception. Therefore, energy storage and the change in the regulation of the whole power system is becoming a necessity. This forces the need for expansion of ICT systems.

Energy shortages can be resolved by building relatively small units, ready in a short space of time to take up energy production and deliver it to the grid. To implement this, these units must be in constant readiness, which unfortunately increases the cost of the entire system. There are also subsidies for those customers who commit themselves not to use energy in a particularly sensitive time.

Until recently these issues were unknown in Poland, which require quiet and factual analysis.

In Poland, we have relatively unfavorable geographical conditions in terms of significantly increasing the use of renewable energy sources. In addition, the previous experience of using coal, as well as the development of clean combustion technologies provide the basis for optimal solutions to meet of the country's energy needs in a prudent combination of further coal use and the deployment of alternative energy sources.

2 Solar Energy in Poland

It seems that one of the main types of renewable energy in Poland will be solar installations—for heat production and electricity generation.

In the case of hydropower, it seems that its capacity is already exhausted and a further significant increase in the share of this generation in the country's electricity system is unlikely. Wind energy is characterized by a relatively low value of the average annual efficiency. It is estimated that in Poland the potential use of wind installations does not exceed 20%. Renewable sources include still biomass, which is, however, the most effective natural way of capturing CO_2 from the air and an element of the proper carbon circulation in nature. Increasingly, this aspect is raised in global discussions and is considered as one of the effective methods of reducing the excessive presence of this gas in the atmosphere [9].

In recent years, a significant increase in investments in solar systems has been observed in Poland. Sale of high quality solar collectors and solar system components is growing. This is, among others, the result of the policy of subsidies to alternative energy sources by the state entities, as well as increase ecological awareness of society. Solar installations are increasingly effective.

They are mainly used for heating water and dual-function systems—for heating and the production of domestic hot water. Increasing the number of solar installations is reducing the demand for fossil fuels in the heating sector. And thus change the structure of the sources of energy.

The forecast for the use of low and medium temperature solar collectors until 2030 is shown in Fig. 1 [10].

Analyzing the forecasts presented in Fig. 1, it should be emphasized that the solar installation will be used in the individual dimension and public sectors. This energy will also be a source of cooling, parallel to the use of solar energy for heat production (central heating and hot water preparation).

Solar power is one of the cleanest and most efficient energy technologies, taking into account the entire life cycle of the equipment (from their production to the recycling or disposal) [10].

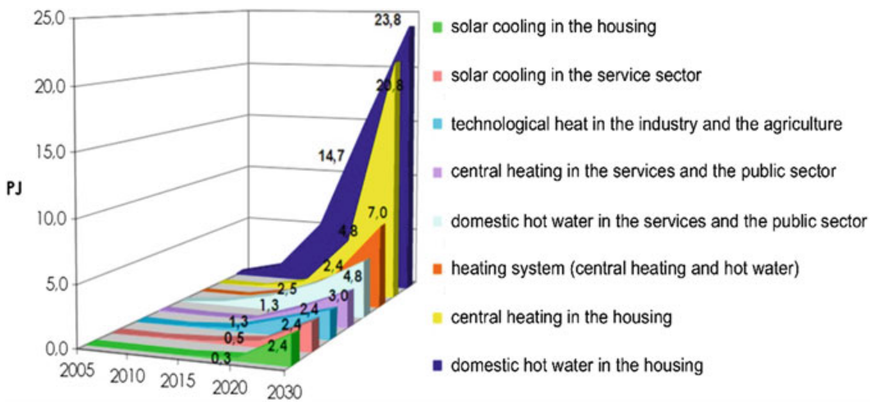


Fig. 1 Forecast for the development of solar energy in the local demand of heat and cold in the housing, services, also taking into account public services, industry and agriculture in Poland to 2030 [10]

3 Modernized Academic Heating as an Example of a Modern Heating Plant

Many objects in the country in the area of district heating, as well as in the energy sector require modernization. Existing objects are obsolete with high risk of failure, and, in addition, their work does not guarantee to produce heat or electricity while maintaining appropriate regimes of environment clean [7, 11]. Incurred penalties for non-compliance with emission standards will be a factor that could lead to unprofitable operation of these objects.

Modernized academic heating plant [12] is the subject of the paper, in the case where coal is the primary fuel. Currently three modern boilers are operating in the heating plant.

The heating plant generates heat for the needs of academic institutions, which economically is the cheapest way to meet the needs of district heating customers in academic housing. The generated heat is used for heating (central heating) and preparation of domestic hot water (dhw) [12]. From October to April, the heat is used for heating and hot water, and from May to September only for hot water.

In 2006, the entire heating system was modernized, resulting in, inter alia, installation of additional heat source—solar installation [12]. Solar energy is meant to aid in the process of hot water preparation and, therefore, partial replacement of coal. The solar installation consists of 117 solar collectors, divided into two sets. The maximum potential power of the solar energy system is 910 W/m^2.

The work regime of the academic heating system is determined by the specificity of the academic year. The heating system supplies the objects in which the students live. So the demand for heat is directly linked to the structure of the academic year. At summer time, when students and university employees are on holiday the demand for heat is significantly lower. Thus, this correctness had to be taken into account in the modernization plans of the academic heating plant. It was decided to use solar systems but only to the extent that there was no problem using the heat from these systems in the summer.

In addition, as already mentioned, alternative energy sources are characterized by randomness. Thus, in the event of unfavorable periods for such energy sources, it was necessary to take account of the existence of an alternative and flexible a heat source (coal boilers).

4 Effects of the Work of the Heating Plant and Their Analysis

Generally hot water is consumed periodically, with peak values of demand in the morning and evening. The heat demand in central heating systems is also characterized by similar variability. Staying at home (in the morning, afternoon, evening, night), we want the room to be warm.

The work involved measuring the amount of heat produced by district heating companies in 2014, 2015 and 2016. The amount of heat received by the heating medium—water was measured. For this purpose, the flow calorimeters were used. The amount of medium flowing through the measuring system and the temperature difference of the flow medium and the flow of the measuring system are determined. Measurement data was aggregated for each month in the analyzed periods.

The amount of heat absorbed in the solar installation depends primarily on the intensity of solar radiation and the length of the day. In Poland, both of these factors are most favorable in summer time.

Figure 2 shows the results of solar systems throughout the 2014, 2015 and 2016. In most cases, July was the month relatively warmest and then the highest values of absorbed heat were recorded. Winter months are essentially the disappearance of the efficient operation of solar collectors. This graph confirms the well-known regularity. In Poland, the length of the day and intensity of solar radiation, derived from the angle of incidence of sunlight, most favorably determine the efficiency of solar collectors in summer, the least favorable—in winter.

The aim of the paper is to present the possibilities of using solar systems in the academic heating plant as a means of changing the structure of energy sources. Figures 3, 4 and 5 illustrate the possibilities of the solar system in comparison with the effects of conventional coal boilers. Figure 3 summarizes the amount of heat generated in 2014, Fig. 4—in 2015, and Fig. 5 in 2016.

In the academic heating plant for seven months the amount of produced heat meets the needs of the heating and hot water, while for five months the heating plant only satisfies the needs of hot water. This is particularly evident in the months July, August and September. Relatively large amounts of heat in May and June are due to the presence of students in student homes.

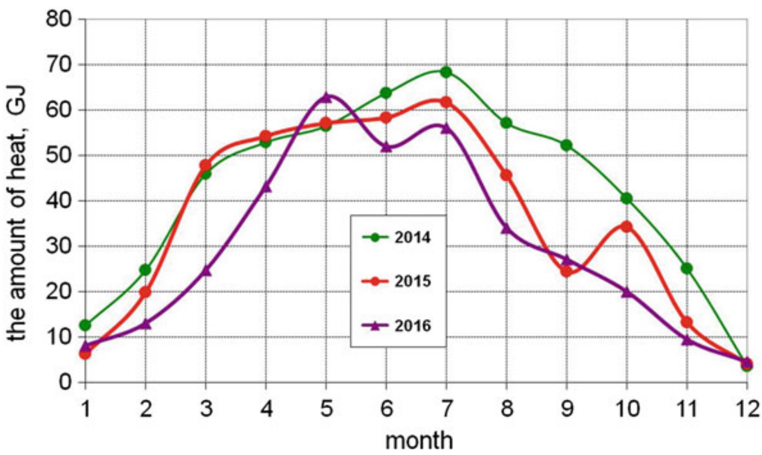


Fig. 2 The amount of heat absorbed by the solar installation in 2014, 2015 and 2016

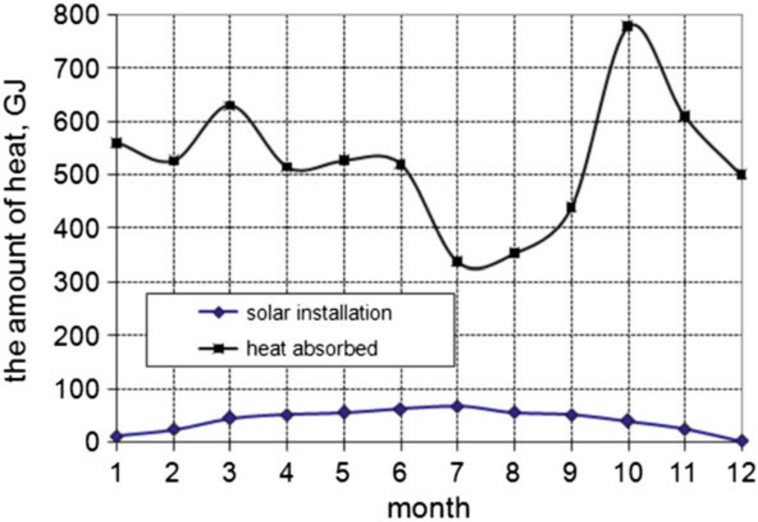


Fig. 3 The amount of heat produced by coal boilers and heat absorbed by the solar installation in 2014

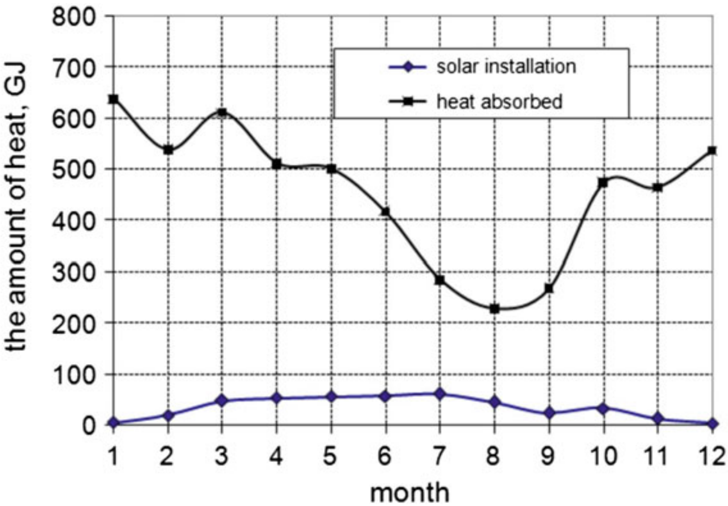


Fig. 4 The amount of heat produced by coal boilers and heat absorbed by the solar installation in 2015

By comparing the potential solar system with respect to the operation of coal boilers, it should be noted that they are not large. The heating plant produces the most heat in the winter months, when the potential of the solar system is negligible. In summer, the work of only solar collectors is insufficient, the work of coal boilers

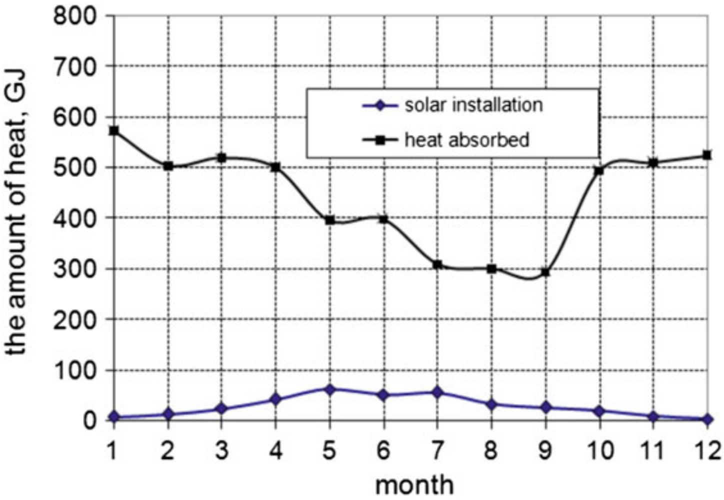


Fig. 5 The amount of heat produced by coal boilers and heat absorbed by the solar installation in 2016

is also essential. It would be possible to extend the surface of the collectors. However, this would require additional space.

5 Conclusions

Effective operation of solar panels can reduce the amount of coal burned. In our country this is also possible. However, the important determinants that characterize this type of energy source must be taken into account. One of the most important aspect is the geographical location of the area where they are planned to be used. In addition, the intensity of radiation, and also the efficiency of solar systems, depends on the time of the year. Mostly solar systems are used for heating purposes. In our latitudes this is very important because we use more heat in winter, and then the solar radiation efficiency is the lowest. In summer, the heat consumption decreases, while the intensity of the sun's rays increases. In case of improper selection of solar system power in relation to the amount of heat received, it may cause excessive heat, which in turn may result in system failures.

On the basis of presented analysis, it can be concluded the possibility of co-operating coal and renewable energy sources is a good idea to solve environmental problems without violently interfering with the social structure of the territory. Solar radiation seems to be a good ecological investment, but the specificity of this type of energy source makes it necessary to interact with another source of energy.

References

1. Gawlik, B.M., Sobiecka, E., Vaccaro, S.: Quality management organisation, validation of standards, developments and inquiries for solid-recovered fuels—an overview on the QUOVADIS-Project. Energy Policy **35**(12), 6293–6298 (2007)
2. Dyrektywa Parlamentu Europejskiego i Rady 2001/77/WE z dn. 27 września 2001 r. w sprawie wspierania produkcji na rynku wewnętrznym energii elektrycznej wytwarzanych ze źródeł odnawialnych
3. Gałusza, M., Paruch, J.: Odnawialne i niekonwencjonalne źródła energii. Poradnik. Tarbonus, Kraków–Tarnobrzeg (2008)
4. Krawiec, F.: Odnawialne źródła energii w świetle globalnego kryzysu energetycznego, Wybrane problemy, Wyd. Difin, Warszawa (2010)
5. Kubica, K.: Efektywne i przyjazne środowisku źródła ciepła – ograniczenie niskiej emisji, POLSKI KLUB EKOLOGICZNY OKRĘG GÓRNOŚLĄSKI, Katowice (2007)
6. Kuciński, K.: Energia w czasach kryzysu. Centrum Doradztwa i Informacji Dyfin, Warszawa (2006)
7. Lewandowski, W.M, Proekologiczne odnawialne źródła energii, Wydawnictwa Naukowo-Techniczne, Warszawa (2006)
8. Tutak, W., Jamrozik, A.: Generator gas as a fuel to power a diesel engine. Therm. Sci. **18**(1), 206–216 (2014)
9. LNCS Homepage, http://biznesalert.pl/minister-srodowiska-spotkal-sie-z-unijnym-komisarzem-ds-klimatu. Last accessed 21 May 2017
10. Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (KOBiZE). Krajowy bilans emisji SO_2, NO_x, CO, NH_3, NMLZO, pyłów, metali ciężkich i TZO za lata 2011–2012 w układzie klasyfikacji SNAP. Raport Syntetyczny, Warszawa (2014)
11. Koenig, J.Q., Hanley, Q.S., Rebolledo, V., Dumler, K., Larson, Ang, S.W., Checkoway, H., Van Belle, G., Pierson, W.E.: Lung function changes in young children associated with particulate matter from wood smoke. Am. Rev. Respir. Dis. **139**, A425 (1990)
12. Bera, D.: Porównanie działania kotłowni Politechniki Częstochowskiej, przed i po modernizacji, Praca dyplomowa, Częstochowa (2007)

The Use of Concentrated Solar Power for Heat Generation

Jolanta Fieducik

Abstract Various systems have been developed for converting solar radiation into heat. Conventional lenses, Fresnel lenses and parabolic trough collectors are used to concentrate solar power and increase the efficiency of heat generation systems. Solar energy is converted to thermal energy in systems where sunlight is concentrated onto a small area to drive electrical power generators. The present study analyzes the applicability of solar parabolic trough collectors for heating water in a four-person household in Poland in accordance with the relevant standards. The correlations between the length of the trough collector, solar irradiation, the number of sunshine hours and the values of absorption and emission coefficients were determined. Concentrated solar power can be used to heat household water on a seasonal or annual basis, to heat indoor and outdoor swimming pools, to heat farm water in the production of crops and livestock and water in food processing plants.

Keywords Concentrated solar power · Parabolic collector · Thermal energy

1 Introduction

A wide variety of systems for harvesting solar energy have been developed. Solar collection systems are generally classified as passive or active.

In passive systems, solar power is converted to heat with the involvement of the natural phenomena of radiation, conduction and convection. Passive systems are very simple and relatively cheap. They are installed in residential buildings in view of the building's orientation, architectural design and the area of glazed openings.

Active systems are equipped with special devices that convert solar power into other types of energy, including solar collectors and photovoltaic panels. In active systems, solar energy is converted in three types of reactions:

J. Fieducik (✉)
Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: jolanta.fieducik@uwm.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_21

- photochemical reactions during photosynthesis in biomass-producing plants,
- photovoltaic reactions which generate electricity, and
- photothermal reactions which generate thermal energy.

This study analyzes the conversion of solar energy in photothermal systems equipped with solar power concentrators. The operating parameters of a system converting concentrated solar power into thermal energy will be optimized to meet the hot water demands of a four-person household.

2 Methods of Concentrating Solar Power

The average solar irradiance measured perpendicular to incoming sunlight at the top of the Earth's atmosphere is 1367 W/m^2, and it is referred to as the solar constant. Due to atmospheric absorption and scattering, only a part of the Sun's energy reaches the Earth's surface, and maximum solar irradiance is estimated at 1000 W/m^2 [1]. The solar power industry also relies on the concept of insolation to determine a system's ability to convert the Sun's energy into useful energy. Insolation is solar irradiance integrated over time, namely the amount of solar energy received on Earth per unit area over time. This parameter is expressed in kWh/m^2/year, and it denotes the amount of solar power received in a given place and time. In Poland, average annual insolation is estimated at 1000 kWh/m^2, where 77% is received in summer months and only 23% in winter months (October–April). Around 43% of annual insolation is received in June, July and August. Poland has 1300–1900 h of sunshine per year, with an annual average of 1600 days. Solar irradiance is determined by cloud cover (Fig. 1).

Solar power can be concentrated with the use of various methods. Optical systems for concentrating sunlight rely on conventional lenses, Fresnel lenses, parabolic collectors (flat and concave mirrors), parabolic trough collectors (linear and concave mirrors) and linear Fresnel reflectors. Systems that concentrate solar power are usually mounted on heliostats which turn around to compensate for the Sun's apparent movement in the sky (Fig. 2).

In solar power systems with concentrating collectors, solar radiation is concentrated to produce a heat flux of up to 2000 W/m^2 which exceeds natural irradiation levels many-fold [2, 3]. In solar concentrators, solar irradiance can reach very high levels of up to 2×10^6 W/m^2. Solar power concentrators are most effective when they are mounted on heliostats which adjust the position of a concentrator to compensate for the Sun's apparent movement in the sky and keep reflected light on a target [4].

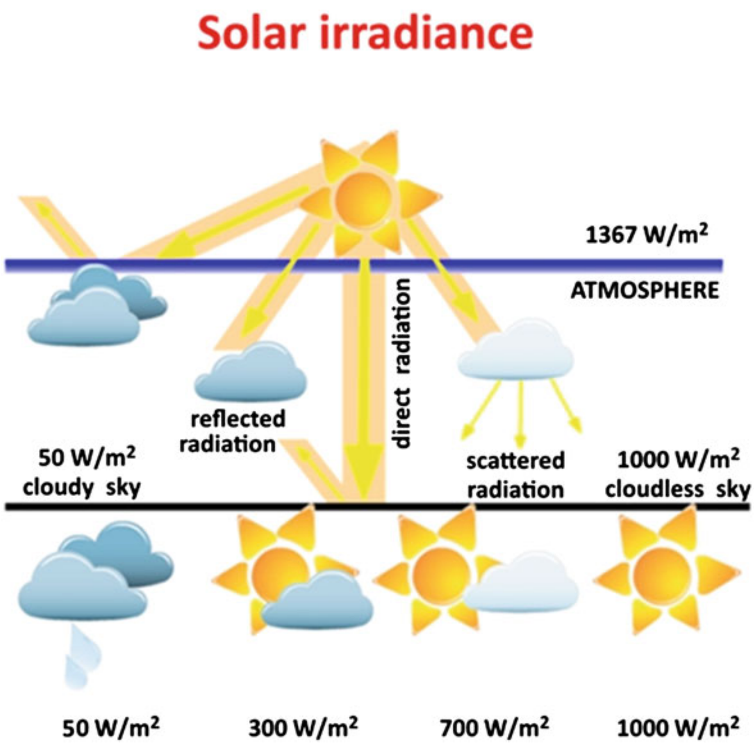


Fig. 1 Solar irradiance under different weather conditions [5]

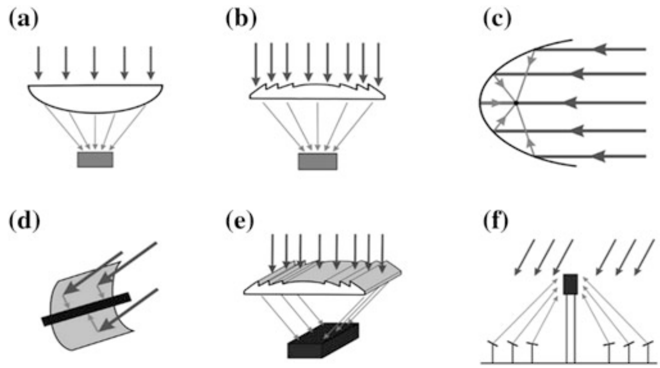


Fig. 2 Most popular methods of concentrating solar power: **a** conventional lens, **b** Fresnel lens, **c** parabolic collector, **d** parabolic trough collector, **e** linear Fresnel lens, **f** power tower with an array of solar concentrators [6]

3 Concentration of Solar Power in an Array of Parabolic Trough Collectors

Solar power can also be concentrated in a linear array of parabolic mirrors referred to as parabolic trough collectors. Most solar power concentrators with parabolic trough collectors rotate in one direction only to guide sunlight along the collector's axis [7].

Solar energy conversion systems with parabolic trough collectors are composed of two parts. The first part consists of parabolic collectors which reflect sunlight and focus solar radiation on tube receivers filled with a working medium. The tubes are installed along an axis delimited by a beam of concentrated sunlight. The concentrators are connected to a control system which adjusts their position at an optimal angle relative to incident sunlight. The working medium inside the tube is heated to a high temperature, and it accumulates energy. The second part of the solar energy conversion system features a steam turbine and a steam circuit similar to those found in a conventional condensation electric power plant. The turbine shaft is connected to a generator which produces electricity [8] (Fig. 3).

Most parabolic collectors are equipped with a tracking system which monitors the Sun's angle of incidence. Solar trackers do not rotate in azimuth.

Parabolic trough collectors with tracking systems have been thoroughly researched, and they are widely used around the world. The temperature of the working medium in parabolic trough collectors reaches 400 °C [9]. These systems accumulate energy and use it for night-time operation. A solar energy generating station with many arrays of parabolic trough collectors in California is presented in Fig. 4.

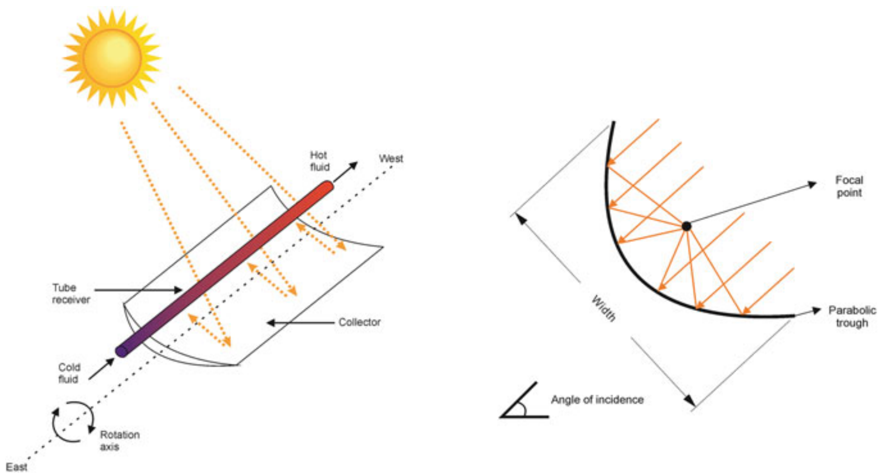


Fig. 3 Diagram of a parabolic trough collector and its position relative to the Sun which causes sunlight to be focused on the tube receiver

Fig. 4 Solar energy generating station with many arrays of parabolic trough collectors in California [1]

The present study analyzes the effectiveness of solar parabolic trough collectors in meeting the hot water requirements of a four-person household in Poland.

4 The Use of a Parabolic Trough Collector for Heating Water in a Four-Person Household in Poland

This study analyzes the solar power conversion capability of a parabolic trough collector for meeting the hot water requirements of a four-person household. Parabolic collectors are particularly effective in generating thermal energy, and they are capable of heating household water to high temperatures, including in autumn and winter, at relatively low cost.

In the analyzed model, parabolic trough connectors were aligned on the east-west axis and rotated relative to the Sun's position to direct sunlight along the collector's axis. A tube receiver which absorbs solar radiation is placed at the collector's focal point. The position of the tube receiver inside the collector is presented in Fig. 5.

The heat balance equation for absorbed solar radiation over time is presented below. Solar energy absorbed by the collector was compared with energy loss in the system and the energy required for heating household water. The heat balance equation contains the following mathematical expressions:

$$\begin{gathered} Absorbed\ solar\ energy = Energy\ loss + Energy\ for\ water\ heating \\ P_0 \cdot l \cdot b \cdot \alpha \cdot t \cdot \tau = \varepsilon \cdot 2 \cdot \pi \cdot r \cdot l \cdot \sigma \cdot T^4 \cdot t + m \cdot c_w \cdot (T - T_w) \end{gathered} \tag{1}$$

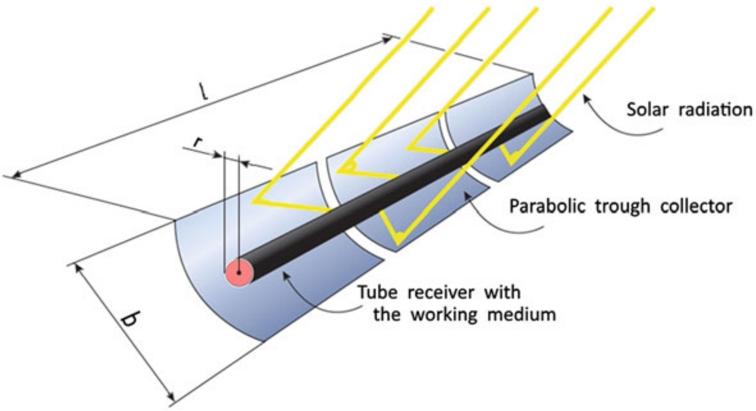


Fig. 5 Diagram of a parabolic trough collector with a tube receiver

where

Absorbed solar energy:

P_o solar irradiation [W/m^2],
l length of collector [m],
b width of collector [m],
α solar absorption coefficient,
τ solar reflection coefficient,
t time [s].

Energy loss:

ε emissivity coefficient,
r tube radius [m],
σ Boltzmann constant [W/m^2 K^4],
T tube temperature [K].

Energy for heating household water:

m mass of water heated by solar power in time t [kg]
c_w specific heat of water [J/kg K],
T_w initial temperature of water [K],
T temperature of heated water [K].

The mass of heated water is determined by insolation conditions and the length of the collector. This parameter can be controlled by changing the length and width of the collector. Formula (1) was transformed to produce Eq. (2) which describes the length of a trough collector:

$$l = \frac{m \cdot c_w \cdot (T - T_w)}{P_0 \cdot b \cdot \alpha \cdot \tau \cdot t - \varepsilon \cdot 2 \cdot \pi \cdot r \cdot \sigma \cdot T^4 \cdot t} \quad (2)$$

The following input values were used to calculate the length of a trough collector:

$$\alpha = 1; \quad \tau = 1; \quad \varepsilon = 1; \quad for \;\; c_w = 4.19 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}; \quad \sigma = 5.67 \cdot 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$$

It was assumed that the collector's width (b) has a constant value of 1 m. The hot water demand of a 4-person household was set at 240 L based on Polish water consumption standards (Regulation of the Minister of Infrastructure of 14 January 2002 on water consumption standards, Journal of Laws, No. 8, item 70).

The initial temperature of water (T_w) was set at 283 K.

T temperature of heated water—328 K, therefore
ΔT temperature difference—45 K,
ρ water density—1000 kg/m^3,
c_w specific heat of water—4180 J/kg K,
t number of sunshine hours—5 h daily,
d external tube diameter—27 mm.

Based on the above parameters, the length of a trough collector was calculated for different values of solar irradiance. The results are presented in Table 1.

The results are presented graphically in Fig. 6.

The results indicate that at average solar irradiance of Po = 400 W/m^2, a parabolic trough collector should have the length of 7.3 m to supply a four-person household with 240 L of hot water per day. The average number of sunshine hours was 5 h daily.

In the following analysis, the length of a trough collector was calculated for 5 and 8 sunshine hours per day: t − 5 sunshine hours per day, t_1 − 8 sunshine hours per day. The remaining parameters in the equation were not changed.

The results are presented in Table 2.

The results are presented graphically in Fig. 7.

The results indicate that a trough collector should have the length of 7.3 m for 5 sunshine hours per day or 4.6 m for 8 sunshine hours per day. The above results

Table 1 Correlations between the length of a trough collector and solar irradiance

Solar irradiance	Po (W/m^2)	100	200	300	400	500	600	700	800	900	1000
Collector length	l (m)	57.0	17.5	10.3	7.3	5.7	4.6	3.9	3.4	3.0	2.7

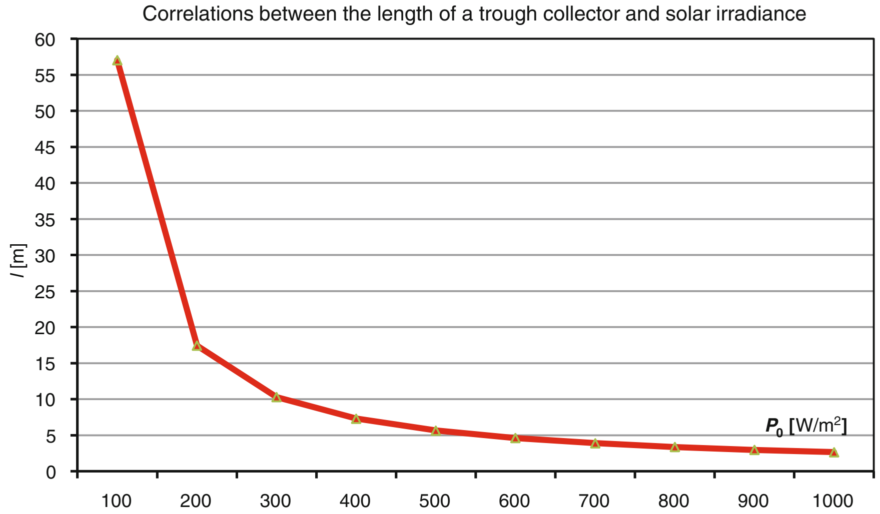


Fig. 6 Correlations between the length of a trough collector and solar irradiance for meeting the hot water requirements of a four-person household

Table 2 Correlations between the length of a trough collector and solar irradiance for different numbers of sunshine hours per day

Solar irradiance	Po (W/ m^2)	100	200	300	400	500	600	700	800	900	1000
Collector length for t = 5 h	l (m)	57.0	17.5	10.3	7.3	5.7	4.6	3.9	3.4	3.0	2.7
Collector length for t_1 = 8 h	l (m)	35.7	10.9	6.4	4.6	3.5	2.9	2.4	2.1	1.9	1.7

were obtained for average solar irradiance of $P_0 = 400$ W/m^2 and hot water requirements of a four-person family of 240 liters per day.

The following analysis was conducted for two values representing the difference between the initial temperature of water and the temperature of heated water: ΔT = 45 K and ΔT = 55 K. The length of a trough collector was analyzed in view of selected differences in water temperature. The results are presented in Table 3.

The results are presented graphically in Fig. 8.

The results indicate that a trough collector should have the length of 7.3 m when the difference in water temperature is ΔT = 45 K or 8.9 m when the difference in water temperature is ΔT = 55 K. The above results correspond to average solar irradiance of $P_0 = 400$ W/m^2, hot water requirements of a four-person family of 240 liters per day, and 5 sunshine hours per day.

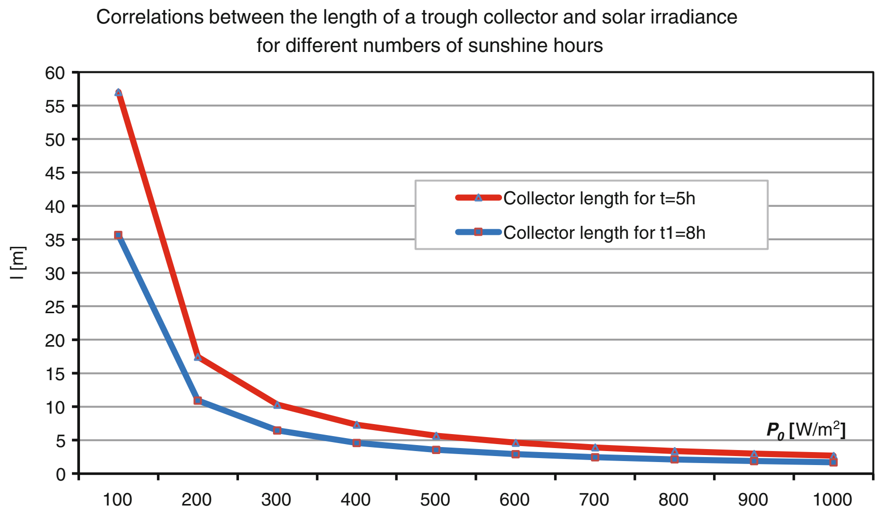


Fig. 7 Correlations between the length of a trough collector and solar irradiance for different numbers of sunshine hours per day

Table 3 Correlations between the length of a trough collector and solar irradiance for selected differences in water temperature

Solar irradiance	*Po* (W/m^2)	100	200	300	400	500	600	700	800	900	1000
Collector length for ΔT = 45 K	l (m)	57.0	17.5	10.3	7.3	5.7	4.6	3.9	3.4	3.0	2.7
Collector length for ΔT = 55 K	l (m)	69.7	21.3	12.6	8.9	6.9	5.6	4.8	4.1	3.6	3.3

The following analysis was carried out for different values of the solar absorption coefficient α and the solar reflection coefficient τ: $\tau = 1$, $\alpha = 1$ and $\tau = 0.85$, $\alpha = 0.60$. The results are presented in Table 4.

The results are presented graphically in Fig. 9.

The results indicate that in order to meet the hot water requirements (55 °C) of a four-person household of 240 liters per day with 5 sunshine hours per day, a trough collector should have the length of 7.3 m when $\tau = 1$ and $\alpha = 1$, or 17 m when $\tau = 0.85$ and $\alpha = 0.60$. The above results were obtained for average solar irradiance of $P_0 = 400$ W/m^2. Coefficient values of $\tau = 1$ and $\alpha = 1$ represent an ideal system of trough collectors, whereas the proposed values of $\tau = 0.85$ and $\alpha = 0.60$ represent real-life conditions.

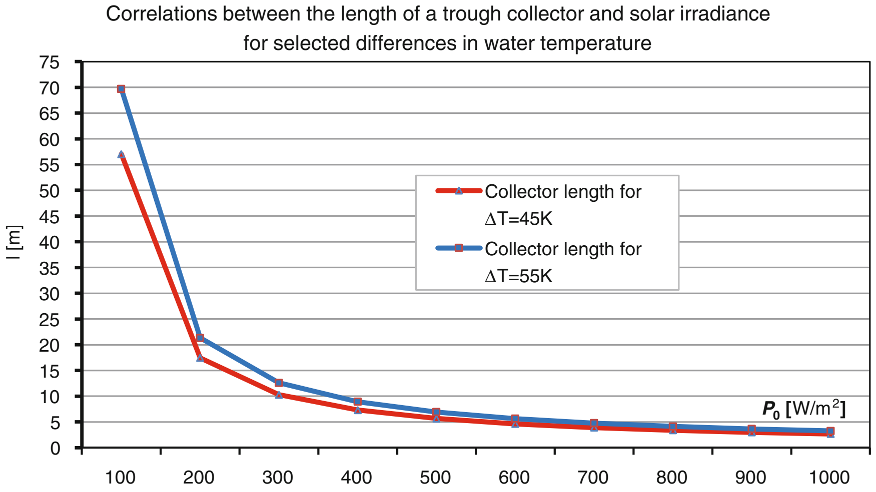


Fig. 8 Correlations between the length of a trough collector and solar irradiance for selected differences in water temperature

Table 4 Correlations between the length of a trough collector and solar irradiance for selected values of τ and α

Solar irradiance	*Po* (W/ m^2)	100	200	300	400	500	600	700	800	900	1000
Collector length for τ = *1;* α = 1	*l* (m)	57.0	17.5	10.3	7.3	5.7	4.6	3.9	3.4	3.0	2.7
Collector length for τ = 0.85; α = 0,6	*l* (m)		54.6	25.9	17.0	12.6	10.1	8.4	7.1	6.2	5.5

5 Conclusions

The results of this study indicate that a solar power system equipped with parabolic trough collectors can be effectively used to heat household water to a temperature of 55 °C and cater to the hot water needs of a four-person household of 240 liters per day. The proposed system is relatively simple, and it can be installed in a small household garden.

The use of parabolic trough collectors for heating household water contributes to a reduction in carbon dioxide, sulfur dioxide, nitric oxide and dust emissions, and it is an environmentally-friendly solution.

Solar power systems equipped with parabolic trough collectors can be used for:

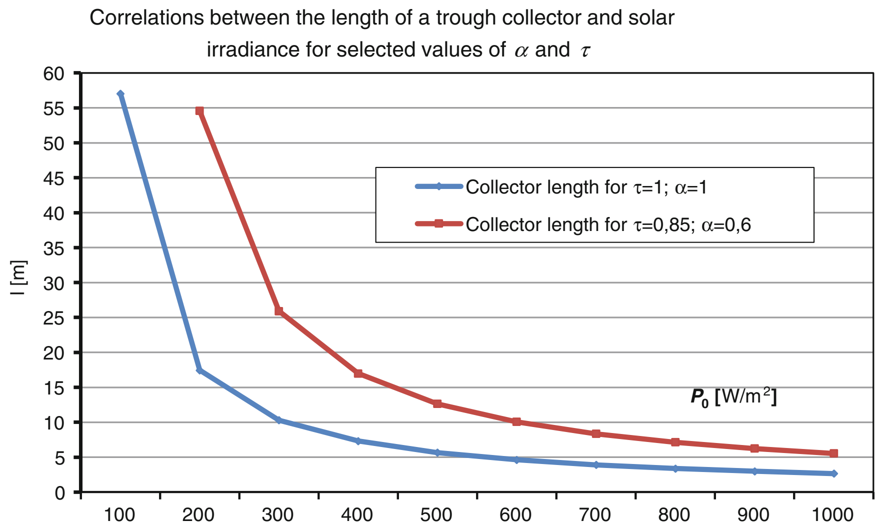


Fig. 9 Correlations between the length of a trough collector and solar irradiance for selected values of α and τ

– heating household water on a seasonal or annual basis,
– heating indoor and outdoor swimming pools,
– heating farm water in the production of crops and livestock and water in food processing plants.

References

1. http://www.nrel.gov/
2. Sintali, I.S., Egbo, G., Dandakouta, H.: Energy equations for computation of parabolic-trough collector efficiency using solar position coordinates. Am. J. Eng. Res. **3**, 25–33 (2014)
3. Tzivanidis, C., Bellos, E., Korres, D., Antonopoulos, K.A., Mitsopoulos, G.: Thermal and optical efficiency investigation of a parabolic trough collector. Case Stud. Therm **6**, 226–237 (2015)
4. Fieducik, J., Godlewski, J.: Ekonomiczne i środowiskowe aspekty skoncentrowanej fotowoltaiki. Przegląd Elektrotechniczny **91**(9), 24–26 (2015)
5. https://jmdtermotechnika.pl/blog-2/
6. Fieducik, J., Godlewski, J.: Fotowoltaika skoncentrowana, osiągnięcia i perspektywy rozwoju. Czasopismo Inżynierii Lądowej, Środowiska i Architektury **63**(2), 431–444 (2016)
7. Fieducik, J., Godlewski, J.: Elektrownie słoneczne. Czysta Energia **6**, 38–39 (2015)
8. Algora, C., Rey-Stolle, I.: Handbook on Concentrator Photovoltaic Technology. Wiley, London (2016)
9. Khamooshi, M., i inni.: A review of solar photovoltaic concentrators. Int. J. Photoenergy (2014)

The Effects of Biomass Transport Between Plantation and Industrial Facility on Energy Efficiency of Biofuel Production System

Andrzej L. Wasiak and Olga Orynycz

Abstract Production of biofuels requires transportation of substantial amounts of biomass between plantations and industrial facilities that converts this biomass onto biofuel. This transport might strongly affect energetic effectiveness of the whole production system. Basing on computer model, developed in our earlier works, the contributions of the energy consumed in various transport solutions are analyzed, and their effects on the energy efficiency are estimated. The dependencies of the energy efficiency upon technical characteristics of transportation means are shown for several solutions of production organization. Conclusions suggest optimal choices of transportation means, and transport organization as dependent upon the type and the size of a plantation.

Keywords Biofuel · Biomass · Production system · Energy efficiency

1 Introduction

Shortage of fossil energetic resources, parallel to harmful effects to natural environment became a challenge to contemporary economies. Both factors mentioned constitute the real problems especially that they cause contradicting results. Expected shortages of fossil fuels may lead to energy crisis, while further use of those fuels leads to almost catastrophic environmental problems.

In this situation biofuels are frequently recommended [1–4], and considered as the replacement for fossil ones. It is bellied that use of biofuels may contribute to mitigation of the danger of energy crisis, as well as of those fuels to reduce environmental threats. Implementation of biofuels is also considered as important contribution towards achieving sustainability of agriculture [5–7].

A. L. Wasiak (✉) · O. Orynycz
Bialystok University of Technology, 15-351 Bialystok, Poland
e-mail: a.wasiak@pb.edu.pl

O. Orynycz
e-mail: o.orynycz@pb.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_22

Recent publications by Wasiak and Orynycz [8–10] present analysis of energy efficiency of biofuel production systems, as well as offer an attempt to redefine energetic aspects of sustainability Wasiak [11]. It was shown that (EROEI type) indicator of energetic efficiency, ε, of the energy production system built of, *i*, subsystems can be expressed by the law of additivity of reciprocals of partial efficiencies, ε_i, describing each of subsystems:

$$\frac{1}{\varepsilon} = \sum_i \frac{1}{\varepsilon_i} \tag{1}$$

The partial efficiency of a subsystem, in turn, is defined as the ratio of the energy, E_{tot}, obtained (during a chosen period of time) from the whole system to the sum of the energy inputs, E_k, needed to maintain functioning of that subsystem, i.e.:

$$\varepsilon_i = \frac{E_{tot}}{\left(\sum_k E_k\right)_i} \tag{2}$$

Application of the above approach to the analysis of agricultural part of biofuel production systems [12] have shown that energetic efficiency of s.c. "energetic" plantation varies from about 10 to about 200 depending upon the choices of plant species being cultivated, production technology, productiveness of machinery used, as well as some aspects of production organization.

On the other hand, transportation of goods between fields, and transportation of crops from plantation to the factory converting biomass into biofuel require additional inputs of energy. In the previous publications the influence of energy consumed by inter-fields transport was estimated without separation from energy contributions resulting of tillage operations. It was shown, however, that the role of energy needed for tillage is predominant.

The amount of crops that have to be transported between plantation and the industrial facility, that performs conversion into biofuels, appears to be quite large, as well as transportation distances might also be relatively large. This means that the energy consumption on the route connecting agricultural and industrial subsystems may be quite large, and may seriously affect final energy efficiency of the production system.

Consequently, estimation of the role of energy needed for transportation of crops, as well as investigation of the dependence between choices of transportation means, and final efficiency of the system seems to be substantiated.

2 Structure of the Biofuel Production System

Production of fuel from biomass requires coordination of two types of processes. The first one is growing and harvesting of biomass, while the second consists the conversion of that biomass onto specified biofuel.

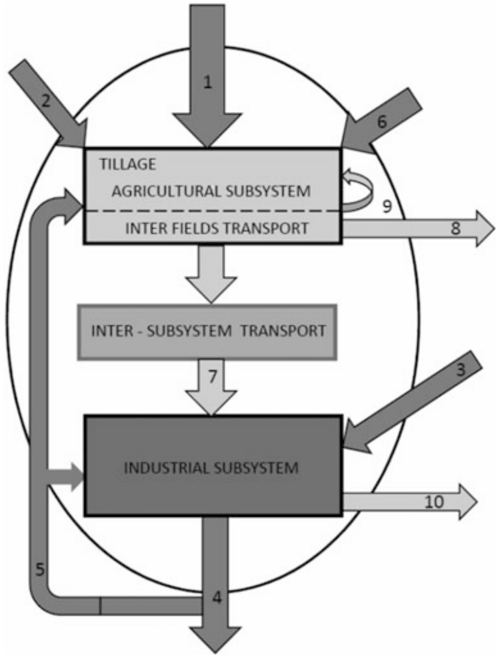


Fig. 1 The structure of the biofuel production system

The structure of biofuel production system, as shown in Fig. 1, consists of two subsystems: agricultural and industrial. The system as a whole interacts with surrounding by exchange of flows of energy and materials. Arrows 1–3 on the figure show energy flows from surrounding to the system, while arrow 4 indicates energy flow from the system to its surrounding. Arrow 5 denotes the energy flow that is returned to the system e.g. biofuel used for agricultural operations. Material flow to the system is represented by arrow 6. Arrow 7 indicates the stream of biomass from agricultural to industrial subsystem, while arrows 8 and 10 the fluxes of biomass destined to non-energetic use, and transferred out of the system. Small loop 9 indicates biomass for non-energetic application produced and consumed inside of the agricultural subsystem.

3 Method of Research

Similarly to the earlier our works, this paper presents the part of research also based upon computer modelling, enabling to follow dependencies being of interest. It is worth to mention that computer modelling and computer simulations become the tool successfully used in quite broad range of technical problems [13–17]. Values of independent variables assumed for simulations are being chosen in the ranges corresponding to realistic situations. Consequently, rapeseed grain was accepted as

Table 1 Properties of trucks considered for transportation of rapeseed grains

Transportation means	Capacity (m^3)	Load (Mg)	Fuel consumption (l/km)
Truck 3 t	10	3	0.1
Truck 10 t	20	10	0.2
Truck 30 t	30	30	0.3

Table 2 Values of ε_{aggreg} resulting from various combinations of ε_{agri} and ε_{ind}

ε_{agri}	10	30	50	70	90	100	500
ε_{ind}	10	30	50	70	90	100	500
ε_{aggreg}	5	15	25	35	45	50	250
ε_{agri}	10	30	50	70	90	100	500
ε_{ind}	500	90	70	50	30	20	10
ε_{aggreg}	10	23	30	30	23	17	10

the type of transported biomass. Its bulk density was taken as 0.655 Mg/m^3, and plantation yield was taken as 3 Mg/ha (ha = hectare). Those data were used for computation of the number of transportation units (trucks). Properties of trucks chosen for computations are given in Table 1. Low calorific value of the diesel fuel used for transportation was accepted as 36.74 MJ/l. Three transportation distances equal to 50, 100, and 200 km driven for each course were considered. Basing on those data energy consumption for each type of truck and each distance was computed as a function of plantation size.

Energy consumption was estimated on the basis of a distance driven, specific fuel consumption for each type of truck, and low calorific value of the diesel fuel. Energy obtained in form of biofuel was estimated basing on plantation yield, biodiesel yield form rapeseed grain (equal to 380 l/Mg), and calorific value of biodiesel equal to 31 MJ/l.

In order to compute the effect of transport on energy efficiency of biofuel production system estimated values of energy efficiency for transport were combined with aggregated energy efficiency for agricultural and industrial subsystems jointly. These aggregated values were computed using Eq. 1, and several combinations of energy efficiency of agricultural subsystem obtained in previous papers, and roughly estimated similar data for industrial subsystem. The aggregate values obtained from various combinations of realistic values of partial effectiveness, ε_{agri} and $\varepsilon_{ind,}$ are summarized in Table 2.

It is evident from Table 2 that in combination of very different values of contributing partial efficiencies substantially reduces the aggregate value to even equal to the smaller contributing value. It seems remarkable, that the larger is the difference the more pronounced reduction of aggregate efficiency is observed.

4 Results

The plot representing the number of truck courses needed for transportation of grain between plantation and industrial facility is given in Fig. 2.

Obviously the smaller is truck's load capacity the bigger is number of necessary courses. The highest values visible in Fig. 2 might be unrealistic from the viewpoint of production organization, and time needed for transportation. Those problems will be considered in further research.

The energy consumed during transportation processes depends upon fuel consumption, and the travelled distance, as well as is proportional to the number of courses. According to Eq. (2), the partial energy efficiency of transport, ε_{tr}, can be computed as ratio of energy obtained in form of biofuel to the energy consumed during transportation of the grain needed for production. The resulting dependencies of, ε_{tr}, upon field's size and type of truck, as well as transportation distance are given in Fig. 3.

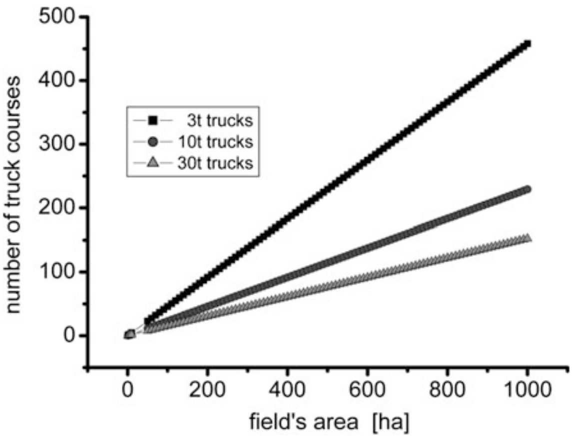


Fig. 2 Number of truck courses for rapeseed grain transportation as a function of plantation size and type of truck

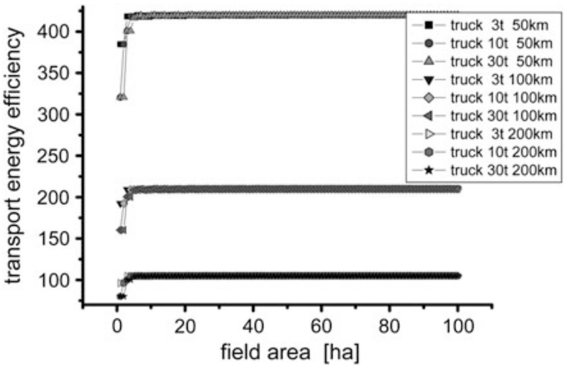


Fig. 3 Dependencies of transport energy efficiency, ε_{tr}, for rapeseed grain transportation by various transportation means on various distances

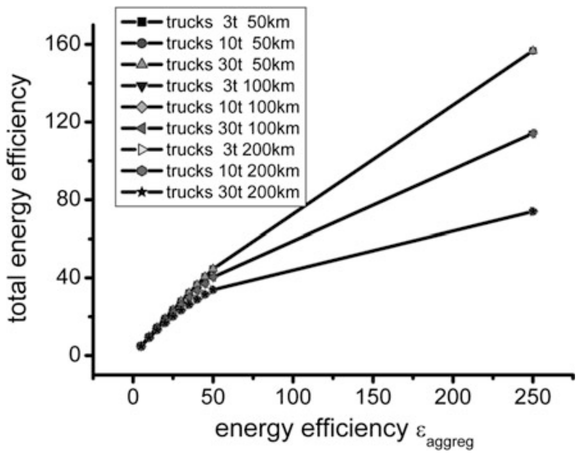


Fig. 4 Total energy efficiency of rapeseed biodiesel production system as function of aggregated energy efficiencies of agricultural and industrial subsystems for different trucks, and various driving distances

It can be seen that, except small fields, transport energy efficiency is practically independent on field's area. The deviation from this rule showing reduction of efficiency for small fields seems to be a result of not complete filling of trucks. The other factor strongly affecting energy efficiency of transport is the distance that has to be driven. The larger is the distance, the lower energy efficiency. Surprisingly the load capacity of the trucks do not show strong effect, and curves for different truck types are practically undistinguishable.

The total energy efficiency for the production system, as computed according to Eq. (1), presented as function of aggregated energy efficiency of agricultural and industrial subsystems is given in Fig. 4.

It is seen that the total energy efficiency decreases with a decrease of aggregated energy efficiency and shows nonlinear behavior, especially in the region of small values of aggregate efficiency. Again the main effects are due to transportation distance. The load capacity of the trucks do not play significant role. This surprising result might result of the small differences in the ratio of load capacity to fuel consumption for the trucks chosen for analysis. It has to be pointed out that total efficiency might reach very low values when all partial efficiencies are low. In the fortunate case of high aggregate efficiency its decrease caused by transport might reach from half to the one third of initial value. Consequently, the correct choice of transportation means, and first of all a reduction of the distance between agricultural and industrial parts of the system might be crucial.

5 Conclusions

Computations of the influence of transport energy efficiency on the total energy efficiency of rapeseed biodiesel production system indicate that the most pronounced effect is connected with the distance between the agricultural part of production system and the industrial part of that system. Since composition of production system from parts strongly differing in energy efficiency substantially decreases of the total efficiency of the whole system, it is important to assure possibly high efficiency for any individual component of production system.

Energetic efficiency of the whole system seems to be crucial factor for biofuel production. The low efficiency might cause rather small energy gain from such production, and might be a reason for questioning the feasibility of investment in such production.

Acknowledgements The research have been performed under financial support from Bialystok University of Technology. Statutory Research Project S/WZ/1/2015.

References

1. Nigam, P.S., Singh, A.: Production of liquid biofuels from renewable resources. Prog. Energy Combust. Sci. **37**, 52–68 (2011)
2. Paneque, M.: Bioenergy—a sustainable and reliable energy source. Agric. Res. Technol.: Open Access J. **4**, 1–3 (2017). https://doi.org/10.19080/ARTOAJ.2017.04.555642
3. Bharathiraja, B., Chakravarthy, M., Ranjith Kumar, R., Yuvaraj, D., Jayamuthunagai, J., Praveen Kumar, R., Palani, S.: Biodiesel production using chemical and biological methods—a review of process, catalyst, acylacceptor, source and process variables. Renew. Sustain. Energy Rev. **38**, 368–382 (2014)
4. Abnisa, F., Wan Daud, W.M.A., Husin, W.N.W., Sahu, J.N.: Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process. Biomass Bioenergy **35**, 1863–1872 (2011)
5. Russo, D., Dassisti, M., Lawlorb, V., Olabi, A.G.: State of the art of biofuels from pure plant oil. Renew. Sustain. Energy Rev. **16**, 4056–4070 (2012)
6. Alluvione, F., Moretti, B., Sacco, D., Grignani, C.: EUE (energy use efficiency) of cropping systems for a sustainable agriculture. Energy **36**, 4468–4481 (2011)
7. Muller, A.: Sustainable agriculture and the production of biomass for energy use. Clim. Change **94**, 319–331 (2009)
8. Wasiak, A., Orynycz, O.: Formulation of a model for energetic efficiency of agricultural subsystem of biofuel production. In: IEEE International Energy Conference: ENERGYCON’2014 Croatia, pp. 1333–1337 (2014)
9. Wasiak, A., Orynycz, O.: The effects of energy contributions into subsidiary processes on energetic efficiency of biomass plantation supplying biofuel production system. Agric. Agric. Sci. Proced. **7**, 292–300 (2015)
10. Wasiak. A., Orynycz. O.: Modelling of the dependence of energetic efficiency of biomass plantations upon energy fluxes going into subsidiary processes accompanying biomass production. In: EUBCE, 23rd European Biomass Conference and Exhibition, 1–4 June, pp. 289–293 (2015)
11. Wasiak, A.: The effect of biofuel production on sustainability of agriculture. Biol. Syst. Open Access **5** (2016). 17.4172/2329-6577.1000171
12. Wasiak, A., Orynycz, O.: The effect of external transport on energetic efficiency of biodiesel production. J. Ecol. Eng. **18**, 57–62 (2017). https://doi.org/10.12911/22998993/67851
13. Świć, A., Zubrzycki, J., Taranenko, V.: Modelling and systemic analysis of models of dynamic systems of shaft machining. In: 11th International Conference on Industrial, Service and Humanoid Robotics (ROBTEP 2012), Strbske Pleso, Slovakia, pp. 211–220 (2012)

14. Ziabicki, A., Jarecki, L., Wasiak, A.: Modelling of melt spinning. Comput. Theor. Polym. Sci. **8**, 143–157 (1998)
15. Zubrzycki, J., Świć, A., Taranenko, V.: Mathematical model of the hole drilling process and typical automated process for designing hole drilling operations. In: 11th International Conference on Industrial, Service and Humanoid Robotics (ROBTEP 2012), Strbske Pleso, Slovakia, pp. 221–229 (2013)
16. Palchevskyi, B.: Information aspects of optimisation synthesis of functional-modular structure of technological equipment. In: Optimization of Production Process, pp. 75–89. Politechnika Lubelska, Lublin (2013)
17. Painuly, J.P., Rao, H., Parikh, J.: A rural energy-agriculture interaction model applied to Karnataka state. Energy **20**, 219–233 (1995)

Unit Cost of Energy, Obtained by the Methane Fermentation Technology of Agricultural Biomass Conversion

Kateryna Yankovska, Hanna Syrotyuk, Serhiy Syrotyuk and Ryszard Konieczny

Abstract Production of agricultural products results in appearance of a considerable amount of biomass residuals, which can be used as raw material for production of different kinds of energy. It can be differently utilized, obtaining different energy products. Development of the methodology of efficient utilization of agricultural production residuals for energy purposes is complicated by the fact that the biomass differs by its kind and origin, processing technologies and capacity of processing enterprises, etc. These issues should be solved separately for each kind of biomass, way of processing and production capacities. Methane fermentation is one of the efficient methods to converse biomass into energy products. Product of the fermentation process is biogas, which can be used as fuel for internal combustion engines, operating in cogeneration regime. Usually, droppings of animals and poultry are used as primary raw material for such processes, because its utilization is ecologically and economically needed. Under such conditions, it is possible to supply a minimum unit costs of the obtained energy. Generally, energy unit costs is calculated as a ratio of total expenses, minus costs of by-products and additional financial revenues, and amount of produced energy. The indicator will substantially depend on enterprise's capacity, kind of anaerobic fermentation process, primary raw material. Methane fermentation produces biogas and large amount of organic matter, which can be specially processed and used as high quality organic fertilizer. The mentioned technology can supply high energy efficiency, comparing to other

K. Yankovska · H. Syrotyuk · S. Syrotyuk
Department of Accounting and Taxation, Department of Energy, Lviv National Agrarian University, 1 V. Velykoho Str., Lviv-Dubliany 80381, Ukraine
e-mail: katiakate@ukr.net

H. Syrotyuk
e-mail: annasyr@ukr.net

S. Syrotyuk
e-mail: ssyr@ukr.net

R. Konieczny (✉)
Department of Agroengineering and Quality Analysis, Wrocław University of Economics, 180/120 Komandorska Str., 53-345 Wrocław, Poland
e-mail: ryszard.konieczny@ue.wroc.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_23

kinds of biomass utilization. Results of the calculations prove efficiency of operation of biogas installation with cogeneration module, costs of electric energy, produced on it, constitutes 0.012 EURO kWh^{-1} and thermal energy—0.003 EURO MJ^{-1}. The price is almost six and four times lower than market price, respectively.

Keywords Biomass · Energy products · Methanogenic fermentation

1 Introduction

Residuals of agricultural production need appropriate utilization and conversion into energy products to improve the production efficiency, on one hand, and to protect environment, on the other hand.

Production of agricultural products results in appearance of a considerable amount of biomass residuals, which can be used as raw material for production of different kinds of energy (thermal, electric, kinetic). It can be differently utilized, obtaining different fuels, i.e. solid, liquid and gas.

It is not easy to develop the methodology of efficient utilization of agricultural production residuals for energy purposes, because the biomass differs by its kind and origin, processing technologies and capacity of processing enterprises, etc. Thus, development of a common methodology is a complicated process. The problems should be solved separately for each kind of biomass, way of processing and production capacities.

Residuals of biomass can be used for energy purposes by means of methane fermentation, gasification, pyrolysis, granulation and baling of solid biomass, fermentation and etherification [1].

Aim of the research is to develop a methodology for assessment of efficiency of residuals utilization for energy purposes. It is made on the example of production of animal breeding products, particularly milk production. In the example, droppings of animals are the main residuals. It is of great importance to process them, as the droppings can cause environmental pollution.

2 Description of the Technology of Biomass Utilization by Means of Methane Fermentation

Anaerobic fermentation is usually used for utilization of animals' droppings to produce ecologically clean and biologically active fertilizers of high quality and an "energy-rich" product, i.e. biogas (Table 1) [2]. The obtained biogas can be used for production of thermal and electric energy in heating installations, which operate in cogeneration regime, supplying 90% efficiency of gas fuel transformation.

Table 1 Comparative energy indicators of traditional power carriers and biogas

Product	Measuring unit	Equivalent 1 m^3 of crude biogas 23 MJ m^{-3}	Equivalent 1 m^3 of processed biogas 35.7 MJ m^{-3}
Electric energy	kWh	0.62	0.95
Natural gas	m^3	0.61	0.94
Coal	kg	0.82	1.27

As it is seen in Table 1, biogas is of high energy value, as compared to traditional kinds of energy, proving prospects of development of biogas technologies in agrarian sector of the economy. To improve energy indicators of biogas, it is reasonable to make its further processing to supply raise of energy efficiency in more than 1.5 times.

Application of biogas makes not just energy effect, but also ecological one, which can be qualitatively revealed in the form of prevention of expenses for measures concerning recovery of environmental parameters and sale of quotas for carbon dioxide (CO_2) emission.

Application of the technological process of anaerobic fermentation is the most often used technology of biomass utilization. Structural scheme of the process is demonstrated by Fig. 1.

Process of anaerobic fermentation is a result of activity of anaerobic microorganisms. Intensity and efficiency of the process of anaerobic fermentation depends on regimes of its progress, which are divided into three kinds, depending on temperature in a methane tank: psychrophilic—up to 20 °C; thermophilic—from 48 to 51 °C; and mesophilic—from 25 to 45 °C [3].

Thermophilic process is characterized by a higher specific gas outcome per a unit of solid weight of a product, but it needs twice more energy expenses in production process, as compared to mesophilic one, because of the necessity to heat the mass before digestion and support the temperature in the reactor.

Thus, in the present research, the variant of anaerobic fermentation of animals' droppings with mesophilic regime is taken as a base, because it is more saving in terms of rational use of energy resources to support technological process of biomass utilization under conditions of moderate continental climate.

Figure 2 presents the most widely spread scheme of biogas installation for conversion of animals' droppings and utilization of the obtained biogas in cogeneration unit [4].

It is worth mentioning that efficient process of anaerobic fermentation of biomass in different temperature regimes requires application of certain kinds of bacteria. In its turn, they need a permanent microbiological examination.

Technical base for implementation of the technology of anaerobic fermentation is presented by methane tanks, equipped with devices of automatic mixing of substrate and its heating with application of different kinds of energy, mainly low-potential heat, including the one with application of the produced biogas.

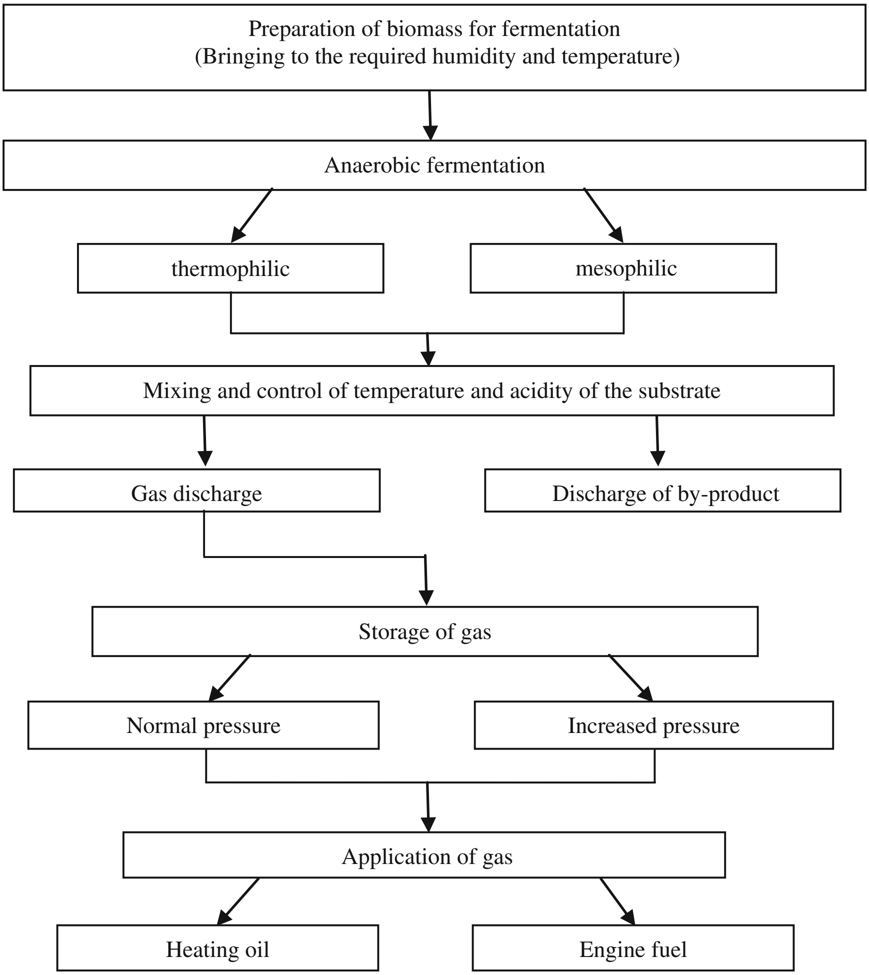


Fig. 1 Biomass utilization by means of anaerobic fermentation (biogas production)

Process of gas production is a biological one and thus, it is necessary to support stability of both temperature regimes and a regime of supply of fresh substrate with its previous processing.

Variant of utilization of animals' droppings at a dairy farm is considered as an example. Cows' droppings are the main kind of residuals at such enterprise and are taken for anaerobic processing in biogas installation.

The authors make economic and energy assessment to estimate efficiency of application of biogas technology of animals' droppings processing with obtaining and utilization of energy product, i.e. biogas.

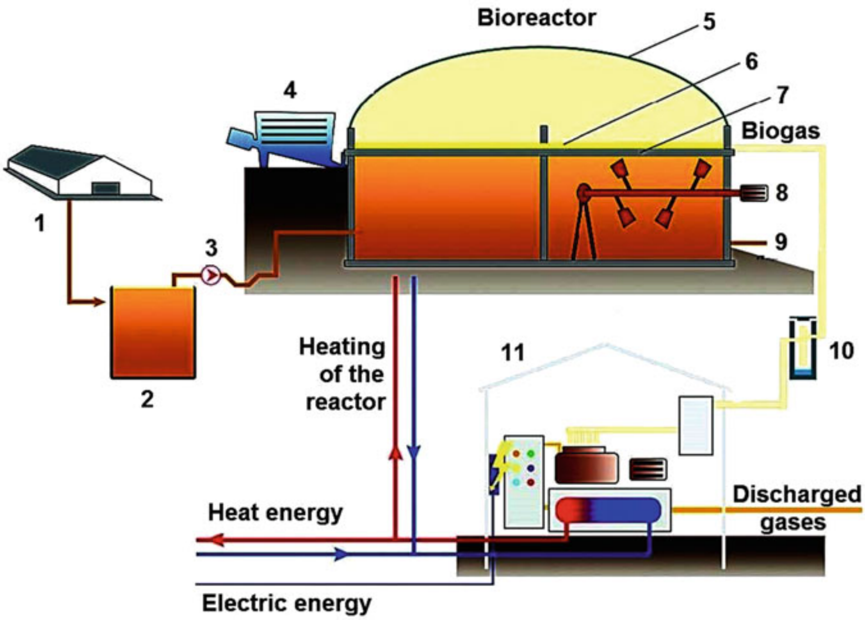


Fig. 2 Scheme of biogas installation with cogeneration unit of biogas utilization: 1—farm; 2—container for collection and homogenization of liquid raw materials; 3—pump station; 4—auger loader of solid raw material; 5—gasholder; 6—insulation; 7—beam ceiling; 8—mixer; 9—tube for discharge of fermented mass; 10—condensate water discharge; 11—cogeneration unit

3 Economic Assessment of the Technology of Biomass Utilization by Means of Anaerobic Fermentation

Integral assessment of economic efficiency of biomass utilization by means of anaerobic fermentation is represented by cost price of a unit of the obtained thermal and electric energy, as well as biologically active fertilizers.

Costs of a unit of energy is determined as a ratio of total expenditures, minus costs of by-products and additional financial income, to the amount of produced energy. The indicator will substantially depend on capacity of the enterprise, kind of the process of anaerobic fermentation, type of primary raw material, etc.

Costs of a unit of energy of cows' droppings utilization in biogas installation with application of the obtained biogas for generation of thermal and electric energy in cogeneration regime will be determined by the formula:

$$C_{en} = \frac{C_p - C_{of} - C_{CD}}{C_t}, \text{ [EURO]} \tag{1}$$

where

C_{en} costs of a unit of energy, EURO,
C_p expenditures for supply of energy production, EURO,
C_{of} costs of organic fertilizers sale, EURO,
C_{CD} money income from sale of quotas for carbon dioxide, EURO,
C_t costs of produced electric and thermal energy, EURO.

Expenditures for supply of energy production are determined as costs of raw materials, depreciation charge for equipment and buildings, wages of employees, costs of the energy, used for support of fermentation process, costs of materials, costs of maintenance and repair, transport, overheads, and other expenditures, and also expenses for storage of raw materials and obtained products, determined according to generally approved methodology.

Costs of primary raw materials and products of anaerobic processing, i.e. organic fertilizers, are argued by their market price.

Annual amount of obtained droppings of animals (in dry organic matter—DOM), is determined according to the following dependence:

$$N_{ad} = n_{an} \cdot \beta \cdot C_1 \cdot C_2 \cdot D_y, \ [\mathrm{kg}] \tag{2}$$

where

N_{ad} annual amount of obtained droppings of animals, kg,
n_{an} number of animal (cows),
β daily amount of droppings (DOM) from 1 animal, kg animal^{-1}, for cattle $\beta = 8.5$ [5],
C_1 coefficient of droppings production, characterizing number of animals, kept in closed premises, for cattle $C_1 = 0.62$ [6],
C_2 coefficient of availability, characterizing amount of dung, which can be collected and shipped to biogas installation by technical means, for cattle $C_2 = 0.93$ [7, 8],
D_y duration of a year, day.

Potential amount of obtained energy (electric and thermal) is determined as:

$$E = N_{ad} \cdot \alpha \cdot Q_{ml}, \ [\mathrm{MJ}] \tag{3}$$

where

E amount of obtained energy (electric and thermal), MJ,
α maximum potential of methane formation per 1 kg of dry organic matter (DOM) of dung/droppings, m^3 CH_4 kg^{-1}, for cattle $\alpha = 0.193$ CH_4 kg^{-1} [9],
Q_{ml} low heating power of methane, MJ m^{-3}, constitutes 35.9 MJ m^{-3}.

Using cogeneration installation with biogas as a primary source of energy, and depending on typical size, one can reach the following efficiency of energy transformation in the form of efficiency coefficient: electric (η_e)—from 31 to 43%;

thermal (η_{th})—from 42 to 59%, and general coefficient of efficiency of cogeneration installation—from 80 to 90%.

Thus, amount of produced electric and thermal energy, will respectively constitute

$$E_e = E \cdot \eta_e, \ [\text{MJ}] \tag{4}$$

$$E_t = E \cdot \eta_{th}, \ [\text{MJ}] \tag{5}$$

where

η_e, η_{th} electric and thermal coefficient of efficiency of cogeneration installation.

Percentage correlation of the amounts of production of thermal and electric energy depends on structural scheme of installation and on the complex capacity [10]. Production expenses in costs are distributed proportionally to the amount of produced kind of energy; "green" tariff is considered in calculation of electric energy, but not considered in calculation of thermal one.

The authors of the article have studied costs of a unit of energy with application of the technology of biogas production of animals' droppings at a dairy farm with typical size of 600 cows, and next combustion of the biogas in cogeneration installation for producing of electric and thermal energy. Initial data and results of the calculations are presented in Table 2.

Process of energy production will also result in formation of high quality fertilizer and its costs can be considered as economic effect. However, one should consider legal and restrictive factors of immediate application of biologically active fertilizers, produced by methane fermentation.

4 Ecological Assessment of the Technology of Biomass Utilization by Means of Anaerobic Fermentation

Money revenues from sale of quotas for carbon dioxide emission are determined as a product of the amounts of prevented production of the exhausts and price of a quota unit.

In case of biogas installation with cogeneration module, the indicator is calculated by comparing of their annual average thermal productivity, revealed in MJ, and amount of saved fuel, revealed in conditional tons or kg. Amount of conditional fuel in kg is calculated according to its lowest heat of combustion with consideration of efficiency coefficient of a corresponding boiler.

$$m_{cf} = \frac{Q_{th}}{\eta \cdot q_{low}}, \ [\text{kg}] \tag{6}$$

Table 2 Calculation of the indicators to assess efficiency of application of the technology of biomass anaerobic fermentation

Indicators	Unit	Value
Amount of primary raw materials	Mg	246,763.36
Costs of primary raw materials	EURO	74,029.01
Balanced costs	EURO	302,672.59
Depreciation	EURO	30,267.26
Maintenance	EURO	30,267.26
Labor payment	EURO	28,551.13
Exploitation expenses	EURO	15,635.14
Overheads	EURO	68,052.10
Total production expenditures	EURO	595,761.72
Amount of produced energy total	MJ	1,861,119.14
Amount of energy for proper needs	kWh	185,683.75
Costs of energy for proper needs	EURO	348,959.82
Residual amount of energy	MJ	1,302,783.40
Yield of electric energy	kWh	433,826.87
Yield of thermal energy	MJ	756,917.16
Amount of prevented emission CO_2 electric energy	Mg	155.09
Amount of prevented emission CO_2 thermal energy	Mg	105.20
Costs of prevented emission CO_2 electric energy	EURO	44,977.01
Costs of prevented emission CO_2 thermal energy	EURO	30,511.34
Costs of electric energy	EURO	402,976.97
Costs of thermal energy	EURO	327,002.67
Total costs of energy	EURO MJ^{-1}	0.003
Costs of electric energy	EURO kWh^{-1}	0.012
Costs of thermal energy	EURO MJ^{-1}	0.003

Source Own elaboration

where

m_{cf} amount of conditional fuel, kg,
Q_{th} annual average thermal productivity, MJ,
η consideration of efficiency coefficient of a corresponding boiler,
q_{low} lower heating value of conditional fuel, MJ kg^{-1}.

Energy coal, with carbon as the main combustible component, is a physical equivalent of a conditional ton. To determine amount of carbon dioxide, the authors present equation of carbon combustion reaction:

$$C + O_2 = CO_2, \tag{7}$$

where:

C carbon, kg,
O_2 oxygen, kg,
CO_2 carbon dioxide, kg.

According to the known atom weight of the elements—14, 32 and 44 respectively, it is determined that combustion of 14 kg of carbon results in 44 kg of carbon dioxide. Thus, considering correlation (6), application of thermal energy installation prevents emission of carbon dioxide into air, and its weight is calculated by the formula:

$$M_{th} = \frac{m_{cf} \cdot 44}{14} = 1.1 \cdot m_{cf}. \text{ [kg]} \tag{8}$$

where

M_{th} weight of carbon dioxide emission, kg.

Let us determine money estimation of reduction of CO_2 emission by implementation of quotas for emission.

Costs of quotas for CO_2 emission can be determined by the formula (using heating installation):

$$C_{CD}^{th} = M_{th} \cdot C_{ecd}, \text{ [EURO]} \tag{9}$$

where

C_{CD}^{th} costs of quotas for CO_2 emission, using heating installation, EURO,
C_{ecd} price of a quota for CO_2 emission, EURO Mg^{-1}. An average world price makes $C_{ecd} \approx (8 - 10) \times 10^{-3}$ EURO Mg^{-1}.

Similarly, one can make calculation for the system of utilization of electric energy with the use of cogeneration installation.

Amount of conditional fuel, which is saved in a year, is calculated by multiplying of annual average productivity of cogeneration installation and coefficient of electric energy substitution:

$$m_{cfe} = 0.351 \cdot W_e^y, \text{ [kg]} \tag{10}$$

where

m_{cfe} amount of conditional fuel, kg, 0.351—coefficient of electric energy substitution,
W_e^y annual average productivity of cogeneration installation, kWh.

Use of cogeneration installation prevents emission of carbon dioxide into air, and its weight is calculated by the formula:

$$M_e = \frac{0.351 \cdot W_e^y \cdot 44}{12} = 1.287 \cdot W_e^y. \text{ [kg]} \qquad (11)$$

where

M_e weight of prevented emission of carbon dioxide into air, using cogeneration installation, kg.

Costs of quotas for CO_2 emission can be calculated by the formula (using electricity generating unit):

$$C_{CD}^e = M_e \cdot C_{ecd}, \text{ [EURO]} \qquad (12)$$

where

C_{CD}^e costs of quotas for CO_2 emission, using electricity generating unit, EURO.

Thus, total income from sales of quotas for CO_2 emission can be calculated according to the formula:

$$C_{CD} = C_{CD}^{th} + C_{CD}^e, \text{ [EURO]} \qquad (13)$$

where

C_{CD}^e total income from sales of quotas for CO_2 emission, EURO.

5 Conclusions

Results of the calculations prove efficiency of operation of biogas installation with cogeneration module, costs of electric energy, produced on it, constitutes 0.012 EURO kWh^{-1} and thermal energy—0.003 EURO MJ^{-1}. The price is almost six and four times lower than market price, respectively.

Annual economic effect of biogas production will be assessed after receiving of money income from sales of electric and thermal energy, and will constitute 730,013.6 EURO.

Development of biogas technologies for agricultural enterprises is particular prospective direction of production activity due to the fact that costs of thermal and electric energy of biogas is substantially lower than traditional kinds of energy, and ecological effect of environmental protection is substantial, because of reduction of greenhouse gases emission and, thus, decrease of expenses for maintenance of population's health and fall of death rate.

References

1. Syrotiuk, K., Ruszel, M.: Energetyczny potencjał biomasy rolniczo-przemysłowego kompleksu obwodu Lwowskiego [Energy potential of biomass of agro-industrial complex in Lviv region]. In: Bezpieczeństwo energetyczne na wspólnym rynku energii UE, red. S. Gędek, S. 297–309. (Wydawnictwo Rambler, Warszawa, 2015)
2. Energetika: istoriya, nastoyashchee i budushchee. [Energy: history, present and future]. T. 4. Vozobnovlyaemaya energetika. Funktsionirovanie i razvitie energetiki v sovremennom mire. 612 s. Kiev (2010)
3. Ratushnjak, Gh.S., Dzhedzhula V.V., Anokhina, K.V.: Energhozberighajuchi vidnovljuvaljni dzherela teplopostachannja. [Energy saving renewable sources in heating]. 170 s. Vinnycja: VNTU, (2010)
4. Tekhnologhiji ta obladnannja dlja vykorystannja ponovljuvanykh dzherel energhiji v siljsjkoghospodarsjkomu vyrobnyctvi. [Technologies and equipment for use of renewable energy sources in agriculture]. Posibnyk za red. Kravchuka V.I., Dubrovina V.O. 184 s. Doslidnycjke: UkrNDIPVT im. L. Poghorilogho (2010)
5. Vykhid bioghazu z riznykh vydiv substrativ [Biogas yield from various types of substrates] http://www.biteco-energy.com/vyhod-biogaza-iz-razlichnogo-syrya-2. Last accessed 16 June 2017
6. Zabarnyj, Gh.M., Shurchkov, A.B.: Energhetychnyj potencial netradycijnykh dzherel energhiji Ukrajiny [Energy potential of renewable energy sources in Ukraine]. ITTF NAN Ukrajiny, Kyjiv, s. 211 (2002)
7. Geletuha, G.G., Marcenju, Z.A.: Jenergeticheskij potencial biomassy v Ukraine [Energy potential of biomass in Ukraine]. Promyshlennaja teplotehnika, T. 20. № 4. S. 52–55 (1998)
8. Tytko, R., Kalinichenko, V.: Vidnovljuvani dzherela energhiji [Renewable Energy Sources]. S. 532. QWG, Varshava (2010)
9. Nacional'nyj kadastr antropogennyh vybrosov iz istochnikov i absorbcii poglotiteljami parnikovyh gazov v Ukraine za 1990-2013 gg [National inventory of anthropogenic emissions by sources and absorption of greenhouse gases in Ukraine in 1990–2013]. 569 s. Kiev, Min-vo jekologii i prirodnyh resursov Ukrainy (2015)
10. TEDOM Group http://kgu.tedom.com. Last accessed 16 June 2017

Stimulatory Impact of Stymjod on Sorghum Plant Growth, Physiological Activity and Biomass Production in Field Conditions

Zdzislawa Romanowska-Duda, Mieczyslaw Grzesik and Regina Janas

Abstract The effects of a new generation ecological nano-organic-mineral fertilizer Stymjod made by PHU Jeznach Sp.J., Poland [1], applied 1 and 2 times to sorghum (*Sorghum bicolor* L.) plants at concentration of 0.1–3.0% on their growth in field conditions and physiological activity were studied, in order to explore the possibility of increasing energy biomass yield. Stymjod applied to plants, greatly increased dynamics of their growth, fresh and dry biomass yield. These improvements were associated with a greater activity of the selected physiological events which make the essential impact on plant development and production of biomass, including activity of enzymes: acid (pH = 6.0), alkaline (pH = 7.5) phosphatase, RNase and dehydrogenase. The growth of plants was related to the increased physiological activities in leaves, measured by the index of chlorophyll content, net photosynthesis, transpiration and stomatal conductance and intercellular CO_2 concentration. The increased growth of sorghum plants and their biomass yield were determined by the percentage and number of applications of the studied biological compound to leaves. Stymjod applied to plants at concentration of 1.5–3% was most effective in increasing the plant growth, fresh and dry biomass yield and physiological activity in leaves than 0.1–0.75%. Similarly, its double application was more effective in improving growth of plants. The positive effect of Stymjod on development, biomass yield and physiological activity of plants indicates its suitability in sorghum cultivation, which may limit the use of synthetic fertilizers, favorably affect the environment and reduce the amount of toxic substances in plants.

Z. Romanowska-Duda (✉)
Laboratory of Plant Ecophysiology, Faculty of Biology and Environmental Protection, University of Lodz, Str. Banacha 12/16, 92-237 Lodz, Poland
e-mail: romano@biol.uni.lodz.pl

M. Grzesik · R. Janas
Department of Nursery and Seed Research, Research Institute of Horticulture, ul. Konstytucji 3 Maja 1/3, 96-100 Skierniewice, Poland
e-mail: mieczyslaw.grzesik@inhort.pl

R. Janas
e-mail: regina.janas@inhort.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_24

Keywords Sorghum · Growth · Biomass production

1 Introduction

Integrated and ecological production of crops, which limits the using of fertilizers and pesticides, is becoming a top issue in the agriculture, including production of foods and energy biomass round the world. Most of attempts in this production focus on gaining of the high yield of plants which are free of toxic pollutants and do not contaminate the environment after the crop processing. These demands is becoming more important at present, due to the increased needs for healthy food manufacturing and production of a large amount of biomass which is transferred to energy and after this processing, the obtained from them waste goes into the environment. Thus, in order to reduce pollution of the environment and of plants with toxic substances there are attempts to replace synthetic fertilizers and pesticides with the biological agents that favorably increase the growth, health and yield of plant biomass and have no harmful effects on consumers [2].

Among the many biological agents applied to plants, in order to accelerate their growth and increase yielding, a lot of interest in horticulture is paid to Biojodis and lately to Stymjod, which is the new generation ecological nano-organic-mineral fertilizer (PHU Jeznach Sp.J., Poland [1–3]. Foliar application of Biojodis was beneficial for the growth of many plants of horticultural species [4]. Its application to corn plants stimulated their growth and alleviates the adverse effects of hydrothermal stress [2]. Applied to Virginia fanpetals (*Sida hermaphrodita* L.) plants accelerated growth and biomass yield [3]. Stymjod is a new generation nano-organic-mineral fertilizer, produced in recent years and it is an improved form of Biojodis. It contains several macro- and micronutrients, organic substances and water iodine concentrate (I_n^+) which are particularly important for proper plant growth and development (Table 1).

So far, the studies and field trials have shown its stimulating effect on the growth of some horticultural and agriculture species plants, including maize [2]. According to manufacturer's recommendation it can be used as foliar application to plants alone or with soil improver Apol-humus (Poli Farm, Sp. Z o.o., Poland) which should be applied to ground [1]. Scientific data concerning the impact of Stymjod on growth, yielding of plants and their physiological activity in particular species are still very scant, because the compound is still being tested and initially placed on the market and therefore further research is needed in this area.

Table 1 Macro- and micronutrient content (%) in Stymjod, containing an additional 48.8% of organic substance (including amino acids and other organic compounds) and 0.0025% (80 mg L H_2O^{-1}) of water iodine concentrate

Macro- and micronutrient content (%)											
N	K_2O	P_2O	CaO	SO_4	MgO	Fe	Mn	Cu	Mo	Zn	B
6.3	13.2	5.3	0.17	2.9	2.7	0.21	0.23	0.11	0.045	0.27	0.12

Due to the lack of information concerning the impact of Stymjod on energy plant growth and yielding of its biomass, the aim of the presented research is to evaluate the effects of foliar application of this biological compound on growth of sorghum plants in field conditions and their physiological activity.

2 Experimental Method and Setup

The commercial seeds of sorghum (*Sorghum bicolor* L.), obtained from the plant breeding company in Poland (Kutnowska Hodowla Buraka Cukrowego, Kutno), were sown to the sandy soil in the field conditions, according to the procedure used in production of this species.

The separate plots of plants grown under field conditions were once, and double sprayed, in three week intervals, with Stymjod (a new generation ecological nano-organic-mineral fertilizer; PHU Jeznach Sp.J., Poland) [1] at concentrations of 0.1, 0.75, 1.5 and 3.0%. The concentrations were chosen on the base of the manufacturer's recommendations and on the previous laboratory studies performed in Phytotoxkit tests.

For each treatment three replicates, in three series, were prepared and every replicate contained 30 plants grown in the separate plots, arranged in the system of random blocks. Plant exposure period were kept for the all vegetative season up to the winter.

3 Experiment Stages Description

The influence of foliar application of Stymjod on sorghum plant growth and physiological activity was evaluated on the base of measurements of the plant height (a few times during vegetation), index of chlorophyll content, gas exchange (activity of net photosynthesis, transpiration, stomatal conductance and concentration of intercellular CO_2), activity of acid and alkaline phosphatase, RNase and total dehydrogenases in leaves. Plant height was measured with ruler from soil to the top of plants [5]. Index of chlorophyll content in leaves was evaluated using Minolta SPAD-502, Japan [4]. Gas exchange (activity of net photosynthesis, stomatal conductance, intercellular concentration of CO_2 and transpiration) were evaluated using the gas analyzer apparatus TPS-2 (PP Systems, USA) [5]. Activity of acid and alkaline phosphatase and RNase in leaves were studied according to methods described by Knypl and Kabzinska [6]. The measurement of activity of total dehydrogenases were based on the fact that 2,3,5-triphenyl tetrazolium chloride (TTC) interacts with the reduction processes of living cells and accepts hydrogen from dehydrogenases. By hydration of the TTC a red, stable and non-diffusible substance, triphenyl formazan is produced in living cells [7]. The samples of leaves were placed in Eppendorf tubes, ground and incubated in 1 ml of 0.1 M sodium phosphate buffer, pH 7.2 containing 0.7% (w/v) of 2,3,5-triphenyl tetrazolium chloride at 25 °C for 24 h. After that time samples were centrifuged and the pellet was extracted six times with 1 ml of acetone. The solution absorbance was measured at 488 nm. A standard curve was prepared from a known concentration of formazan. Each determination was made four times [8].

4 Statistical Analysis

The results regarding plant height, index of chlorophyll content, gas exchange and activity of enzymes were analysed using analysis of variance. The means were separated using Duncan multiple range test (LSD) at an alpha level of 0.05.

5 Results and Discussion

The obtained results showed that the studied sorghum plants were very sensitive to the applied ecological compound Stymjod. This compound, applied at the concentrations of 0.1, 0.7, 1.5 and 3% to plants greatly increased their height and physiological activity, exhibited by index of chlorophyll content, gas exchange (activity of net photosynthesis, transpiration, stomatal conductance and concentration of intercellular CO_2), activity of acid and alkaline phosphatase, RNase and total dehydrogenases (Figs. 1, 2 and Tables 2, 3). The accelerated growth and improved physiological activity have resulted in increased yield of fresh and dry biomass (Fig. 2). Double application of Stymjod to plants at concentration of 0.1–3.0% were most effective than once use, especially at the end of growing season, when probably the accumulation of the used compound in plants was higher (Fig. 1). Also, sprayings of plants with Stymjod at concentration of 1.5–3.0% were most profitable than treatments with 0.1–0.7% (Figs. 1, 2 and Tables 2, 3).

The obtained findings in sorghum are in agreements with the general manufacturer's recommendation. It indicate that Stymjod increases biomass growth, improves plant resistance to unfavorable weather conditions and alleviates the negative effects of stress [1]. Stimulating impact on the plant development and physiological activity could be caused by iodine, macro and micronutrients, amino acids and other organic compounds, which are present in Stymjod. Positive impact of macro and micronutrients and other organic compounds on plant development is well described in literature [2–5, 8]. There is less information about the role of iodine. Unlike many other biostimulators, Stymjod is manufactured according to a modern recipe and contains iodine, which makes this preparation more effective. According to Smolen et al. [9], the influence of iodine on the content of P, K, Mg, Ca, S, Na, B, Cu, Fe, Mo, Mn and Zn in plants can be varied depending on their applied form, as it was found in the leaves and fruits of tomato. Iodine alone, added to ground at dosage of 1 and 2 mg I dm^{-3} of soil, applied individually or together with sucrose did not significantly affect spinach yield and the level of nitrate, phenolic compounds and soluble sugars in plants, as well as iodine content in soil

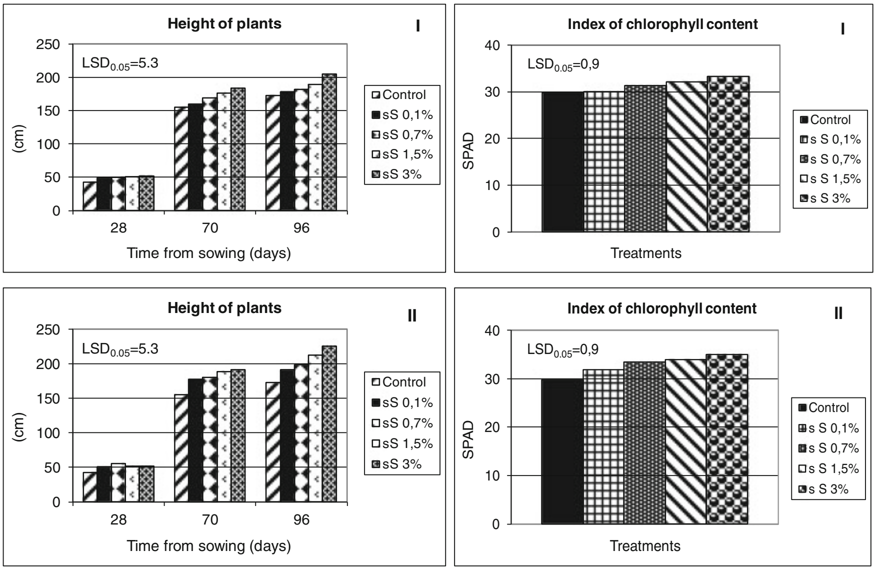


Fig. 1 Height of sorghum (*Sorghum bicolor* L.) plants grown in the field conditions and index of chlorophyll content in leaves, as affected by once (I) and double (II) foliar sprays with Stymjod at concentration of 0.1–3.0%. The LSD were calculated at the significance level of $p = 0.05$

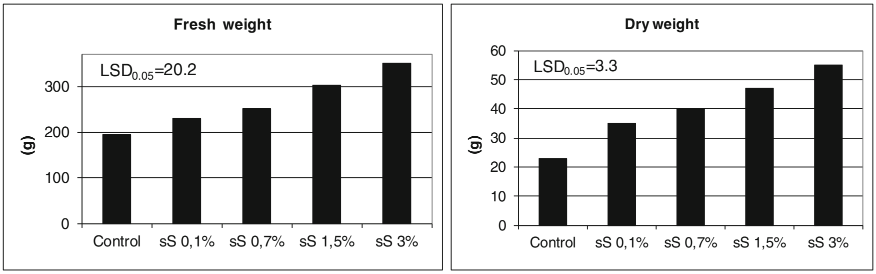


Fig. 2 Fresh and dry biomass of sorghum (*Sorghum bicolor* L.) plants grown in field conditions, as affected by double foliar sprays of plants with Stymjod at concentration of 0.1–3.0%

after cultivation [10]. On the other hand the studies on *Eschericha coli* extracts [11] and on marine phytoplankton [12, 13] indicated that iodine affect the nitrogen metabolism in tissues which is essential in plant productivity.

The research shows that Biojodis (containing iodine and other nutrients) had a significant impact on the growth and development of certain tissues and metabolic processes. Among others, the vascular tissue of plants positively reacted to its foliar application. Conductive bundles (phloem and xylem) increased their diameter and the cell walls were noticeably thickened [4]. Iodine I_n^+ collected by the plant is cumulated mostly by the leaves (59–61%) and directly used there in biochemical

Table 2 Activity of the selected enzymes in sorghum (*Sorghum bicolor* L.) leaves, as affected by double foliar application of Stymjod, at concentration of 0.1–3.0%, to plants grown in field conditions

Conc. of Stymjod %	Phosphatase (pH = 6.0) U g^{-1} f.w.	Phosphatase (pH = 7.5) U g^{-1} f.w.	RNase U g^{-1} f.w.	Total dehydrogenase mg formazan × g $leaf^{-1}$
0 (Control)	0.61 a*	0.26 a	2.8 a	0.55 a
0.1	0.64 b	0.30 b	3.3 b	0.60 b
0.7	0.66 c	0.33 c	3.5 c	0.66 c
1.5	0.87 d	0.37 d	3.8 d	0.76 d
3.0	1.02 e	0.41 e	4.8 e	0.81 e
$LSD_{0.05}$**	0.009	0.006	0.07	0.04

*The data marked with the same letters, within column, are not significantly different, according to Duncan multiple range test at an alpha level of 0.05

**The LSD were calculated at the significance level of $p = 0.05$

Table 3 Activity of the gas exchange parameters in sorghum (*Sorghum bicolor* L.) leaves, as affected by double foliar application of Stymjod, at concentration of 0.1–3.0%, to plants grown in field conditions

Conc. of Stymjod (%)	Net photosynthesis (μm CO_2 m^{-2} s^{-1})	Transpiration (mmol H_2O m^{-2} s^{-1})	Stom. cond. (mmol H_2O^{-1} M^{-2} s^{-1})	C inter. CO_2 (μmolCO_2 mol^{-1})
0 Con.	4.8 a*	1.32 a	453 a	298 e
0.1	5.1 b	1.37 b	464 b	290 d
0.7	5.4 c	1.42 c	507 c	278 c
1.5	5.7 d	1.67 d	551 d	265 b
3.0	6.2 e	1.75 e	595 e	249 a
$LSD_{0.05}$**	0.02	0.04	42	11

*The data marked with the same letters, within column, are not significantly different, according to Duncan multiple range test at an alpha level of 0.05

**The LSD were calculated at the significance level of $p = 0.05$

processes. The remaining amount of iodine is transported with assimilates in phloem to stems and roots (19–20%) and to bark (20–21%) [14]. Iodine I_n^+ can be permeated also by the root hairs and together with the plant enzymes, enter to the rhizosphere and activate certain types of soil microorganisms. If I_n^+ iodine is applied to soil, the way of its penetration into the plant is inversely similar and begins with the root hairs and accumulate in plants. Iodine ions usually settle in cell walls and participate in biochemical processes [1].

The use of Stymjod, containing iodine concentrate I_n^+ at dosage of 80 ml g L^{-1} of H_2O, resulted in a higher yielding of various cabbage and cucumber varieties. In cabbage 'Chopin F_1' the yield was increased by 4–5% (with lower N fertilization) as compared to control with full N fertilization. The applied formula positively influenced the yield structure. There were a smaller amount of cabbage heads weighting less than 2 kg, in comparison with controls [15]. In the case of canned cucumbers, the commercial yields increased by 10% after Stymjod treatment. The treated cucumbers plants showed greater resistance to wilting and crop yields were more equal, and of higher commercial quality. It was also found that despite limited fertilization, the yield of cucumbers did not decrease. This indicate that the application of Stymjod to plants promise to reduce their fertilization with artificial fertilizers and thus the crops and environment can be less polluted [15].

The performed research showed that the Stymjod foliar application improve physiological activity in sorghum plants, their growth and yield of biomass and thus this compound can be recommended to use in the studied crop production. The studies also showed that the tests used for physiological activity measurements are very useful in the performed studies and they can be the valuable markers of plant quality evaluation [5].

Acknowledgements The research was financed by National Center for Research and Development in Poland, Grant BIOSTRATEG2/296369/5/NCBR/2016.

References

1. P.H.U. Jeznach SPJ. 2017 www.phu-jeznach.com.pl
2. Piotrowski, K., Romanowska-Duda, Z., Grzesik, M.: How Biojodis and Cyanobacteria alleviate the negative influence of predicted environmental constraints on growth and physiological activity of corn plants. Polish. J. of Environ. Stud. **25**(2), 741–751 (2016). https://doi.org/10.15244/pjoes/60894
3. Grzesik, M., Romanowska-Duda, Z.B.: The effect of potential climatic changes, Cyanobacteria, Biojodis and Asahi SL on development of the Virginia fanpetals (*Sida hermaphrodita* L.) plants. Pamiętnik Puławski **151**, 483–491 (2009)
4. Jeznach, A.: Effect of iodine on the cabbage fruits ontogenesis and seed quality. M. Sc. thesis. WSEH Skierniewice, Poland (Pol) 1–68 (2011)
5. Grzesik, M., Romanowska-Duda, Z., Kalaji, H.M.: Effectiveness of cyanobacteria and green algae in enhancing the photosynthetic performance and growth of willow (*Salix viminalis* L.) plants under limited synthetic fertilizers application. Photosynthetica **55**(3), 510–521 (2017). https://doi.org/10.1007/s11099-017-0716-1
6. Knypl, J.S., Kabzińska, E.: Growth, phosphatase and ribonuclease activity in phosphate deficient *Spirodela oligorrhiza* cultures. Biochem. Physiol. Pflanzen. **17**, 279–287 (1977)
7. Pandey, D.K.: Ageing of French bean seeds at ambient temperature in relation to vigour and viability. Seed Sci. Technol. **17**(1), 41–47 (1989)
8. Gornik, K., Grzesik, M.: Effect of Asahi SL on China aster 'Aleksandra' seed yield, germination and some metabolic events. Acta Physiol. Plantarum. **24**(4), 379–383 (2002). https://doi.org/10.1007/s11738-002-0033-5
9. Smoleń, S., Sady, W. Wierzbinska, J.: The effect of KI and KO_3 fertilization on iodine uptake, efficiency and content of mineral elements in leaves in tomato cultivated in hydroponics (NFT System). Ochrona Środowiska I Zasobów Naturalnych **48** (2011)
10. Smoleń S., Sady W.: Influence of iodine fertilization and soil application of sucrose on the effectiveness of iodine biofortification, yield, nitrogen metabolism and biological quality of spinach. Acta Sci. Pol., Hortorum Cultus **10**(4), 51–63 (2011)

11. Tsunogai, S., Sase, T.: Formation of iodide-iodine in the ocean. Deep-Sea Res. **16**, 489–496 (1969)
12. Wong, G.T.F., Hung, C.C.: Speciation of dissolved iodine: integrating nitrate uptake overtime in the oceans. Cont. Shelf Res. **21**, 113–128 (2001)
13. Hung, C.C., Wong, G.T.F., Dunstan, W.M.: Iodate reduction activity in nitrate reductase extracts from marine phytoplankton. Bull. Mar. Sci. **76**(1), 61–72 (2005)
14. Strzetelski, P., Smoleń, S., Rożek, S., Sady, W.: The effect of diverse iodine fertilization on nitrate accumulation and content of selected compounds in radish plants (*Raphanus sativus* L.). Acta Sci. Pol. Hort. Cult. **9**(2), 65–73 (2010)
15. Babik, J.: Evaluation of the suitability of Biojodis for use in vegetable cultivation. Report of the Research Institute of Vegetables Crops in Skierniewice, Poland (Pol) 1–9. (2006)

Effect of Storing on Fertilizing Properties of Sewage Sludge

Marcin Landrat

Abstract The disposal of sewage sludge may be combined with its economic utilization. It depends on the physical, chemical and microbiological characteristics of the substance and the manner of sludge treatment. Organic, but also inhibiting substances (pathogenic microorganisms, heavy metals, etc.) included in the sludge may determine the manner of its management or disposal, e.g. through agricultural utilization or combustion. In case of agricultural utilization, this manner of sludge management is also influenced by the specificity of agricultural cultivation and periods of the reclamation of agricultural lands. Thus, the problem of periodic storage and the possibility of its effects on changes of sewage sludge properties occurs. The article presents results of research concerning changes of basic fertilizing properties of sludge during its year-long storage in field conditions. The research analysed, among others, changes of the content of organic substance, organic carbon, nitrogen and phosphorus.

Keywords Sewage sludge · Fuel properties · Fertilizing properties

1 Introduction

An important problem of the modern technology of purifying sewage is both managing and processing the sediment which is created during these processes. Constructing new wastewater treatment plants and constant improving the existing ones results in a marked increase in production of side waste—the sewage sludge.

In connection with this, the main aims of managing the communal sewage sludge according to the State Plan of Waste Management (KPGO) for the upcoming years until 2022 are:

M. Landrat (✉)
Department of Technologies and Installations for Waste Management,
Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland
e-mail: marcin.landrat@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_25

- limiting the storage of the sewage sludge,
- increasing the number of both the communal sewage sludge processed before introducing into the environment and transformed with the aid of thermal methods,
- maximizing the degree of using biogenic substances in the sludge when remembering about all the safety regulations—the sanitary, chemical and environmental ones [1].

Disposing and managing the sludge ought to be conducted in a way which does not threaten the natural environment or harm the health or life of the live forms. The possible ways of using and disposing can be natural:

- natural use of the sludge,
- composting,

or thermal:

- burning and co-burning the waste,
- wet oxidizing,
- pyrolysis,
- gassing [2].

Most popular methods of sludge utilization are its use as fertilizer in agriculture and recultivation, thermal treatment (incineration, co-combustion, pyrolysis process) and landfilling.

In recent years thermal methods of sludge utilization in Europe were used in following countries: Netherland (95% of sludge thermally treated), Switzerland (90%), Germany (over 50%), Belgium (about 50%), Austria and Slovenia (about 35%). In the same time in other countries only small amounts of sludge are incinerated or are not utilized at all [3].

The literature sources dealing with sewage sludge utilisation are really extensive, but there are not much publications referring to the change of parameters of the sludge in time of its storage [3]. There are publications about the change of the number of pathogenetic microorganisms [4, 5] or about the influence of liming of sludge on its parameters in time or the influence of liming on the soil [6–8].

Communal sewage sludge is a source of floral nutrition ingredients and has strong soil creating features. When introduced into the upper layers of soil they enrich it with biological activity, typical for fertile soil. Content of organic substance and mineral fertilisers such as nitrogen, phosphorus, calcium and macroelements decide about the soil creating and fertilising features of the sludge. Organic substances in the sludge are the source of nutrients necessary for development of microorganisms, which decide about the soil's life and about plants' vegetation.

The sewage sludge differs when it comes to the fertility value and is similar to mineral fertilisers and in some ways to the farmyard manure.

The content of fertility components greatly depends on the manner and degree of its stabilisation. In excessive raw sediments, nitrogen usually makes 4–8% of dry mass while in the introductory raw sediments it makes even more than 8% of dry mass and in the one stabilised by the metan fermentation the value of nitrogen is lower—usually 2.5–4% of dry mass. To compare, the content of nitrogen in farmyard manure is as high as 0.4–2.8% and in the slurry about 3.5–6.7% of dry mass.

Content of phosphorus is comparable or higher than in the typical organic fertilizers (in the sludge about 2–3%, in organic fertilisers about 2%, in the farmyard manure 1.2% of dry mass) [9].

The content of organic substance in the sludge is:

- 75–85% of organic substance in dry mass of raw sludge,
- about 50% of organic substance in dry mass in stabilised sludge [10].

As it was mentioned before, the content of organic substance in the sewage sludge is the main indicator proving its usefulness in improving the soil's structure.

Unfortunately the plant vegetation excludes using the fertilizers for all year long. The periodicity of using the sludge in farming makes it necessary to examine the change in the substance's content in the time of storing the sludge for a long time [11, 12]. That is why the examination in the Department of Technologies Installations for Waste Management was conducted to determine the physico-chemical changes in the sludge stored [13].

2 Experimental Procedures

The sludge which underwent the examination comes from the wastewater treatment plant in Silesia. The plant functions as a mechanic-biological one and uses the multi phase process of active sediment to remove organic carbon, phosphorus and nitrogen from the sewage being purified. The plant is considered to belong to the group of big plants (above 100,000 RLM) with a high degree of purifying and the capacity of 33.400 m^3/d.

The sludge under examination underwent the process of fermentation, was de-gassed and dehydrated in high speed separators. The dehydrated sludge with dry mass of 25% was subjected to calcium hygienisation, put into two containers and stored there in conditions similar to natural (Fig. 1).

Test samples were taken from the center of container (points 2 and 4) and from the top layer of the sludge (points 1 and 3). First container was analysed by 8 months and the second one by 12 months. The sludge was analysed to determine the content of:

- humidity,
- general nitrogen,
- organic carbon,
- overall phosphorus,
- overall content of organic substances,

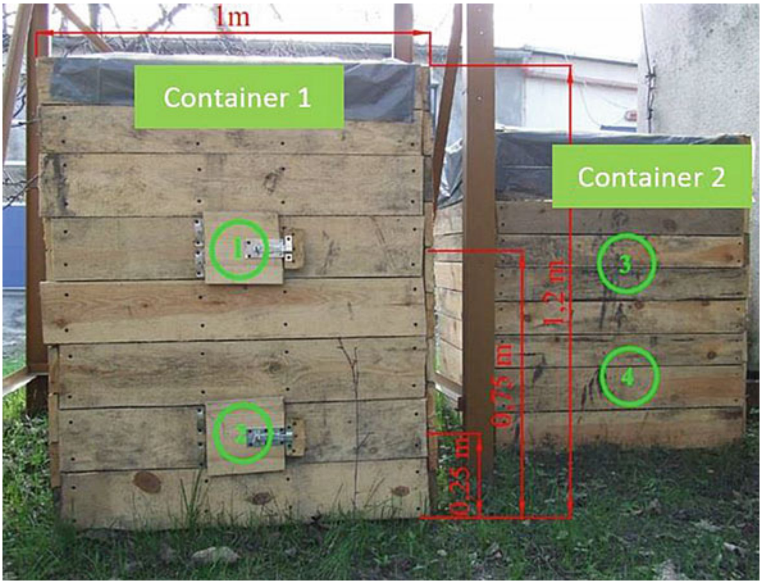


Fig. 1 Containers used for testing

- humic substances,
- chlorides,
- pH.

All tests were carried out in accordance with valid Polish Standards [14–20].

3 Results and Discussion of Results

Detailed results were presented in the Table 1.

The analysis of the examination shows that the length of storage has no meaningful influence on the sludge under observation. There are some changes in the content of general organic substance and of humic substance.

Both in the period of 8 and 12 months of storing a big fall in the level of general organic substance was observed. Storing the sludge for a longer period of time influenced in a slight way the content of humic substances, causing their increase to about 7.5% in the sludge stored for 8 months and to about 8% in the one stored for 12 months. This increase improves the efficiency of soil-creating sediment during its storing. In the time of storage no marked changes in the level of phosphorus or azote were noticed, but the sediment under examination contained a high level of general phosphorus. These elements can be described as the ones with a changeable tendency, but no important influence of the period of storing was noticed.

Table 1 Beginning and end values of shares of individual analysed components of sludges at the up and down of containers

Determination	Sludge in the container I		Sludge in the container II	
	Down	Up	Down	Up
Humidity [%]	70.38–63.37	71.46–74.78	71.41–62.40	66.86–73.50
Overall nitrogen [%]	3.43–4.08	3.64–4.08	3.89–3.43	3.53–3.68
Organic carbon [%]	22.81–19.59	22.15–19.73	21.55–20.63	22.25–19.15
Overall phosphorus [%]	9.40–8.30	5.01–6.73	7.82–10.91	5.97–10.53
Overall content of organic substances [%]	60.25–50.35	59.75–49.90	61.89–48.85	58.89–50.48
Content of humic substances [%]	6.91–7.53	6.80–7.56	7.17–8.21	7.25–7.96
Chlorides [g Cl^-/kg]	0.76–1.03	0.67–0.76	0.92–0.81	0.78–1.15
pH	6.9–6.4	6.9–6.5	7.0–6.6	7.1–6.4

The analysis of the content of organic carbon in the period of storage indicates an insignificant fall, not influencing the efficiency of the substance under examination.

4 Conclusions

To sum up, the analysis of the sludge in the wastewater treatment plant stored in natural conditions in the period of 8 and 12 months shows no signs of worsening its quality. The sludge is suitable for disposing in farming. It must be remembered that the mere content of fertility ingredients is not the only indicator allowing to introduce the sludge to the ground.

Apart from all this, it is necessary to conduct a detailed investigation of the sample of the sludge to determine the content of heavy metals and sanitary condition. The sludge implemented to the ground must have the right consistency, must not be arduous in terms of smell or create any disease or epidemic threat. In spite of its positive fertility qualities, the sludge is not to have any negative influence on the environment (heavy metals or any disease creating organisms). Another criteria is to check the soil in terms of the presence of heavy metals in the upper layers. It ought to be remembered that every type of sludge has its changeable qualities. That is why it is important to test the sludge sample each time before the application to the ground is going to be conducted.

References

1. Krajowy Plan Gospodarki Odpadami (2014)
2. Miksch, K.: Biotechnologia środowiska. Fundacja Ekologiczna Silesia, Katowice (1995)
3. Kozioł, M., Landrat, M., Ścierski, W.: Changing of thermal properties of sewage sludge during its open-air storage. SET2011. In: 10th International Conference on Sustainable Energy Technologies, Istanbul (2011)
4. Budzinska, K., Jurek, A., Michalska, M., Berlec, K., Szejniuk, B.: Dynamics of changes in bacterial microflora of stored sewage sludge. Rocznik Ochrona Srodowiska **11**, 1155–1164 (2009)
5. Xua, H., Hea, P., Wanga, G., Shaoa, L., Lee, D.: Anaerobic storage as a pretreatment for enhanced biodegradability of dewatered sewage sludge. Biores. Technol. **102**(2), 667–671 (2011)
6. Hillman, J., Hill, J., Wilkinson, J.M.: Effect of season of application on the adhesion, retention and recontamination of herbage by potentially toxic metals and sewage sludge. Sci. Total Environ. **333**(1–3), 283–293 (2004)
7. Torri, R.S., Lavado, S.I.: Dynamics of Cd, Cu and Pb added to soil through different kinds of sewage sludge. Waste Manag. **28**(5), 821–832 (2008)
8. García-Orenes, F., Roldán, A., Guerrero, C., Mataix-Solera, J., Navarro-Pedreño, J., Gómez, I., Mataix-Beneyto, J.: Effect of irrigation on the survival of total coliforms in three semiarid soils after amendment with sewage sludge. Waste Manag. **27**(12), 1815–1819 (2007)
9. Kowalik, P.: Ochrona środowiska glebowego. Wyd PWN, Warszawa (2001)
10. Urbaniak, M.: Przerób i wykorzystanie osadów ze ścieków komunalnych. Wyd Ekoinżynieria, Lublin Łódź (1997)
11. Bień, J.: Osady ściekowe. Teoria i praktyka. Wyd. Politechniki Częstochowskiej, Częstochowa (2007)
12. Skalmowski, K.: Poradnik gospodarowania odpadami. Verlag Dashofer, Warszawa (2009)
13. Górna, A.: Badania właściwości nawozowych osadów ściekowych, Praca dyplomowa magisterska pod kier. M. Landrata, Gliwice (2011)
14. PN-Z-15011-3: 2001. Compost from municipal waste—Determination: pH, organic matter content, organic carbon, nitrogen, phosphorus and potassium (2001)
15. PN-EN 16169: 2012 Sludge, treated biowaste and soil—Determination of nitrogen by the Kjeldahl method (2012)
16. PN-EN 15934: 2013-02 Sludge, treated biowaste, soil and waste—Determination of dry matter by determining the dry matter content or water content (2013)
17. PN-EN 15933: 2013-02E Sludge, treated biowaste and soil—Determination of pH (2013)
18. PN-G-97051-16: 1989, Determination of yield of toluene extract (bitumin), content of resin in the extract and content of humic acids in lignite (1989)
19. PN-EN 14672: 2006P Characterization of sludges—Determination of total phosphorus (2006)
20. PN-ISO 9297: 1994P Water quality—Determination of chloride—Silver nitrate titration with chromate indicator (Mohr's method) (1994)

Utilization of Waste from Methane Fermentation in *Lemnaceae* Plant Breeding Intended for Energy Purposes

Zdzislawa Romanowska-Duda, Krzysztof Piotrowski and Piotr Dziugan

Abstract The increase in environmental pollution caused by waste from agro-food industry and methane fermentation in biogas plants is currently one of the most serious problems. More and more governments launch programs supporting biogas plant construction and conversing biogas into electric energy. One of the methods to utilize the waste from methane fermentation in biogas plants is its utilization as a culture medium for breeding *Lemnaceae* aquatic plants. Water biomass can be diversely used in agriculture, energy production, phytoremediation and as animal feed. The plants *Spirodela polyrrhiza* were cultured in a phytotronic room at 24 °C. The medium was supplemented with various concentrations of leachate coming from the process of methane fermentation from biogas plants. The following physiological parameters were measured (i) plant gas exchange i.e. net photosynthesis (mmol $H_2O/m^{-2}\ s^{-1}$), transpiration (mmol $H_2O/m^{-2}\ s^{-1}$), stomatal conductance (mmol $H_2O\ m^{-2}\ s^{-1}$), and intercellular CO_2 concentration (μmol CO_2 mol air^{-1}), (ii) index of chlorophyll content and (iii) fresh and dry matter. The obtained results justified the use of post-fermentation leachate to supplement the culture medium thus indicating the possible way of its utilization. This method can be an efficient way to recycle waste from methane fermentation in biogas plants, to develop a cost-effective system of high-quality water biomass production with an array of applications in production of liquid and gaseous biofuels, in agriculture (animal feed, fertilizers) and phytoremediation. This will decrease the costs and limit environmental pollution.

Keywords Post-fermentation waste · Water biomass · *Lemnaceae*

Z. Romanowska-Duda (✉) · K. Piotrowski
Laboratory of Plant Ecophysiology, Faculty of Biology and Environmental Protection, University of Lodz, Str. Banacha 12/16, 90-237 Lodz, Poland
e-mail: romano@biol.uni.lodz.pl

P. Dziugan
Faculty of Biotechnology and Food Sciences, Lodz University of Technology, Str. Wólczańska 171/173, 90-924 Lodz, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_26

1 Introduction

Industrial waste poses a global threat to the whole environment i.e. hydrosphere, atmosphere and biosphere. This threat concerns all stages of its presence, during production and collection, transport and utilization as well as during its storage. Rational waste management has become a priority in environmental protection. Industrial waste amounts up to 90% of all waste produced in Poland. Extractive, metallurgical and energetic industries are the major sources (80%) of dangerous and seemingly unusable waste. The way of waste production and its amount largely depend on raw materials, technology, technical advancement as well as ecological culture and ethics. Each type of waste needs a specific, safe technology of its processing. The rising demand for renewable energy and efforts to reduce negative effects of conventional methods of energy production made development of new technologies indispensable. Numerous EU, governmental and local programs boosted the development of biogas industry. Growing amount of energy from plant biomass allowed to develop innovative, environmental friendly at cost-effective technologies. The best way of utilization of agro-food industry waste is to turn it into biogas with the use of methane fermentation which yields post-fermentation leachate. This type of waste may be effectively utilized as a supplement for aquatic plant culture medium. Due to its wide array of applications, *Lemnaceae* became the focus of interest in agriculture, inland water phytoremediation and energy production.

2 Experimental Method and Setup

Lemnaceae (*Spirodela polyrrhiza*) water plants were cultured in vitro in the Laboratory of Plant Ecophysiology, Faculty of Biology and Environmental Protection, University of Lodz. The macrophytes were grown in tap water supplemented with different concentrations (1.5, 2.5 and 5%) of leachate produced during methane fermentation. The control consisted of a standard "Z" medium [1] supplemented with tap water at appropriate concentrations and tap water. The material was cultured in a phytotronic room at 24 °C and continuous light (PHILIPS MASTER TL-D 2 × 18 W/840). The influence of the examined leachate on growth, development and physiological activity of the macrophytes was examined. *Spirodela polyrrhiza* fronds were cultured in 250 ml Erlenmayer flasks with 100 ml of tap water supplemented with different concentrations of the tested post-fermentation leachate. The tests were carried in 5 replicates. The used tests are acknowledged as useful markers of plant metabolic activity and their reaction to external stimuli, which was evidenced in previous research and literature [2].

3 Experiment Stages Description

The influence of application of medium with leachate post-fermentation on aquatic plants *Lemnaceae* growth and physiological activity was evaluated on the base of measurements of the number of fronds (every day during research), index of chlorophyll content, gas exchange (activity of net photosynthesis, transpiration, stomatal conductance and concentration of intercellular CO_2). Kinetics of growth of *Lemnaceae* (*Spirodela polyrrhiza*) was determined on the basis of documentation of the number of all spindle members each day of the bioindication test. All traction members were considered, regardless of their size. Fresh and dry matter were measured on the last day of the experiment by weighing the drained plants. Index of chlorophyll content in fronds of *Spirodela polyrrhiza* was evaluated using Minolta SPAD-502, Japan [3]. Experimental plants (tram stalks) were placed in the camera clip and subjected to radiation through a beam of 650 nm. This was done in a special clip of the device, where a photodetector was used to measure the amount of radiation passing through the tissue to be examined. The principle of operation of the device is based on the measurement of the amount of light that has been absorbed by the chlorophyll. Gas exchange parameters i.e. net photosynthesis (mmol H_2O/m^{-2} s^{-1}), transpiration (mmol H_2O/m^{-2} s^{-1}), stomatal conductance (mmol H_2O m^{-2} s^{-1}), and intercellular CO_2 concentration (μmol CO_2 mol air^{-1}) were assessed with the use of TPS-2, (PP Systems, USA) [4–6].

4 Results and Discussion

The analyses lasted 28 days. Everyday analysis showed that the medium consisting of tap water supplemented with the tested leachate positively affected growth and development of *Spirodela polyrrhiza* (Fig. 1). It seems to be a good alternative for commercial media used to culture macrophytes. The 2.5% concentration proved best with 1.5 and 5% ones being less beneficial. In the tap water control already on 2nd day negative effect of lack of nutrients was observed, growth was inhibited, leaf chlorophyll content was reduced which led to shoot browning and later to death of *Lemnaceae* plants (Fig. 1b).

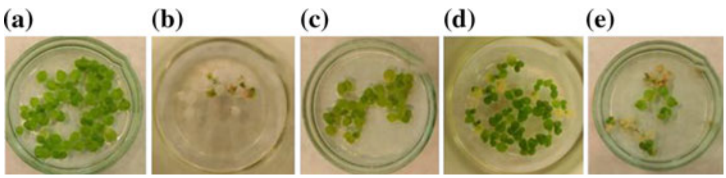


Fig. 1 Fronds of *Spirodela polyrrhiza* plants cultivated in vitro in laboratory conditions, supplemented by leachate coming from the process of methane fermentation: Control "Z" (**a**), Control H_2O (**b**), H_2O + 1.5% (**c**), H_2O + 2.5% (**d**), H_2O + 5.0% (**e**)

Detailed analysis showed that the use of the tested leachate was justified. Growth of *Spirodela polyrrhiza* cultured under laboratory conditions in tap water supplemented with 2.5% leachate was only by 29% lower compared to the “Z” medium control, while at the 1.5 and 5% concentrations it was lower by 55 and 77%, respectively (Fig. 2).

Fresh matter of the plants cultivated in the optimal 2.5% leachate series was 27% lower than in the “Z” control (Fig. 3). While the chlorophyll index in these plants was close to that observed in the “Z” control (Fig. 4). At the other concentrations the chlorophyll content was marked lower. Similar dependencies were observed for plant gas exchange (Fig. 5).

Biogas plants have the potential to become important sources of electric thermal energy [7]. It is expected that by 2020 in Poland 2500 huge biogas plants will be opened and they will produce about 25 million tons of waste per year. Therefore, it is necessary to develop innovative technologies and to improve existing methods of

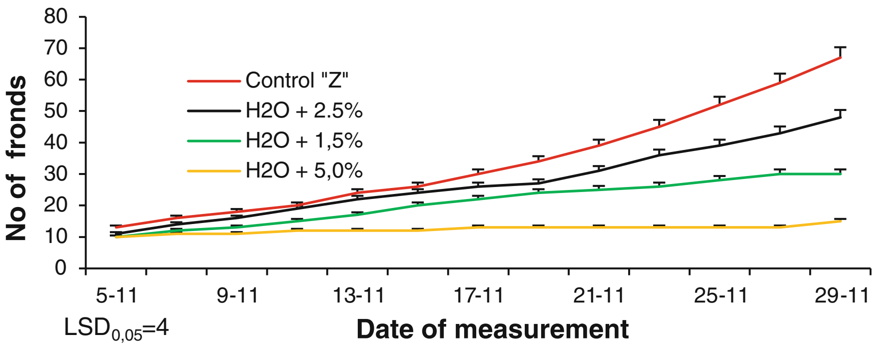


Fig. 2 Number of fronds of *Spirodela polyrrhiza*. Plants cultivated in vitro in laboratory conditions, supplemented by leachate coming from the process of methane fermentation. Vertical bars denote ±SE. LSD at alpha level of 0.05

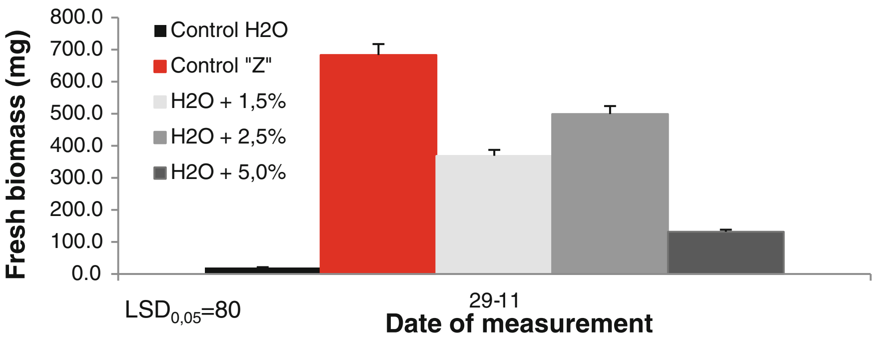


Fig. 3 Fresh biomass of *Spirodela polyrrhiza*. Plants cultivated in vitro in laboratory conditions, supplemented by leachate coming from the process of methane fermentation. Vertical bars denote ±SE. LSD at alpha level of 0.05

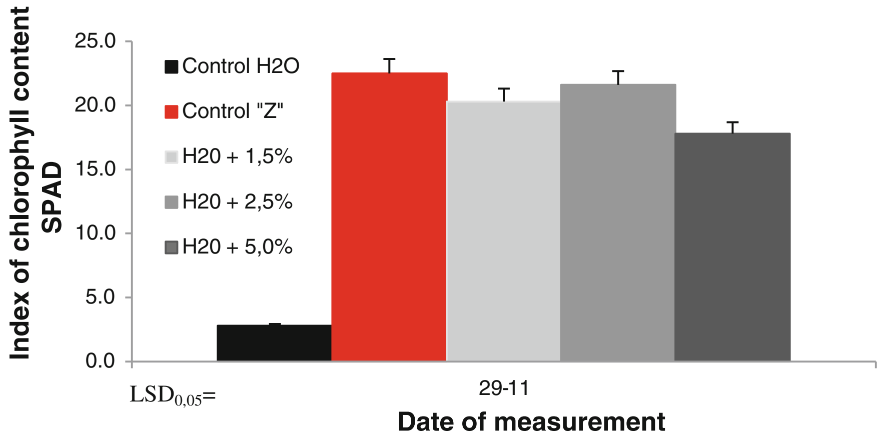


Fig. 4 Index of chlorophyll content in the leaves of *Spirodela polyrrhiza*. Plants cultivated in vitro in laboratory conditions, supplemented by leachate coming from the process of methane fermentation. Vertical bars denote ±SE. LSD at alpha level of 0.05

biogas waste management [8]. Great interest in this subject and the increase in investment in renewable energy technologies will significantly reduce energy production costs as well as the country's independence and energy security, it will also allowed to meet the EU's regulation concerning commitment to reduce emissions [9]. Despite the considerable popularity of biogas plants in Poland and Europe, in most cases the leachate coming from the methane fermentation is most often utilized by thermal treatment or simply stored, which unfortunately results in the loss of its energy and nutrient potential [10, 11]. Developing a technology that uses its organic fertilizer properties in in vitro plant breeding will reduce the costs of growing crops and the use of chemical substances, it will also increase its other applications e.g. in energy, food and agriculture industry.

In Germany, energy plants have been widely accepted, including corn and various kinds of grass that are used for biogas production and come from so-called targeted crops. For the production of biogas they can be used in whole or in part: straw, fruit, tubers, and also in the form of silage (corn). Taking into account economic profit, the use of organic waste and targeted crops is the most beneficial for the production of biogas [12]. Depending on the substrate used, the post fermentation leachate has varied chemical composition and water content, which allows it to be classified as either a solid or a liquid fraction and utilized accordingly. The use of the solid fraction as a fertilizer increases the amount of organic matter in the soil and has a beneficial effect on its water and sorption capacity and significantly limits the use of chemical fertilizers. The liquid fraction, which is the leach from mechanical separation, has significant amounts of soluble forms of nitrogen (N), phosphorus (P) and potassium (K), and is a high quality liquid organic

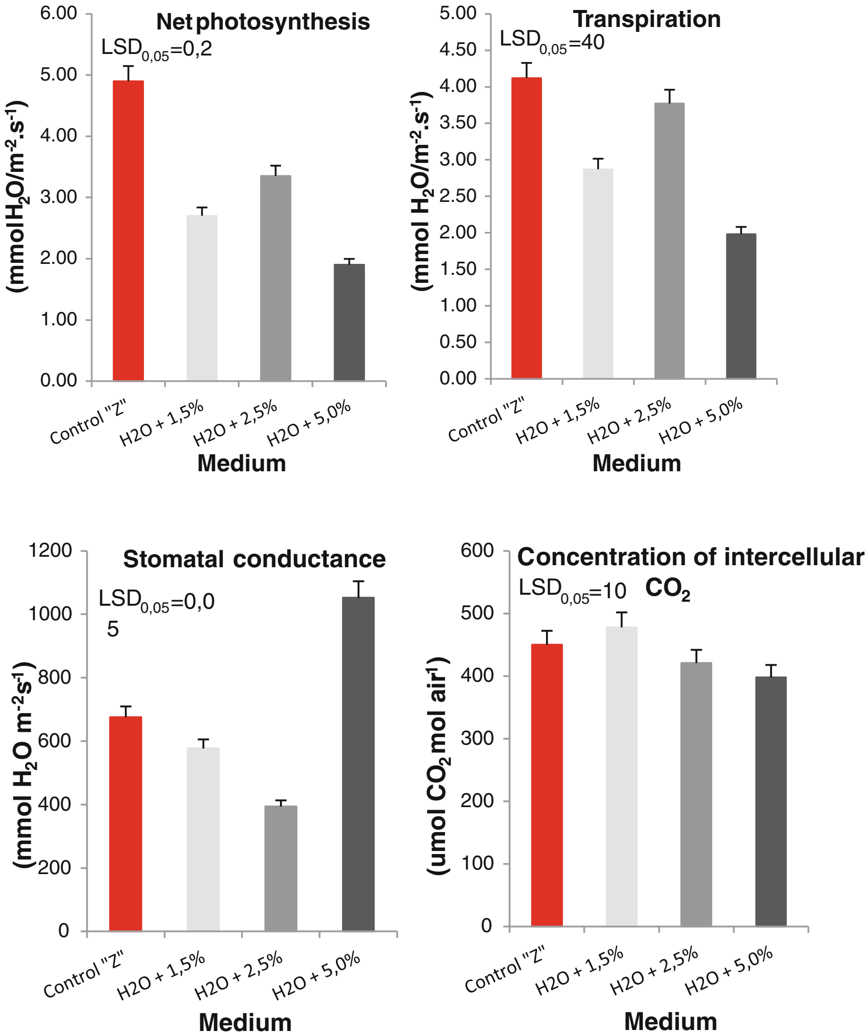


Fig. 5 Net photosynthesis, transpiration, stomatal conductance and concentration of intercellular CO_2 in the leaves of *Spirodela polyrrhiza* plants cultivated in vitro in laboratory conditions, supplemented by leachate coming from the process of methane fermentation. Vertical bars denote ±SE. LSD at alpha level of 0.05

fertilizer which can be used for the cultivation of aquatic plants (*Lemnaceae*) which can be diversely used, as it is shown in this paper. In sustainable agriculture post fermentation leachate can be applied to supplement the use of other organic fertilizers both in soil and aquatic (*Lemnaceae*) cultures. Moreover, it can be an additional source of income for a company.

5 Conclusions and Recommendations

The obtained results showed that the leachate coming from the methane fermentation conducted in biogas plants can be a cost-effective supplement to the medium used to produce plants from *Lemnaceae* family. Growth and development of *Spirodela polyrrhiza* was best under 2.5% leachate concentration. The use of the post-fermentation leachate in in vitro culture can be an effective way to recycle biogas plant waste and a cost-effective system to produce water biomass of high quality and a wide array of applications. This method may significantly lower the cost of aquatic plant biomass production which next can be used to produce renewable energy. This will significantly decrease environmental pollution. Further research under natural conditions in lagoons is necessary.

Acknowledgements Research were supported by National Centre for Research and Development Grant No. BIOSTRATEG 2/296369/5/NCBR/2016.

References

1. Zehnder in Staub R.: Ernährungphysiologish-autökologische Untersuchung an den planktonischen Blaualge Oscillatoria rubescens DC. Schweiz. Z. Hydrol. **23**, 82–198 (1961)
2. Badek, B., Romanowska-Duda, Z., Van Dujin, B., Grzesik, M.: Rapid evaluation of germinability of primed china aster (Callistephus chinensis Ness.) seeds with physiological and biochemical markers. J. Hort. Res. **22**, 2. https://doi.org/10.2478/johr-2014-0017 (2014)
3. Grzesik, M., Romanowska-Duda, Z.: Improvements in germination, growth, and metabolic activity of corn seedlings by grain conditioning and root application with cyanobacteria and microalgae. Polish J. Environ. Stud. **23**(4), 1147–1153 (2014)
4. Grzesik, M., Romanowska-Duda, Z., Kalaji, H.M.: Effectiveness of cyanobacteria and green algae in enhancing the photosynthetic performance and growth of willow (*Salix viminalis* L.) plants under limited synthetic fertilizers application. Photosynthetica **55**(3), 510–521 (2017). https://doi.org/10.1007/s11099-017-0716-1
5. Kalaji, M.H., Carpentier, R., Allakhverdiev, S.I., Bosa, K.: Fluorescence parameters as an early indicator of light stress in barley. J. Photochem. Photobiol. **112**, 1. https://doi.org/10.1016/j.jphotobiol.2012.03.009, (2012)
6. Kalaji, M.H., Schansker, G., Ladle, R.J., Goltsev, V., Bosak, K., Allakhverdiev, S.I., Brestic, M., Bussotti, F., Calatayud, A., Dabrowski, P., Elsheery, N., Ferroni, L., Guidi, L., Hogewoning, S.W., Jajoo, A., Misra, A.N., Nebauer, S.G., Pancaldi, S., Penella, C., Poli, D., Pollastrini, M., Romanowska-Duda, Z.B., Rutkowska, B., Serodio, J., Suresh, K., Szulc, W., Tambussi, E., Yanniccari, M., Zivcak, M.: Frequently asked questions about chlorophyll fluorescence: practical issues. Photosynth. Res. **122**, 121–158 (2014). https://doi.org/10.1007/s11120-014-0024-6
7. Alburquerque, A.J., Fuente, C., Ferrer-Costa, A., Carrasco, L., Cegarra, J., Abad, M., Bernal, P.M.: Assessment of the fertilizer potential of digestates from farm and agroindustrial residues. Biomass Bioen. **40**, 181–189 (2012)

8. Czekała, W., Pilarski, K., Dach, J., Janczak, D., Szymańska, M.: Analysis of management possibilities for digestate from biogas plant. Technika Ogrodnicza Rolnicza Leśna **4** (2012)
9. Bień, J., Bień, B.: Biogazownia rolnicza elementem programu gospodarki odpadami i wytwarzania zielonej energii w gminie. Inżynieria i Ochrona Środowiska **13(**1), 17–27 (2010)
10. Pontus, K.: Osad pofermentacyjny oraz jego wykorzystanie. InnoBaltica, 108–117 (2013)
11. Kowalczyk-Juśko, A., Szymańska, M.: Poferment nawozem dla rolnictwa. Fundacja na rzecz Rozwoju Polskiego Rolnictwa (2015)
12. MAE: Biogaz rolniczy—produkcja i wykorzystanie. Mazow. Agencja Energ, Warszawa (2009)

The Energy Efficiency in a Commune. The Formal and Legal Requirements with Examples of a Good Practice

Barbara Tomaszewska, Anna Sowiżdżał and Anna Drabik

Abstract The energy efficiency together with the utilization of renewable energy resources are considered to be crucial parts of a transition to the low-carbon economy. Their development can involve various administrative levels, nevertheless, the tremendous potential is assigned to a commune. Thus, the paper presents the most important formal and legal regulations that have an influence on the improvement of the energy efficiency, considering mainly obligations arising directly from the Energy Law and the Energy Efficiency Act. Moreover, the importance of the effective energy management in a commune is strongly emphasized, as the key for the low-carbon and resource-efficient economy. In the instance of the development of the energy efficient economy, many benefits are pointed out, and in case of the collaboration between neighboring communes, they are often multiplied at that. The particular examples of projects that have been realized in Polish communes of Niepolomice (the installation of renewable energy systems for public and private buildings) and Charasznica (the modernization of the street lighting), together with the indication of costs and profits relevant to the investment in the energy efficiency, as well as the environmental and socio-economic aspects, are also presented.

Keywords Energy efficiency · Low emission economy · Commune
Legal framework

B. Tomaszewska · A. Sowiżdżał · A. Drabik (✉)
Faculty of Geology, Geophysics and Environmental Protection, Department of Fossil Fuels, AGH University of Science and Technology, Mickiewicza 30 Av, 30-059 Kraków, Poland
e-mail: adrabik@agh.edu.pl

B. Tomaszewska
e-mail: barbara.tomaszewska@agh.edu.pl

A. Sowiżdżał
e-mail: ansow@agh.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_27

1 Introduction

The contemporary economy, and in particular the energy sector, faces a number of challenges consequent on the ever-increasing energy demand in parallel with limited energy resources and the need to prevent the climate changes. Consequently, it is an extremely important issue to look for ways for an effective and environment-friendly management of the energy sector. The efficient use of energy resources, including the utilization of renewable energy sources, the low-carbon economy, and the reduction of greenhouse gases emissions into the atmosphere, are the main directions for the development of European Union community. All legal acts adopted by the European Union have a significant impact on the internal legislation of the Member States. As a result, the European Union, by issuing successive directives, obliged Member States to pursue a sustainable energy policy and care for the natural environment. In addition to the EU climate and energy packages that oblige community members to meet their strategic goals in the years 2020 and 2030, the Energy Efficiency Directive [1] is an extremely important document. Being the Member State of EU, Poland has aligned the national law by amending current documents or implementing further legislation so as to ensure the total implementation of energy efficiency legislation and low-carbon economy. The most important of the legal acts on the energy sector in Poland is the Energy Law [2]. However, there are equally important documents facilitating the transformation of the Polish economy into a low-carbon economy, namely, the Renewable Energy Act [3], the Energy Efficiency Act [4] as well as the Polish Energy Policy [5] or the National Low Carbon Development Program [6].

The Art. 2 of the Energy Efficiency Act [4] defines the term of the energy efficiency as the ratio of the attained utility value of a facility, technical unit or installation, to the amount of energy consumed by that facility, technical device or installation, or as a result of the service required to achieve this effect. The improvement of energy efficiency limits the increase in fuel and energy demand, contributing to the country's energy security, as a result of a reduced import dependency. At the same time, it reduces the environmental impact of the energy sector, by reducing emissions. Also, according to the International Energy Agency [7], the energy efficiency is believed to be a key to ensuring a safe, reliable, affordable and sustainable energy system for the future. It seems to be the quickest and least costly way to overcome present economic, energy security and environmental challenges. Being still significantly undervalued, the investment in energy efficiency can provide multiple benefits, locally as well as globally [8].

The improvement of the energy efficiency might be considered in various economic sectors and at any different levels—worldwide, European, internal, regional, local or as individuals (i.e. individual buildings or enterprises) [9, 10]. Nevertheless, considering the challenge that is to enhance the energy efficiency together with the utilization of renewables and reducing the issue of so-called low emission, the great attention should be paid to the prodigious potential of communes—both rural and urban. As it was mentioned before, the energy efficiency constitutes a strategic development vector within several distinct sectors as its target [11], that are: a consciousness of society [12], a transportation sector [13], an industry [14], a waste management [15], an agriculture [16], as well as a building and construction sector [17]. From the perspective of a commune, the transformation to a low carbon economy might be a significant challenge, so it is on vital importance to have knowledge of the formal and legal requirements effectual within the country as well as the possibility of obtaining financial resources for the planned projects. With the right background, the necessary step to succeed in the field of energy efficiency, is to know and then to transfer good practices from other areas.

2 Formal and Legal Requirements

2.1 The Energy Law

All matters related to the energy sector in Poland are determined by the Energy Law [2]. In general, it represents the energy policy of the entire State, including the principles of fuel and energy supply, energy concessions and tariffs, as well as energy devices, installations, networks and the manner of their operation. Directly from the Art. 17 of the Energy Law [2], it arises that the local government of the province, as a smaller territorial unit, participates in the planning of heat and energy supply in the province, and is obliged to check the compliance of the energy and fuel supply plans with the country's energy policy. According to the Art. 18 of the Energy Law [2], communes as the smallest administrative units, are obliged to plan and organize the heat, electricity and gas supply, as well as to determine the measures aimed at the rationalization of the energy consumption and to promote solutions that reduce energy consumption. The commune is also responsible for implementing energy efficient heating (or cooling) systems as well as of assessing the potential for electricity generation in high-efficiency cogeneration. Considering the efficient energy management, the borough is also responsible for the proper planning, placement and financing of lighting in the municipality. These tasks should be carried out with the adopted policy of the municipality, i.e. according to the Local Spatial Development Plan, or in the lack of such elaboration, in accordance with the directions set out in the Study of Conditions and Directions of the Spatial Development of the Municipality. What is more, the regulations emerged from the Environmental Protection Law [18] on air protection and on the individual components of the environment, should be respected.

According to the Art. 19 of the Energy Law [2], the mayor of the commune is obliged to elaborate the Project of Assumptions for the Plan of Supply of Electricity, Heat and Gas Fuels. This document is made at least once every 15 years, and should be updated every 3 years. The project assumes the current status of the energy sector along with forecasts for the future demand for heat, electricity and gas fuels. It takes into account all the instruments that affect the structure of energy use, including: energy efficiency of buildings, infrastructure, lighting, gas, heating and electricity networks. The plan should also indicate what measures should be taken to make the use of fuels and energy more efficient, taking into account existing excesses, the development of local resources and the use of renewable energy sources, as well as waste heat. The identification of opportunities for implementation of measures to improve the energy efficiency, and the evaluation of possible cooperation with other municipalities and/or communes, are equally important elements of the Plan. The project of Assumptions for the Plan of Supply of Electricity, Heat and Gas Fuels, is a subject to the opinion of the local (provincial) government and in accordance with the Energy Law [2], the Art. 19.6, it should be submitted to the public view for a period of 21 days.

2.2 The Energy Efficiency Act

The Energy Efficiency Act [4] is a document that addresses issues related to energy efficiency. It defines the principles of developing a national energy efficiency action plan, carrying out energy audit of enterprises, realizing the obligation to achieve energy savings, as well as tasks of a public sector entities in the field of energy efficiency. The Law [4] lays a duty upon the local administrations to initiate actions to enhance the energy efficiency. According to the Art. 6 of the Energy Efficiency Act [4], each public sector entity is required to implement at least one of the energy efficiency improvement measures. The actions aimed at the general improvement of energy efficiency cover three main areas, i.e. the reduction of energy consumption, improvement of energy efficiency and reduction of energy loss in industry and distribution. According to the Art. 19 of the Act [4], a detailed list of measures to improve energy efficiency is defined by the Energy Minister's Notice [19]. According to the aforementioned document [19], the extensive efforts that should be taken by a commune to improve the energy efficiency are connected to the consecutive areas: the isolation of industrial installations, the reconstruction and renovation (including thermo-modernization) of buildings together with installations and technical equipment, the modernization and/or replacement of lightening and appliances, as well as in fields of the energy recovery and decline of losses.

2.3 The Low Emission Economy Plan

As it was mentioned before, the subject of low-carbon economy remains an inseparable issue of an effective energy management. Poland, in order to transform the high-carbon economy into a low-carbon economy, has developed the National Low Carbon Development Program (NPRGN) [6]. The province, or the commune, as the smaller local administrative units, is not obliged to develop the Low-Carbon Economy Plan (PGN). Nevertheless, in order to obtain the co-financing for any activity aimed at the enhancement of energy efficiency (e.g. thermo-modernization, transport, or deployment of renewables), the municipality must have this strategic document—this remains a prerequisite. The main goal of developing the Low-Carbon Economy Plan is to define a vision for the municipality towards a low-carbon economy, by setting clear goals (strategic and specific) and the ways in which they ought to be implemented. These goals should be specific, ambitious but real and measurable in time. The basis for the development of a good plan is to match it to the socio-economic realities of the region and to make a reliable inventory of greenhouse gases emissions from the municipality, based on its energy balance, including public buildings, housing, transportation, waste management as well as industry and services. The essential element of the PGN's development is to ensure its consistency with other actions undertaken within the municipality and multi-annual financial plans. It is worth noting that the project should be subjected to an environmental impact assessment [6].

3 The Effective Energy Planning

The energy efficiency, as a priority in the context of our country's energy and climate goals, as well as the pursuing of a low-carbon and resource-efficient economy, require detailed and well-developed planning [20]. Since the energy planning starts in individual households, thus the education aimed at raising public awareness in the subject area of the energy efficiency remains a very important issue. Undoubtedly, in order to be able to plan effectively, it is important to be aware of how even the simplest action (e.g. shutting down household appliances rather than leaving them in the standby mode) undertaken by the one can aid the economic growth in the region and consequently in the country.

The effective planning of energy management in the commune requires a comprehensive presentation of the current situation on the level of energy consumption and production, and energy demand within the analyzed area, setting the basis point [21]. When developing an energy efficiency management plan, it is important to analyze the change in energy demand in several scenarios and thus prepare more than one proposals for changes. It is strongly advised to take advantages of the experience gained during the years by other municipalities/communes with similar socio-environmental conditions, both from Poland and abroad. Also, identifying the possible sources of funding for the proposed investment is an essential element of planning. The municipality, having a planning authority, also plays a significant role in planning the deployment of renewable energy sources' installations, contributing to the development of distributed energy, and thus to the achievement of national strategic targets for RES share in the energy balance. It should be noticed that the prepared project should be in line with the vision and belief of the inhabitants and at the same time, meet the requirements imposed by EU and national regulations [21]. The first step on the road to success is involving all stakeholders—local authorities, entrepreneurs, investors, academics and the local community.

Establishing the energy efficient commune is based on a reliable definition of the current state—the base for the further examination. At this stage, it is necessary to gather the following information about the area of interest: energy demand, production and consumption rates of heat and electricity, local power grid structure, technical condition of transmission networks, communication infrastructure, emissions of pollutants into the atmosphere, as well as urban, environmental and social conditions, together with structure of the local economy and industry. These data provide a basis point for defining the strengths and weaknesses (e.g. SWOT analysis) of the region, and to identify priority actions. At the stage of developing the energy efficiency management plans, it is recommended to specify at least four main areas, namely, households, public sector, business activity (trade, services, industry), transport [21]. In the sectors of households and public buildings, it is necessary to identify in detail all buildings and to know their characteristics: location, type and destination, age, technical condition, insulation and tightness of the building, quality of glass divisions, type and efficiency of heat source. In the field of business, it is important to distinguish two areas, the energy demand for buildings—the same information as for households is required, and the second case that is the energy consumed by industrial processes. In this instance, determining the energy consumption of electrical installations and equipment, their technical state and the type and amount of fuel used for technological purposes, play an important role. The transport sector in each municipality is divided into individual, public and in business. The data should be gathered in the same areas and concern following issues: structure and type of vehicles, their technical condition, fuel sales structure and number of kilometers traveled.

Forecasting the energy demand within the analyzed area is another but very important step. At this stage, particular attention should be paid to the determination of the rate of increase in the number of new buildings and/or institutions in the municipality area, also taking into account their energy standard. The designation of an estimated reduction in energy demand, as a result of the thermo-modernization activities carried out, as well as the introduction of energy-saving technologies, should be considered. It is also important to take into account the dynamic changes in the price of fuel and energy, which translate into the level of energy consumption as well as the possible changes in economic, industrial and service structures.

Defining the priority objectives for a given commune remains a very individual matter and depends to a large extent on the results of the executed analysis of the current state of the area, and the local policy. Among the most frequently encountered objectives, it is possible to distinguish: reduction in the energy consumption of transport and industrial processes with limitation of the low-emission, cutback in the demand for electricity and heat by skillfully managing energy sector, and reduction in the energy transmission losses combined with the increased use of local renewable energy sources [21].

The last stage is to set the time limit and to create the schedule for consecutive actions. There is also a question of the investment costs accompanying the transformations. An important aspect, in both the municipality and the individual investor, is the possession of own funds. However, there are a number of support agencies to which the application for the subsidy can be submitted.

4 Enhancing Energy Efficiency—Good Practices

Communes are a vital partner of the Polish government in achieving the goals of the country's energy policy and implementing the low-carbon economy. At the same time, they are entities that work with local communities, investors and energy companies, having a direct impact on stimulating sustainable economic development. One must not forget that efficient planning of energy management in the borough requires qualified staff. So far, few municipalities in Poland have a separate body liable for the energy management and implementation of the low-carbon economy [22], but it is a rapidly developing sector. Improving energy efficiency in the municipality requires the implementation of new concepts and technological solutions, which entails significant financial outlays. Some municipalities are able to finance the planned activities with their own funds, nevertheless, predominantly the budget is quite limited. Therefore, it is necessary to attract external financing support—grants, subsidies, loans, or public-private partnerships and energy contracts.

In addition to the obligation to meet the requirements determined by the formal and legal regulations, the municipality can derive environmental, economic and social profits. These include broadly understood benefits, namely, reduction in energy demand and emission of pollutants, support for economic growth with the secure energy sector, as well as to enhance a social development and provide a healthy area to live.

There is no end of examples of municipalities from Poland and Europe that have implemented measures aimed at building a low-carbon economy based on the energy efficiency and the utilization of renewables [22]. Below, the selected examples of communities of the Lesser Poland Voivodeship, together with an indication of actions taken and benefits that result from them, are presented.

4.1 The Charasznica Commune

Charasznica commune is a rural municipality located in the northern part of the Lesser Poland Voivodeship, in the Miechow district. It consists of 18 towns, giving a total area of 78 km^2. It is an agricultural municipality (80% of the area remains the agricultural land) with the developing service and industry sector. The population of the municipality is almost 8 thousand [23]. All buildings in the municipality are heated by individual heat sources, using coal, wood and gas.

The commune possesses strategic documents such as [23]: the Local Spatial Development Plan, the Study of Conditions and Directions of Spatial Development, the Community Development Strategy for 2016–2025 [24], and the Low Carbon Economy Plan [25] (adopted in December 2015).

One of the actions undertaken by the local government was to modernize street lighting in the commune. The project was implemented in 2014 and cost about 2.3 million PLN, with financial support (45% subsidy and 55% loan) from the National Fund for Environmental Protection and Water Management (NFOSiGW) [23]. The modernization of 1011 lighting points from 1107 existing in the commune, was covered within the project [22]. It consisted in replacing the mercurial lightening into the soda luminaires (817 pcs.) and LEDs (194 pcs.), as well as installing 62 intelligent lighting cabinets with astronomical clocks equipped with GPS-enabled controllers [22]. The implementation of the project has brought measurable economic and environmental benefits. The cost of running an outdated lighting system was a heavy financial burden on the commune's budget. Thanks to the investment, energy consumption was reduced by 60% and cost of living was reduced by 62%, ipso facto reducing the expenses incurred by the commune. The emission of carbon dioxide (CO_2) has been reduced by 400 tons per year [22].

Subsequent actions of the Commune, presented in The Commune Development Strategy [24], establish a strategic goal as improving the environment in the municipality, including atmospheric air, with the sustainable and efficient use of energy carriers through the support of a low carbon economy. The municipality assumes the development of the RES sector, the modernization of public and private buildings and the ecological education of inhabitants and local entrepreneurs. The fields of investment activities for years 2014–2020 include: energy consumption in buildings, installations and transport, waste management and energy production [25]. It is worth emphasizing that the municipality received the subsidy from the National Fund for Environmental Protection and Water Management (NFOŚiGW) of 85% of the costs of carrying out the tasks mentioned in the Low Carbon Economy Plan [25].

4.2 The Niepolomice Commune

Niepolomice borough, located in the Lesser Poland Voivodship, in the Wieliczka district, remains the another example of a community that invests in the energy efficiency.

Since 2013, the commune of Niepolomice in cooperation with the boroughs of Wieliczka, Skawina and Miechow, as well as Myslenice and Zabierzow (since 2015), has implemented the project "Installing Renewable Energy Systems for Public Buildings and Private Houses" [22, 26], focusing on the efficient use of fossil fuels in the communal sector and reduction in the phenomenon of low emission. As a part of the project, 4058 private houses and 32 public utilities have been equipped with solar collectors, 20 public buildings with photovoltaic installations, also, 9 heat pumps have been installed. What is more, the thermo-modernization of 40 public buildings was carried out, item, the LED lighting has been installed in 18

Table 1 The reduction in pollutants' emissions; based on [27]

Pollutant	Amount in T/year
CO_2	5000
CO	100
SO_2	32
NO_x	4.1
Particulate matter	57.9

public buildings and 400 street lighting lamps [27]. The project was finished in June 2017 and its value amounted to 86 million PLN, of which almost 65% was covered by the Swiss-Polish Cooperation Program [27].

In addition to supporting distributed energy and reducing the fossil fuel consumption by 1920 tons per year, the measurable result of the project is the significant reduction of pollutant emissions of about 5.2 thousand tons in the annual cycle (Table 1) and the increase in energy savings of approximately 52.5 TJ per year [27].

In the commune of Niepolomice, the project leader, 660 solar collectors were installed on private buildings and 15 public buildings underwent thorough the thermal-modernization [27]. Moreover, all public buildings, such as schools, cultural centers and fire halls, as well as the indoor swimming pool in Niepolomice, were equipped with photovoltaic installations. In the Bona Queen Garden, near the Royal Castle, a photovoltaic installation of 150 kWp was established [26, 27]. At this point, it should be also mentioned that the municipality has not stopped at these activities. Namely, in April 2017, the pilot Low Emission Reduction Program (PONE) has been launched. It facilitates to obtain subsidies (co-financing) for the exchange of coal-fired furnaces in private houses. At the moment, the application submission has been closed, thus, the project is at the stage of the energy audit in the reported buildings [28].

5 Conclusion

Communes as the smallest administrative units hold the greatest planning and legislative power, thereby they have the tremendous potential for introducing changes in the management of energy sector, as well as creating ecological awareness of the local community. What is more, its compliance with formal and legal regulations together with applying the good practices/experience gained from other communes, significantly increases the good chance for leading the low-carbon economy based on the efficient utilization of renewables. As it is presented in the paper, effects of introduction of renewable energy resources may differ dependable on the basis state of the analyzed borough and it capability for implementation of environment-friendly technology. For instance, the Charasznica Commune implemented the project of modernization of street lightening—1011 mercurial lightning points were changed into soda luminaries and LEDs technology, gaining the reduction on the energy consumption of about 60%. On the other hand, the Niepolomice Commune constitutes the perfect example of the collaboration with five neighboring communes, focusing on the reduction of so-called low-emission. They developed the project that was aimed at the installation of renewable energy systems (solar collectors, photovoltaic panels and heat pumps) on about 4.2 thousand private and public buildings, cumulatively. Also the thermo-modernization of 40 public buildings and 400 street lightening points, was implemented within the project. These are only few examples of activities that may be taken by a commune. Nevertheless, it is vital to be emphasized that the improvement of the energy efficiency and increase in the utilization of renewables undoubtedly constitute strategic targets of many Polish communes and the whole country.

The paper has been prepared under the AGH-UST statutory research grant No. 11.11.140.031.

References

1. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency
2. Ustawa Prawo energetyczne (Dz. U. 2017 poz. 220) (in Polish)
3. Ustawa o odnawialnych źródłach energii (Dz. U. 2017 poz. 1148) (in Polish)
4. Ustawa o efektywności energetycznej (Dz. U. 2016 poz. 831) (in Polish)
5. Ministerstwo Gospodarki: Polityka energetyczna Polski do 2030 roku. Warszawa (2009) (in Polish)
6. Ministerstwo Gospodarki: Narodowy Program Rozwoju Gospodarki Niskoemisyjnej. Warszawa (2015) (in Polish)
7. International Energy Agency Homepage, https://www.iea.org/topics/energyefficiency/. Last accessed 25 June 2017
8. Rosenow, J., Bayer, E.: Costs and benefits of energy efficiency obligations: a review of European programmes. Energy Policy **107**, 53–62 (2017)
9. Szulc, A., Podlewska, E., Tomaszewska, B.: Discussion on the possibilities of efficient energy management on the example of the Rozprza Municipality, Part I: low-temperature geothermal energy as a source of heat and cold. Technika Poszukiwań Geologicznych **2**, 79–92 (2016) (in Polish)
10. Gyamfi, S., Diawuo, F., Kumi, E., Sika, F., Modjinou, M.: The energy efficiency situation in Ghana. Renewable and Sustainable Energy Reviews (in press) (2017)
11. Poggi, F., Firmino, A., Amado, M.: Assessing energy performances: a step toward energy efficiency at the municipal level. Sustain. Cities Soc. **33**, 57–69 (2017)
12. R.W.E. Polska: Świadomość energetyczna Polaków. Warszawa (2013) (in Polish)
13. Llorca, M., Jamas, T.: Energy efficiency and rebound effect in European road freight transport. Transp. Res. Part A Policy Pract. **101**, 98–110 (2017)
14. Abdelaziz, N.H., Saidur, R., Mekhilef, S.: A review on energy saving strategies in industrial sector. Renew. Sustain. Energy Rev. **15**, 150–168 (2011)
15. Ragoßnig, A.M., Wartha, C., Kirchner, A.: Energy efficiency in waste-to-energy and its relevance with regard to climate control. Waste Manage. Res. **26**(1), 70–77 (2008)
16. Jankowski, K.J., Dubis, B., Budzyński, W.S., Bórawski, P., Bułkowska, K.: Energy efficiency of crops grown for biogas production in a large-scale farm in Poland. Energy **109**, 277–286 (2016)

17. Freire-González, J., Vivanco, D., Puig-Ventosa, I.: Economic structure and energy savings from energy efficiency in households. Ecol. Econ. **131**, 12–20 (2017)
18. Ustawa Prawo ochrony środowiska (Dz. U. 2017 poz. 519) (in Polish)
19. Obwieszczenie Ministra Energii w sprawie szczegółowego wykazu przedsięwzięć służących poprawie efektywności energetycznej (Dz. U. 2016 poz. 1184) (in Polish)
20. Dzwonkowska, D.: Energetyka prosumencka jako pomoc w poprawieniu efektywności energetycznej. Innowacja i Rozwój **1**(6), 10–14 (2015) (in Polish)
21. Visnova, A.G.H.-U.S.T.: Guidelines for the elaboration of Energy Efficiency Plans. Krakow (2014)
22. Węglarz, A., Winkowska, E., Wójcik, W., et al.: Gospodarka niskoemisyjna zaczyna się w gminie. Adelphi, Berlin (2015) (in Polish)
23. The Charasznica commune Homepage, http://www.charsznica.pl/art,2,nasza-gmina.html. Last accessed 25 June 2017
24. Strategia Rozwoju Gminy Charasznica na lata 2016–2025, http://www.charsznica.pl/art,708,strategia-rozwoju-gminy.html. Last accessed 25 June 2017
25. Plan Gospodarki Niskoemisyjnej dla Gminy Charasznica, http://www.charsznica.pl/art,204,plan-gospodarki-niskoemisyjnej-dla-gminy-charsznica.html. Last accessed 25 June 2017
26. The Niepolomice commune Homepage, http://wiadomosci.niepolomice.eu/Informator/projekt-solarny/. Last accessed 25 June 2017
27. The Solar Project Homepage, http://www.niepolomicesolary.eu/pl/. Last accessed 25 June 2017
28. The Low Emission Reduction Program for Niepolomice Commune, http://wiadomosci.niepolomice.eu/Informator/program-wymiany-piecow/. Last accessed 25 June 2017

Evaluation of the Possibility of Use Geothermal Energy Micropiles TITAN 73/53 to Obtain Low-Temperature Heat Energy Accumulated in the Near-Surface Layers of the Ground in Poland Area

Magdalena Tyszer and Barbara Tomaszewska

Abstract Increasing demand in the usage of low-temperature energy sources such as atmospheric air, ground, groundwater or wastewater, which are freely available in the environment, lead to seek new methods and technologies to obtain them. One of these are for example geothermal energy piles (GEP), foundation piles inside which a vertical exchanger is placed to exploit low-temperature geothermal energy. They gained growing popularity over past few years, because of modern assembly technology which allows to make them in any conditions during one technological process. The aim of the work was to estimate the possibility of use geothermal energy micropiles TITAN 73/53 to obtain low-enthalpy heat energy from near-surface layers of the ground in Poland area. Assessment was carried out based on Map of Geological-Engineering of Poland on a scale of 1:500,000, enriched with information gained from literature data and from TITAN Polska Company. Conducted analysis has shown that geothermal energy micropiles TITAN 73/53 in the most parts of the country can be used as very promising and cost-effective technology for more efficient, even 50% more than conventional, acquisition of relatively large amounts of heat energy accumulated in shallow layers of ground in Poland area.

Keywords Low-temperature geothermal energy · Heat pump
Geothermal energy piles · Vertical exchanger

M. Tyszer (✉) · B. Tomaszewska
Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Mickiewicza 30 Av, 30-059 Kraków, Poland
e-mail: mtyszer@agh.edu.pl

B. Tomaszewska
e-mail: barbara.tomaszewska@agh.edu.pl

B. Tomaszewska
Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Wybickiego 7, 31-261 Kraków, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_28

1 Introduction

Rapidly increase in the usage of low-temperature energy sources such as atmospheric air, ground, groundwater or wastewater, which are freely available in the environment, lead to seek new methods and technologies to obtain them. Geothermal energy piles (GEP), which have been used to exploit this energy, gained growing popularity over past few years. Low-temperature heat energy accumulated near the surface of the Earth can be acquired by application of geothermal heat pump coupled with heat exchanger [1–5]. One of the reasons of the increase in the usage is probably directly related to the change in the temperature value of the planet, which increased about of 0.76 °C with respect to pre-industrial levels, according to the Intergovernmental Panel on Climate Change (IPCC), and this trend has not yet been changed. The climate change is also escalated by the emission of greenhouse gases related to human activities. This phenomenon can be reduced by applying systems for heating and cooling of buildings based on renewable energy sources, for example on low-enthalpy geothermal energy micropiles [6, 7]. At present, even wastewaters are increasingly being used as a heat source for low-temperature geothermal installations [8].

Geothermal energy micropiles are closed loop, indirect heat exchangers, where the heat carrier medium does not have the direct contact with the heat source. They are an innovative technology which was designed to exploit in more efficient manner heat, which potentially occurs in the ground. That micropiles besides stabilizing the building are also used to collect heat energy accumulated in a medium [4, 9, 10]. Ground temperatures at near-surface layers of the ground remains almost constant during year. However, this stable ground temperature is very low 10–15 °C at 10–15 m below ground level in most European countries, and 20–25 °C at 10–15 m in the tropic areas [11]. The use of heat exchangers has potential to save energy costs up to two-thirds of conventional systems. The mains advantages of these new systems are excavation costs and space saving with respect to classical geothermal probes [4, 6]. Multidisciplinary studies should have been done to enhance efficiency of the technology by investigate the heat transfer between the carrier medium and the ground.

However, geothermal micropiles TITAN 73/53 are also a foundation piles, within of which is placed heat exchanger, but because of modern assembly technology which allows to make them in any conditions during one technological process and higher than for the conventional systems effectiveness of heat energy acquisition are considered as potentially favorable method [12–14]. The aim of the study was to estimate the possibility of use geothermal micropiles TITAN 73/53 to obtain low-enthalpy heat energy from near-surface layers of the ground in Poland area. Assessment will be conducted based on Map of Geological-Engineering of Poland on a scale of 1:500,000 [15], enriched with information gained from literature data and from TITAN Polska Company.

2 Geothermal Energy Micropiles System

Geothermal energy piles (GEP) are a foundation piles inside which a vertical exchanger is placed. These consist in special heat exchangers obtained inserting probes inside foundation piles which, in addition to structural function, exchange heat with the ground by means of a heat transfer fluid flowing in the probe, connected to the steel frame and positioned before the concrete casting. That micropiles are closed loop, indirect heat exchangers, where the heat carrier medium does not have the direct contact with the heat source and besides stabilizing the building are also used to exploit low-temperature heat energy accumulated in the near-surface layers of the ground for heating in winter time and cooling in the summer. They are an innovative technology which was designed to exploit in more efficient manner heat, which potentially occurs in the ground [6]. Thermal energy is exchanged between the built structure and the heat source (ground) by a fluid, which is circulating via geothermal heat pump and ground exchanger which is attached to the reinforcement cage prior to concreting for bored pipes [10]. The heat pump is used to elevate or decrease the value of temperature of heat energy obtained from source by geothermal energy pile to meet the desired value of temperature. On the efficiency (exploitation power) of the geothermal energy pile influence: the properties of the heat transfer medium (medium filling the pipe system), flow parameters, type of ground and the degree of moist and also the material from which is made geothermal energy pile. The heat transfer mechanism between the GEP and the ground is presented in Fig. 1 and consists:

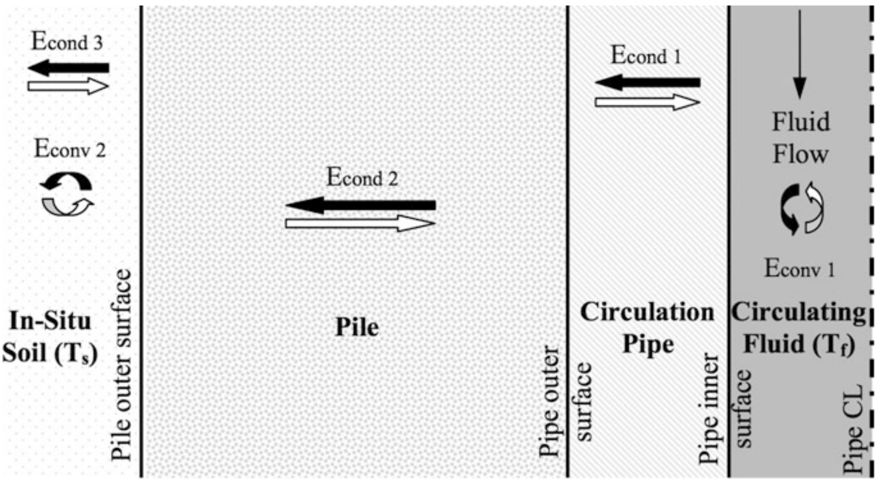


Fig. 1 Heat transfer mechanism [9]

– Convective heat transfer between circulating medium and the internal surface of the pipe ($E_{conv\ 1}$),
– Conductive heat transfer through pipe wall (heat exchanger) ($E_{cond\ 1}$),
– Conductive heat transfer within the pile ($E_{cond\ 2}$),
– Conductive heat transfer within the surrounding ground ($E_{cond\ 3}$),
– Convective heat transfer through groundwater flow (if the ground is moist) ($E_{conv\ 2}$) [9].

Heat transport can take place in two directions: heat injection from the GEP to the ground during reverse pump operation—cooling (black arrows in the Fig. 1) and heat exploit from the near-surface layers of the ground to geothermal energy pile—heating (white arrows in the Fig. 1).

3 Geothermal Micropile TITAN 75/53

In response to the growing interest in technologies which used renewable energy sources for heating and cooling buildings TITAN Polska Company, operating on the Polish market, in its offer presents geothermal energy micropile TITAN 73/53. It fulfills the role of:

– foundation micropile with design bearing capacity of 680 kN,
– geothermal micropile with an energy recovery capacity of 100 W/m.

Modern assembly technology of micropile allows to be made in any conditions during one technological process. Threaded over the entire length of both the steel pipe drill string, the injection pipe and reinforcement rod. Injection carried out simultaneously with the drilling caused creation of grout cover around hole, which perfectly combines with the ground and provides a higher carrying capacity than the conventional method. In the last stage, after final injection, the inside of the reinforcement rod is leached out and the outflow line is placed in hole in the form of a 32 mm diameter tube. The cross-section of geothermal micropile TITAN 73/53 is presented in Fig. 2 [12–14, 16].

In order to check the efficiency of this type of installation in the moisture ground the TITAN Polska Company placed its 16 geothermal micropiles TITAN 73/53 with lengths of 20, 40 and 80 m and made TRT tests in all assembled micropiles. Obtained values of measured parameters were approximately 50% higher than previously determined for the same medium by using different geothermal installation. The results of tests conducted by TITAN Polska Company are presented in Table 1 [16].

Based on conducted tests can be concluded that geothermal micropiles TITAN 73/53 are more economical than classic vertical probe of about 20–30% and characterize much higher heating efficiency than traditional geothermal installations [17]. Moisture grounds with poor load-bearing capacity are particularly beneficial for the dual use of micropiles due to favorable thermal parameters of the medium and unfavorable construction conditions (necessity of assembly of foundation piles).

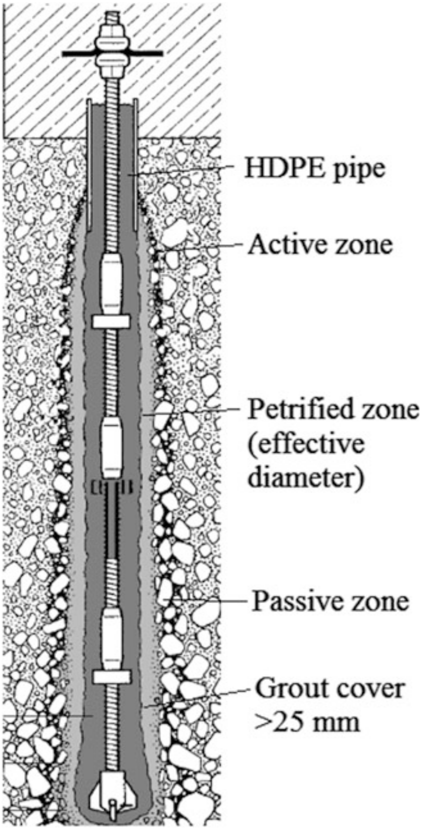


Fig. 2 Cross-section of geothermal micropile TITAN Polska 75/53 [16]

Table 1 Averaged results of the TRT tests of 16 geothermal micropiles TITAN 73/53 [16]

	Standard value	Measured value	Unit
Thermal conductivity λ	2.4	3.8	[W/mK]
Resistance of hole	0.5 up to 0.1	0.05	[W/mK]
Characteristic heat recovery capacity	40 up to 70	105 up to 111	[W/m]

In the large-scale construction, or in the case of occurrence weak or strongly moisture ground it is necessary to realize foundation piles. Because of this, it is profitable to place a vertical probe inside them, as it avoids additional installation costs (additional drilling) and consequently very efficient heat exchangers are obtained. Generally, bifunctional micropiles can be used in objects that are installed in grounds with poor load-bearing capacity or generating very high loads, such us public, residential, office and others buildings with increased thermal requirements and also in maintenance-free elements of road infrastructure, for example platforms, bridges, viaducts, etc.

4 Low-Temperature Heat Energy Potential of Near-Surface Layers of the Ground in Poland Area

In previous work Tyszer and Tomaszewska 2016 [18], based on Map of Geological-Engineering of Poland on a scale of 1:500,000 [15], was presented an example manner assessment of the potential of the use of low-enthalpy energy in Poland area. It has been observed that in the Poland area are mostly powdery and cohesive grounds, practically throughout Poland, whereas organic grounds, loess and hard or soft rocks are found only in small areas (occupy a very small percentage of Poland area). Particularly large areas of powdery grounds have been observed in the lake region in the western part of the country and in the neighborhood of Stalowa Wola, whereas cohesive grounds are found most often in the northern and central parts of Poland, in the south they are also found but excluding mountainous areas, the loess are predominantly in the south-parts of Poland, organics land appears in river valleys mainly in the northern part of the country, and hard and soft rocks are distributed in mountainous areas.

In the powdery ground areas groundwater occurs at different depths depending on terrain morphology. Geological-engineering conditions are generally favorable. Due to literature data about exploitation power of powdery grounds can be observed that its terrains with shallowly located groundwater table and with an approximately flat ground surface may be preferred as heat sources for ground heat pump installations. Moreover, numerous studies and data from literature indicates that moisture sands and gravels are characterized by relatively high theoretical values of exploitation power of vertical and horizontal heat exchangers. However, when the ground exchanger is located completely or partly in dry parts of sands and gravels, the theoretical power of its exploitation is considerably reduced to even economically unprofitable values.

In the areas of organic grounds groundwater occurs shallowly and poorly load-bearing capacity of this type of ground make it an area of unfavorable geological-engineering conditions. Additionally, due to low theoretical values of heat conduction of organic grounds, it is not recommended to locate geothermal installations within these types of grounds.

Cohesive grounds are generally anhydrous and the geological-engineering conditions are average or good. They theoretically exhibit worse values of the possible exploitation power of vertical heat exchangers, but the cost-effectiveness of localization of installations will be determined by the local thermal parameters of the ground and its possible moisture.

The areas of loess land are also mostly anhydrous, but the geological-engineering conditions are variable. The theoretical thermal parameters of the anhydrous loess are worse than the previously described powdery and cohesive grounds.

In the areas of sedimentary rocks, outside the karst areas, the geological-engineering conditions are good. Sedimentary rocks are characterized by relatively large theoretical values of the exploitation power of ground heat exchangers. Moreover, the areas of the occurrence of igneous, metamorphic and sedimentary rocks are characterized by very good geological-engineering conditions and large theoretical values of exploitation power from the ground-based heat exchangers [18].

5 Evaluation of the Possibility of Use Geothermal Energy Micropiles TITAN 73/53 in Poland Area—Results

Evaluation of the possibility of use geothermal energy micropiles TITAN 73/53 was conducted based on Map of Geological-Engineering of Poland on a scale of 1:500,000 [15], enriched with information gained from literature data and from TITAN Polska Company. In general, it can be stated that in the predominantly part of Poland occurs powdery and cohesive grounds, which depending on the degree of moisture, ground structure and local thermal parameters can be an economically variable source of low-temperature heat energy for geothermal installations. According to literature data, with the usage of classical vertical geothermal exchangers, is possible to obtain more than 25 W/m heat energy from anhydrous powdery grounds and approximately 60–100 W/m from moisture ones. For cohesive grounds is observed similar situation, but with lower differences between values of exploitation power for particular type of anhydrous and moisture cohesive ground. The values oscillate between 35–80 W/m, depending on the type of cohesive ground. Organic and loess grounds are characterized as grounds with low theoretical values of heat conduction and respectively the amount of exploitation power usually not exceed 35 and 40 W/m. Furthermore, sedimentary rocks are characterized by relatively large theoretical value of exploitation power, which amounts up to 80 W/m. However, for igneous and metamorphic rocks are also observed large theoretical values of exploitation power for the vertical ground-based heat exchangers, even up to 85 W/m (Table 2) [2]. The use of geothermal energy micropiles TITAN 73/53 to extract heat from a medium is a very promising technological solution. Their dual functionality and higher efficiency of heat recovery from the ground than traditional vertical exchanger, even up to 50% more, results in significant cost savings. Up to now, such type of micropiles has not been installed in Poland, however in recent years have been seen increasing interest of new technologies. Moreover, due to the advantages in terms of foundation and the favorable results of heat recovery tests form ground, this technology may in the future be one of the most commonly used in low-temperature geothermal installations.

Table 2 Theoretical values of exploitation power for classical vertical exchangers possible to obtain in the Poland area

Type of ground	Theoretical exploitation power for classical vertical exchangers	Unit	Occurrence of particular type of ground in Poland area
Powdery grounds	25–100	[W/m]	Predominantly part
Cohesive grounds	35–80	[W/m]	Predominantly part
Organic grounds	Not exceed 35	[W/m]	Small areas
Loess	Not exceed 40	[W/m]	Small areas
Sedimentary grounds	Up to 80	[W/m]	Small areas
Igneous, metamorphic rocks	Up to 85	[W/m]	Small areas

6 Conclusions

Based on Map of Geological-Engineering of Poland on a scale of 1:500,000 and literature data was found that in the most parts of the country occur powdery and cohesive soils, which depending of the degree of moisture, the structure of the soil and the local thermal parameters can be a cost-effective source of heat for low-temperature geothermal installations. Also, powdered by TRT data from 16 geothermal micropiles TITAN 73/53 (lengths 20, 40 and 80 m) gained from TITAN Company can be concluded that use of these type of micropiles is a very promising technology. Conducted analysis has shown that geothermal energy micropiles TITAN 73/53 in the most parts of the country can be used as very efficient and cost-effective technology for, even 50% more than conventional, acquisition of relatively large amounts of heat energy accumulated in shallow layers of ground in Poland area. Notwithstanding, multidisciplinary studies should have been done to enhance efficiency of the technology by investigate the heat transfer between the carrier medium—ground and to identify potentially the most promising areas to localize the geothermal energy piles, and consequently geothermal energy micropiles TITAN 73/53.

Acknowledgements The paper has been prepared under the AGH-UST statutory research grant No. 11.11.140.031.

References

1. Fadejev, J., Kurnitski, J.: Geothermal energy piles and boreholes design with heat pump in a whole building simulation software. Energy Build. **106**, 23–34 (2015)
2. Kapuściński, J., Rodzoch, A.: Geotermia niskotemperaturowa w Polsce i na świecie: stan aktualny i perspektywy rozwoju: uwarunkowania techniczne, środowiskowe i ekonomiczne. Ministerstwo Środowiska, Warszawa, ISBN 83-86286-15-6 (2010)

3. Ng, C.W.W., Ma, Q.J., Gunawan, A.: Horizontal stress change of energy piles subjected to thermal cycles in sand. Comput. Geotech. **78**, 54–61 (2016)
4. Faizal, M., Bouazza, A., Singh, R.M.: Heat transfer enhancement of geothermal energy piles. Renew. Sustain. Energy Rev. **57**, 16–33 (2016)
5. Cecinato, F., Loveridge, F.A.: Influences on the thermal efficiency of energy piles. Energy **82**, 1021–1033 (2015)
6. Carotenuto, A., Marotta, P., Massarotti, N., Mauro, A.: Energy piles for ground source heat pump applications: comparison of heat transfer performance for different design and operating parameters. Appl. Therm. Eng. http://dx.doi.org/10/1016/j.applthermaleng.2017.06.038 (2017)
7. Franco, A., Moffat, R., Toledo, M., Herrera, P.: Numerical sensitivity analysis of thermal response tests (TRT) in energy piles. Renew. Energy **86**, 985–992 (2016)
8. Culha, O., Gunerhan, H., Biyik, E., Ekren, O., Hepbasli, A.: Heat exchanger applications in wastewater source heat pumps for buildings. Energy Build. **104**, 215–232 (2015)
9. Abdelaziz, S.L., Olgun, C.G., Martin, II, J.R.: Design and operational considerations of geothermal energy piles. Geo-Frontiers, 450–459 (2011)
10. Faizal, M., Bouazza, A., Singh, R.M.: An experimental investigation of the influence of intermittent and continuous operating modes on the thermal behavior of a full scale geothermal energy pile. Geomech. Energy Environ. **8**, 8–29 (2016)
11. Brandl, H.: Energy foundations and other thermo-active ground structures. Geotechnique **56**, 81–122 (2006)
12. Maca, N., Ryżyński, G.: Termopale – termoaktywne elementy posadowień obiektów budowlanych (TITAN Polska). XI Międzynarodowe Targi Geologiczne GEO-EKO-TECH 8-9 maja 2013 (2013)
13. Rychlewski, P., Jurasz, W., Sierant, J.: Fundamenty palowe – jako elementy instalacji pozyskującej energię cieplną z gruntu w instalacjach pomp ciepła – termopale. Inżynier budownictwa – vademecum geoinżynierii I (2014)
14. Sierant, J.: Mikropalowa (r)ewolucja – mikropale geotermalne. Materiały budowlane **7** No. 455 (2010)
15. Jakubowicz, B., Łodzińska, W.: Mapa Geologiczo-Inżynierska Polski w skali 1:500 000. PIG (1994)
16. TITAN Polska Company information materials
17. Pająk, L., Tomaszewska, B.: Porównanie efektów energetycznych, ekonomicznych i ekologicznych wykorzystania pompy ciepła typu woda/woda i solanka/woda do ogrzewania domu jednorodzinnego. Ciepłownictwo, Ogrzewnictwo, Wentylacja **47**(4), 152–157 (2016)
18. Tyszer, M., Tomaszewska, B.: Geologiczne uwarunkowania oceny potencjału geotermii niskotemperaturowej w Polsce. Ciepłownictwo, ogrzewnictwo, wentylacja **47**(7), 265–269 (2016)

Municipal Waste Anaerobic Digestion in Poland

Maciej Cyranka, Michał Jurczyk, Krzysztof Dziedzic, Marcin Jewiarz and Bogusława Łapczyńska-Kordon

Abstract The objective of the paper was to analyse the current state and possibilities of municipal waste anaerobic digestion in Poland. The article shows the main legal and technological aspects that determine the circumstances of implementing this technology in Poland. So far in Poland only a few anaerobic digestion plants are operating, what in comparison to other European countries (e.g. Germany) is a poor result. The main way to deal with waste in Poland is landfilling which can be in many ways dangerous for the environment. The EU law have put pressure on Polish waste management systems for which anaerobic digestion technology can play significant role. This work analysis anaerobic digestion from legal and economical point of view together with predictions of potential as waste management option and renewable energy source. The biogas market has been presented from the perspective of market players. Conclusions show why in the current situation development of Polish anaerobic digestion infrastructure is right.

Keywords Anaerobic digestion · Biogas · Municipal waste

M. Cyranka (✉) · M. Jurczyk
Department of Power Engineering and Environmental Protection,
AGH University of Science and Technology in Krakow, Kraków, Poland
e-mail: cyranka@agh.edu.pl

M. Jurczyk
e-mail: jurczykmichal90@gmail.com

K. Dziedzic · M. Jewiarz · B. Łapczyńska-Kordon
Department of Mechanical Engineering and Agrophysic,
University of Agriculture in Krakow, Kraków, Poland
e-mail: dziedzickrzysiek@poczta.fm

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

B. Łapczyńska-Kordon
e-mail: boguslawa.lapczynska-kordon@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_29

1 Introduction

Polish waste management essentially relies on the waste landfilling, while European Union (EU) environmental requirements are becoming stricter. EU-wide requirements are forcing the Polish government apparatus to implement effective waste management programmers abandoning landfilling for other more sustainable waste treatment methods.

Anaerobic digestion (AD) is a biochemical process which takes place in a closed vessel in the absence of oxygen. This process results mainly in the formation of biogas (carbon dioxide and methane gas mixture) which is used to satisfy internal electrical power generation and heating requirements, while surplus electrical power and heat can be sold as renewable energy [1].

AD is a proven technology and has been demonstrated to be a viable alternative waste treatment method for the handling of the municipal solid waste (MSW) organic fraction [2]. In countries with advanced waste treatment systems (like Germany or France—see Fig. 1) the AD infrastructure is an integrated part of the waste management system.

2 Anaerobic Digestion in Polish Legislation

The Polish political environment for production and use of biogas is largely governed by the EU ecological standards which are expected to be achieved [3]. It seems that the MSW anaerobic digestion plants are to marginalized in recent legal solutions in Poland. Legal classification of this type of installation is unclear, and

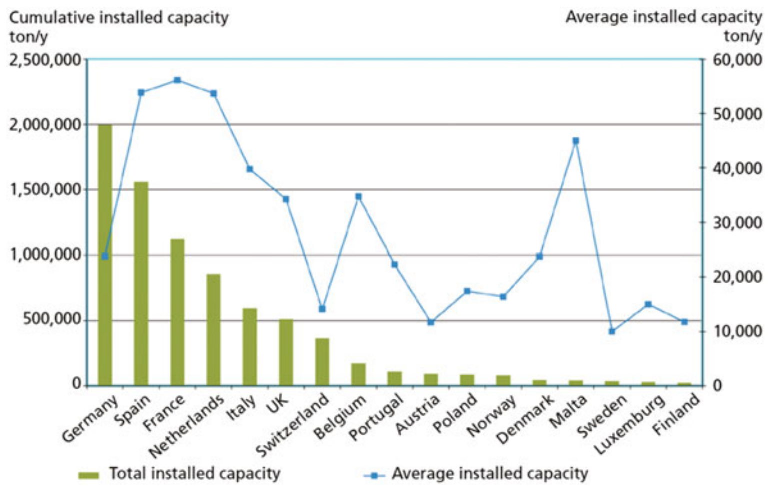


Fig. 1 Total installed municipal waste AD capacity per country [2]

does not give clear reasons for their implementation. What is more there are no established technical and organizational support instruments for MSW biogas plants [4].

2.1 Waste Management and Renewable Energy Production

Anaerobic digestion plants recovering a selected biodegradable fraction of MSW combines two very important functions, namely waste management and renewable energy production. Waste management function of anaerobic digestion technology has a Polish legal definition contained in Waste Act [5]: "Anaerobic treatment of waste (of biodegrade waste under controlled conditions using microorganisms) is a waste recovery process called organic recycling."

Role of anaerobic digestion as renewable energy production process is defined in EU Green paper on the management of bio-waste [6]: "Anaerobic digestion (producing biogas for energy purposes) should be seen as energy recovery."

But according to Polish Act [5]: "Energy recovery—is understood as the waste thermal processing realized for energy recovery."

Therefore the anaerobic digestion plant cannot be classified in Polish legislation as an energy recovery plant, because the process of biodegradation under controlled conditions and using micro-organisms is not a thermal process. It is therefore clear that in the current Polish legal conditions municipal biogas plant is considered as an organic recycling plant [4]. In this perspective, primary product of the anaerobic digestion plant is post-fermentation organic residue/sludge, and biogas and/or energy obtained from it are merely by-products.

2.2 Residues Management

Polish legal regulations regarding the use of post-fermentation sludge for the purpose of fertilization are very restrictive and procedures are costly and long-lasting [7]. Organic residue after anaerobic digestion of biodegradable MSW can be used as organic fertilizer (R10 recovery), assuming that conditions from several official regulations are fulfilled, i.e. among others, [5, 8, 9].

2.3 Financial Aspects

Primary factors limiting investments in new anaerobic digestion plants in Poland are [2, 10]:

- Legal & Financial—Investments in biogas plants face unresolved legal and financial issues causing potential investors refraining from making final decisions.
- Technological—Technology selection depends on quantity, quality and price of substrates available on particular location.
- Social—Knowledge of biogas technology in Poland is still very low and resistance of local community against the planned investment can occur (NIMBY).
- Infrastructural—Costs of building the transmission line for distant biogas plants can be comparable to the costs of plant itself.

Profitability of biogas plant in the current Polish conditions depends not only on the investment and operating costs, but also and above all depends on RES financial support programs [11]. Polish legal basis for RES (including biomass) financial support is Renewable Energy Act [12]. According to this document MSW biodegradable fraction is considered as biomass and electricity produced from such biomass (by means of biogas combustion) can be financially subsidized.

3 Main Reasons for MSW Anaerobic Digestion Development in Poland

Anaerobic digestion plants can become high opportunity for Polish economy regarding waste management and energy from RES. Both aspects are driven by standards and requirements imposed by EU.

3.1 Large Energy Source Available

Annually, Poland produce approx. 11 million tons of municipal waste (i.e. 10,863 thousand tons in 2015 [13]). Polish accession to the European Union (EU) in 2004 significantly influenced the development of the Polish economy which resulted in increased production of waste while the management system was still not prepared to handle it in the proper way. Even now municipal wastes are largely disposed in landfills what is shown in the following chart (Fig. 2) presenting participation rate of each MSW treatment method.

Chemical energy contained in large stream of landfilled MSW (4929 thousand tons in 2015 [13]) should be used to produce usable forms of energy. EU impose duties in that matter by Directive 2008/98/WE [14], which states that all Member States shall take appropriate measures to establish an integrated, modern and proportioned network of facilities for the municipal waste recovery or recycling. Furthermore, from 1 January 2016 landfilling of unprocessed MSW will be forbidden [15, 16].

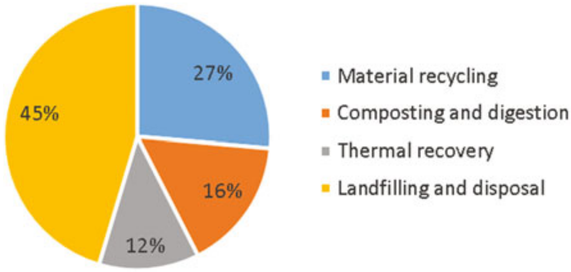


Fig. 2 Treatment of MSW in Poland (2015) [13]

AD plants can be seen as a reliable support for this purpose. Meanwhile biogas in Poland is currently produced mainly on landfills and sewage treatment plants, what is shown on Table 1.

3.2 *Obligatory Reduction of Biodegradable Waste Landfilling*

According to the Regulation on the Levels of Disposed Biodegradable Municipal Waste [17], the acceptable mass level of biodegradable MSW destined to landfills (based on the waste mass produced in 1995) is:

$$2015{-}50\% \rightarrow 2016{-}45\% \rightarrow 2018{-}40\% \rightarrow 2020{-}35\%.$$

Currently even 25% of selectively collected waste can be considered as biodegradable waste fraction (state on 2015—[13]). Forecasts predicts that in 2020 it will be needed to manage approx. 2.8 million tons of biodegradable municipal waste in any other way than by landfilling [4]. Whereas in [7] it was estimated that 385,000 tons of high valuable feedstock for biogas plants can be collected in Poland every year.

Therefore it can be assumed that large part of Polish biodegradable waste can (or even must) be treated by AD processes. What is more use of various technological approaches and systems makes AD preferred treatment technology for the MSW biodegradable fraction. For example in Netherlands and Belgium, it is expected that

Table 1 Production of biogas by source in Poland together with the potential of biogas production [18]

	Source	Unit	Value
Energy produced from biogas (2009)	Agriculture/other sources	PJ	0.19
	MSW/landfills		1.49
	Sewage treatment plants		2.42
	Together		4.10

80% of the composting plants will use AD as the primary MSW treatment technology [2, 19–23].

3.3 Development of Selective Collection

Polish municipalities are implementing the Maintaining Cleanliness and Ordering Municipalities Act [15, 16]. This Act stimulates the selective collection of MSW, including selected organic fraction. Waste segregation at source provide feedstock of much higher quality for the biogas plants than the biodegradable fraction separated from the mixed municipal waste stream [7]. However selective collection of biodegradable waste encounter difficulties because the Polish municipalities are very reluctant in implementing the separate collection of bio-waste from households [24, 25]. Mixed waste are processed mainly in mechanical-biological treatment (MBT) [19] plants which are applied both as a way to recover waste fractions for material and energy recovery and to stabilize the biodegradable waste prior to landfilling [18, 24–26].

4 Biogas Market in Poland

Topic of biogas production is mentioned in many government planning documents. Some of them include plans to build approx. 2000 (one per borough) biogas plants with a total capacity of 2000 MW till year 2020. Implementation of such ambitious government's plans requires building of about 200 biogas plants every year [27, 28]. This plan cannot be taken literally, although it shows specific and clearly defined market trends [29, 30], where building approx. 30–50 such plants in nearest future can be considered as necessity [31, 32].

New international cooperation programs aimed at the biogas use analysis and development (including biogas from MSW) arises currently on the Polish market [33–35]. Special attention is devoted to the use of biogas as a transport fuel, due to EU requirement of 10% share of biofuels in overall transport fuel consumption.

4.1 Current Biogas Market Structure

Poland almost completely ignores the possibility of using biodegradable fraction originating from MSW stream as a biogas source. Biogas from MSW organics is recovered in Poland mainly through the degassing landfills (see Table 1), whereas agricultural biogas market is at the stage of formation. In 2013 in Poland 231 biogas plants are operating with total electric power production capacity 162.2 MW_e (state

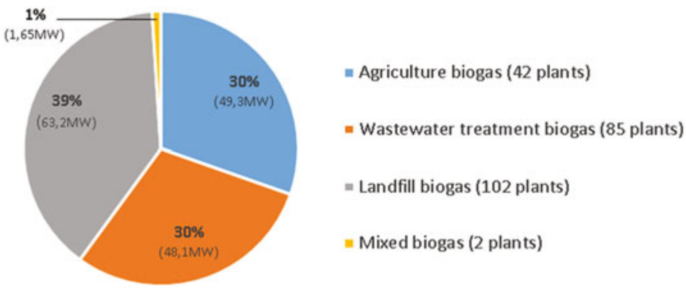


Fig. 3 Biogas sources shares in biogas power production in Poland [27]

on 31.12.2013) [27]. Distribution of biogas substrates used in Polish biogas plants is presented on following chart (Fig. 3).

Optimal biogas plant electrical power output in Polish conditions is in the range between 0.5–1.6 MW_e [19]. The average size of an anaerobic digester in Europe is 31,700 tons per year [2], what can be estimated as approx. 1.1 MW_e. Therefore future of biogas market in Poland are most likely small plants (about 1 MW), using substrates acquired in the local market. However current market for biogas in Poland does not create favourable conditions for the development of small installations [11]. What is more it should be borne in mind that power capacity of biogas plants is restricted—from below—by economic calculation, and—from above—by local availability of substrates and/or possibility of connecting to the grid.

Indicators of profitability and efficiency of particular biogas plants can vary dramatically with the use of different substrates. Hence, technological knowledge and know-how of the contractor are important factors for beneficial entering to the Polish biogas market. Polish biogas market is very difficult but also very interesting for new entrepreneurs. At the moment, biogas market in Poland is quite uncertain, due to the low demand for this type of energy solutions [3]. However, in the nearest future growth trend of market participants can be expected [30].

4.2 Municipal Waste Anaerobic Digestion Plants

MSW anaerobic digestion has matured as a technology and it is assumed that this technology will play a steadily increasing role in the field of the biological treatment of MSW organics. The first MSW anaerobic digestion plants in Poland were associated with wet technology and co-fermentation with sewage sludge [20]. Current legal guidelines regarding recommended conditions for MSW anaerobic digestion are included in Document [21] which is the Polish transposition of BREF for Waste Treatment from August 2006.

Due to inaccuracies in definition of biogas sources, studies on the amount of Polish MSW anaerobic digestion plants are presenting different results. One of the

Table 2 Polish biogas plant processing organic fraction of municipal waste [26, 36]

City	Year of commission	Technology	Throughput [t/a]	Retention time [days]	Power [MW]	Investment costs [mln PLN]
Zgorzelec	2000	Passavant Roediger	10,000	21	0.20_{el}/ 0.39_{th}	9.7
Puławy	2001	BTA/ Horstmann	22,000	20	0.27_{el}/ 0.40_{th}	17.0
Trzebania	2010	OWS DRANCO	70,000	–	0.97_{el}	25.0
Tychy	2014	Strabag (Laran)	18,000	–	–	–
Oława	2014	Kompogas	18,000	–	–	–

studies shows that in 2012 16 MSW biogas plants were operating in Poland, together with 81 composting plants and 31 mechanical-biological waste treatment plants [22]. While according to [31] only 6 MSW biogas plants were operating in Poland in 2012. Polish Central Statistical Office (*GUS*) does not even include biogas from MSW in its reports [3] (Table 2).

Additionally MSW fraction of at least 0–80 mm is separated in mechanical-biological treatment (MBT) plants and it is requiring biological treatment which can be conducted under aerobic or anaerobic conditions. However currently only 19% of MBT installations in Poland (implemented within Operational Programme Infrastructure and Environment) are using MSW anaerobic treatment methods [20]. Detailed MBT plants operation in Poland is governed by the "Regulation on the Mechanical Biological Treatment of Mixed Municipal Waste" [23].

4.3 Anaerobic Digestion Potential

Amount of MSW generated in Poland is approx. 11 million tons per year, while majority of wastes in Poland is landfilled (see Fig. 1), what represents a high-potential for feeding MSW biogas facilities. Additionally, it appears that the 2015 target for biodegradable municipal waste sent to landfill will be not met. Therefore, AD may be regarded as the natural and necessary step for Poland going from landfilling towards higher levels of material recycling and waste reuse presented in Directive 2008/98/WE [14].

Poland is one of the biggest biogas production potentates among the EU member states (based mainly on agricultural substrates). In Germany there are approx. 5000 agriculture biogas plants and approx. 130 MSW anaerobic digestion plants. and it should be noted that Poland have similar agro-climate conditions, what is indicating huge reserves regarding this topic [26, 27, 31]. However it must be pointed out that the biogas plant investment costs estimated in Poland are similar—and sometimes higher—as in Germany, while revenue from electricity sales in Poland is two times lower than in Germany. Thus the risk of AD investment failure much higher [10].

Possible anaerobic digestion plants in Poland can use a variety of plant-based and animal wastes, which are difficult to utilize and expensive to dispose of [26]. According to some experts, Poland could produce annual even more than 10 billion m^3 of biogas only from energy crops and agriculture wastes together with food industry wastes (so potential of MSW organics and sewage sludge is not included) [27]. In addition total Polish energy from biogas production potential is estimated as approx. 84 PJ [18]. Simultaneously potential of biogas production only from MSW anaerobic digestion is equal to 150 million m^3 [31]. For comparison, Poland annually consumes 14–15 billion m^3 of natural gas (approx. 543 PJ [36]), of which 4–5 billion m^3 comes from domestic production and 10 billion m^3 comes from the import (in the vast majority from Russia) [27].

5 Summary

Poland has a very large potential regarding production of biogas from biomass, including MSW organic fraction, agricultural wastes and energy crops. Due to the large mass of biodegradable municipal waste which must be treated by other methods than landfilling, the development of AD infrastructure is highly desirable and should be implemented in order to use energy from MSW organics. Energy recovered from biogas without doubt is a very valuable kind of energy for the national grid, better for the environment than the energy gained from natural gas.

Development of Polish AD industry is right direction and it should be continued at all levels of the national administration. Operation of AD plants not only provide a regional RES but also can improve Polish economy, especially in the environment protection criteria. Currently there are very few plants devoted to process only the biodegradable fraction of MSW, and their quantity is unclear, i.e. is between 2–16 installations.

Use of the biogas plants will enable growth and economic development of the Poland, but for now, despite favourable local conditions, this market is developing too slowly. The slow development of the Polish biogas production market is caused mainly by high investment costs and low public interest in this technology, while this sector has no chance of growth without active participation of the government [3].

References

1. Müller, W., Bockreis, A.: Mechanical-biological waste treatment and utilization of solid recovered fuels – State of the Art. In: Waste Management, vol. 5, pp. 321–338. TK Verlag Karl Thomé-Kozmiensky, Neuruppin (2015)
2. De Baere, L., Bruno, M.: Anaerobic digestion of the organic fraction of municipal solid waste in Europe. In: Waste Management, vol.4, pp. 517–526. TK Verlag Karl Thomé Kozmiensky, Neuruppin (2015)
3. Euro-Centrum.: Rynek biogazowni w Polsce i wojewodztwie Śląskim Katowice (2013)
4. Krasuska, E., Trębacz, D., Oniszk-Popławska, A., Łysek, M., Jacyno, M., Korkosz-Gębska, J., Wójcik, G.: Biogazownia komunalna–kwalifikacja prawna. Czysta Energia **5**, 16–20 (2013)
5. Polish Government.: Ustawa z dnia 14 grudnia 2012 r. o odpadach. Dz.U. 2013 poz. 21, Warsaw (2013)
6. European Commission.: Green paper on the management of bio-waste in the European Union. SEC (2008) 2936, Brussels (2008)
7. Rogulska, M., Smerkowska, B., Samson-Bręk, I.: Biogazownia utylizacyjna. Czysta Energia **10**, 37–40 (2013)
8. Polish Government.: Ustawa z dnia 10 lipca 2007 r. o nawozach i nawożeniu. Dz.U. 2007 nr 147 poz. 1033. Warszawa (2007)
9. Ministry of the Environment.: Rozporządzenie Ministra Środowiska z dnia 20 stycznia 2015 r. w sprawie procesu odzysku. R10, Dz.U. 2015 poz. 132. Warszawa (2015)
10. Dach, J.: Rynek biogazowni w Polsce – ocena i perspektywy. Czysta Energia **5**, 38–42 (2010)
11. Curkowski, A.: Rynek biogazu rolniczego. Stan obecny i perspektywy. In: Energetyka Cieplna i Zawodowa, (12), 74–79 (2011)
12. Polish Government.: Ustawa z dnia 20 lutego 2015 r. o odnawialnych źródłach energii. Dz.U. 2015 poz. 478. Warszawa (2015)
13. Główny Urząd Statystyczny.: Infrastruktura komunalna w 2015r - informacje i opracowania statystyczne. Warszawa (2016)
14. The European Parliament.: Dyrektywa 2008/98/WE z dnia 19 listopada 2008 r. w sprawie odpadów oraz uchylająca niektóre dyrektywy. Brussels (2008)
15. Dziedzic, K., Łapczyńska-Kordon, B., Malinowski, M., Niemiec, M., Sikora, J.: Impact of aerobic biostabilisation and biodrying process of municipal solid waste on minimisation of waste deposited in landfills. Chem. Process Eng. **36**(4), 381–394 (2015)
16. Polish Government.: Ustawa z dnia 13 września 1996 r. o utrzymaniu czystości i porządku w gminach. Dz.U. 1996 nr 132 poz. 622. Warszawa (1996)
17. Ministry of the Environment.: Rozporządzenie Ministra Środowiska z dnia 25 maja 2012 r. w sprawie poziomów ograniczenia masy odpadów komunalnych ulegających biodegradacji przekazywanych do składowania oraz sposobu obliczania poziomu ograniczania masy tych odpadów. Dz.U. 2012 poz. 676. Warszawa (2012)
18. Gis, W., Żółtowski, A., Grzelak, P.: Potencjał Produkcji biogazu w Polsce. Zeszyty Naukowe Instytutu Pojazdów **1**(92), 13–19 (2013)
19. Bio Alians Doradztwo Inwestycyjne Sp. z o.o.: Rynek biogazowni rolniczych BIOGAZ 2012. Warszawa (2012)
20. Krzyśków, A.: Kompostowanie versus fermentacja. In: Strefa RIPOK na POLEKO, Wrocław (2014)
21. Ministry of the Environment.: Wytyczne dotyczące wymagań dla procesów kompostowania, fermentacji i mechaniczno-biologicznego przetwarzania odpadów. Warszawa (2008)
22. Kuczyńska, I.: Biogazownia jako rozwiązanie problemu ograniczenia odpadów biodegradowalnych w Gminie. In: Nowy system gospodarki odpadami komunalnymi, Kraków (2012)
23. Ministry of the Environment.: Rozporządzenie Ministra Środowiska z dnia 11 września 2012 r. w sprawie mechaniczno-biologicznego przetwarzania zmieszanych odpadów komunalnych. Dz.U. 2012 poz. 1052. Warszawa (2012)

24. Malinowski, M.: Selected properties of alternative fuel manufactured from municipal solid waste. Infrastruktura i Ekologia Terenów Wiejskich (2/IV) (2013)
25. Den Boer, E.: Mechanical-biological treatment of municipal waste in poland—dominating technologies and their efficiency in diverting waste from landfills. In: Waste Management, vol. 5, pp. 349–361. TK Verlag Karl Thomé-Kozmiensky, Neuruppin (2015)
26. Jasiulewicz, M.: Potencjał produkcji biogazu w Polsce. In: ochrony środowiska i ekonomiki, Gdańskiej Wyższej Szkoły Administracji, Gdańsk (2010)
27. Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej.: Biogazownia w twojej gminie - praktyczny poradnik dla pracowników samorządu terytorialnego. Warszawa (2014)
28. Jurczyk, M., Mikus, M., Dziedzic, K.: Flue gas cleaning in municipal waste-to-energy plants-Part 1. Infrastruktura i Ekologia Terenów Wiejskich (IV/1), 1179–1193 (2016)
29. Jurczyk, M., Mikus, M., Dziedzic, K.: Flue gas cleaning in municipal waste-to-energy plants Part 2. Infrastruktura i Ekologia Terenów Wiejskich (IV/2), 1309–1321 (2016)
30. Derkacz, A.: Prolegomena do analizy rynku biogazowni rolniczych w Polsce. In: Autobusy: technika, eksploatacja, systemy transportowe, **12**(10), 128–137 (2011)
31. Piskowska-Wasiak, J.: Pozyskiwanie i uzdatnianie biogazu z kontrolowanej fermentacji biodegradowalnej frakcji odpadów komunalnych. Nafta-Gaz **71**(7), 510–519 (2015)
32. Hurka, M., Malinowski, M.: Assessment of the use of EWA bioreactor in the process of biodrying of undersize fraction manufactured from mixed municipal solid waste. *Infrastruktura i Ekologia Terenów Wiejskich* (IV/1) (2014)
33. Frączek, J., Słomka-Polonis, K., Mudryk, K., Wróbel, M., Dziedzic, K.: Analysis of impact of biomass added to rdf oversize fraction on properties of briquettes. Agric. Eng. **20**(4), 39–50 (2016)
34. Swedish-Polish Sustainable Energy Platform, http://www.energyplatform.net/. Last accessed 28 Jan 2017
35. BIOMASTER project, co-funded by the Intelligent Energy Europe-Programme, http://www.biomaster-project.eu/. Last accessed 08 Feb 2017
36. Główny Urząd Statystyczny.: Zużycie Paliw i nośników energii w 2014 r. Warszawa (2015)

The Environmental and Technological Evaluation of Dyed DSSC Cells Production

Milewicz Bartłomiej and Krzysztof Pikoń

Abstract The growing demand for electricity and decreasing fossil fuels resources are a driving factors for research on the technologies that use renewable sources of energy. Solutions that allow using photo-conversion, processing solar energy into electricity are currently going through dynamic development. It could be stated that during the operation phase photovoltaic modules are wastes-free technology, but production and processing after withdrawn from exploration are sources of different sorts of wastes. One of the best solution that gather focuses from scientists are dye-based photovoltaic cells DSSC. During the last decade, many researches gave many specific results that can be used in optimization of this technology. This manuscript discusses a method to expand the lifetime of the module, method to maximize its efficiency as well as reducing the amount of waste during production, use and final waste stage. Natural alternative materials which are possible to apply with current DSSC production technologies and modifications to each individual component of the photovoltaic cell are shown as well.

Keywords Solar cell · DSSC · Photovoltaic

1 Introduction

The ever-increasing demand for electricity, forces people to seek for opportunities for gathering it from renewable sources. One of such solutions is the use of photoconversion to convert solar radiation into electricity. Currently, the dominant solution available on the market is silicon photovoltaic cells. They are expensive and their manufacturing comes with large volume of waste. Because of that new type photovoltaic cells like a dye based DSSC cells are becoming an alternative.

M. Bartłomiej (✉) · K. Pikoń
Faculty of Energy and Environmental Engineering, Department of Technologies and Installations for Waste Management, Silesian University of Technology, 18A Konarskiego St, 44-100 Gliwice, Poland
e-mail: Bartlomiej.Milewicz@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_30

They consist of 4 basic parts: anode, cathode, dye and electrolyte. The performance of each of these parts translates into the ultimate efficiency of the entire panel. The efficiency of the cell is calculated using several formulas and the data necessary for its calculation is obtained by experiment [1].

$$FF = \frac{V_{max} \cdot J_{max}}{V_{oc} \cdot J_{oc}} \tag{1}$$

$$\eta = \frac{V_{oc} \cdot J_{oc} \cdot FF}{P_{in}} \cdot 100[\%] \tag{2}$$

in which:

V_{oc} Voltage of an open circuit [V]
J_{sc} Amperage of the circuit [mA/cm^2]
P_{in} Amount of solar radiation reaching earth [W/m^2]
V_{max} Maximum voltage
J_{max} Maximum amperage
FF Fill up Factor [%]

2 Anode—The Possibilities

One of the possibilities of increasing cell efficiency is the modification of the anode component. In this paper few of the available options are proposed:

- application of silver nanoparticles along with graphene coating [2, 3]
- application of zircon oxide, ZnO with thin layer of TiO_2 [4]
- setting of an Li_2SiO_3 layer on the TiO_2 surface [5]

2.1 *Electron Transfer Process Based on AgNWs and GTMs Co-modified Photo Anode*

One of the many possibilities to maximize the effectiveness of DSSC cells is to use modifications such as the introduction of AG nanoparticles (AGNWs) with or without additional graphene coating (GO). These adjustments allow for easier and more efficient transport of electrons in relation to the cell while minimizing the resistance resulting from the transport of electrical charge between the individual elements of the cell. Studies have shown that the use of varying amounts of graphene in the right proportion to the DSSC TiO_2 cells makes it possible to achieve different results. Assuming a base cell yield of 4.95% with a suitable filter (ligtscatting layer), we can see that the use of a graphene coating with respect to

TiO_2 at 0.01:1 increases the efficiency of the cell to 6.51%, mixtures in other proportions such as 0.005:1 and 0.02:1 produce lower results of 5.98 and 5.62%. The use of silver nanoparticles (AGNWs) allows for an increase in the efficiency of the cell base to 5.97%. It is an Important information that both of these improvements can be applied simultaneously. With both solutions, the efficiency of the system increases to 7.42%, which is more than 100% increase in efficiency compared to the 3.52% filterless cell. It has also been shown that the solution utilizing both modifications is characterized by durability, which makes it possible to increase the life of the entire device. The results were obtained in the exposure conditions of 100 mW/cm^2.

2.2 Ultra Thin TiO_2 Layer Coated on Submicrometer-Sized ZnO Nanocrystallite

Another method of increasing the anode yield in photovoltaic systems is to partially or totally replace the titanium oxide with zinc oxide. Snow is a great substitute for TiO_2 for having similar electrical properties it simultaneously exhibits greater electron mobility. The best solution, using tin oxide is to coat it by atomic deposition with a thin layer of TiO_2. By using this solution, it is possible to reduce gaps between the molecules simultaneously achieving a more efficient transport of electrical charges (electrons) between ZnO molecules. Only ZnO-based cells achieve about 5.2% efficiency while the ZnO and TiO_2 hybrid exhibit efficiency of 6.3%, which in turn provides more than 20% increase of system efficiency.

2.3 Enhanced Power Conversion Efficiency Using Li_2SiO_3

Modifications of the TiO_2 coating to enhance the electron transport process and increase open circuit voltage, Voc have many forms. One of them is the use of Li_2SiO_3 (LS) which can be deposited on the surface of TiO_2 by using a simple process of immersing the prepared titanium oxide deposited substrate in aqueous LS. This process can be carried out at different times, the choice of which significantly affects the final performance of the cell and its characteristics.

As can be seen in Fig. 1, LS modification is most effective when a cell is subjected to 5 min immersion in solution. Comparing the efficiency obtained by the modification, with a base TiO_2/FTO cell we can see an 15% increase, in LS (5) TiO_2/FFTO efficiency increase to 10.58% (while baseline TiO_2/FTO efficiency is equal to 9.20%).

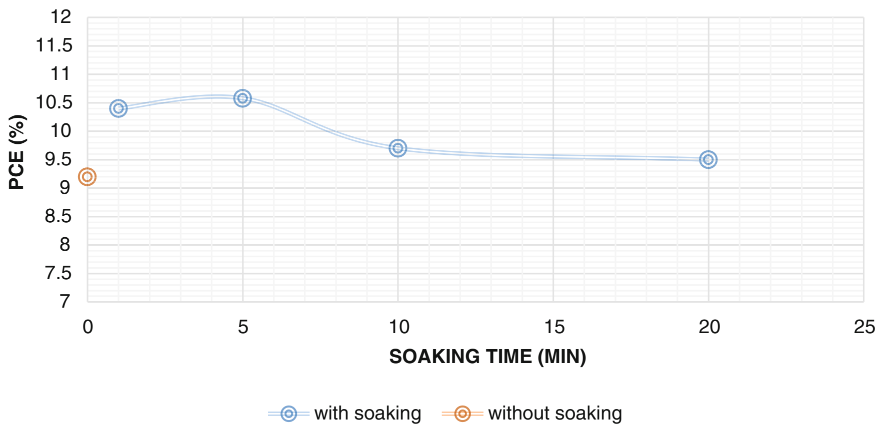


Fig. 1 Increase in cell efficiency after LS modification based on the immersion time of the matrix in the prepared solution

3 Dyes—Possibilities

The use of a suitable dye for efficient conversion of light to electrical energy is essential for DSSC type cells. The ideal dye should meet a number of the following requirements:

- exhibit absorption capacity for light below 920 nm
- have the ability to bond with the conductor surface
- have a high redox potential for efficient electrolyte regeneration
- they must exhibit high stability for about 20 years under natural lighting conditions

DSSC cells can use both organic and inorganic dyes. Complexes of various metals are classified as inorganic dyes while organic dyes include all kinds of natural pigments and their artificially synthesized counterparts. The undisputable advantage of inorganic dyes over their organic counterparts is their higher thermal and chemical stability, however, they are not devoid of defects. Among the most important are:

- High production costs,
- Complicated production cycle,
- Limited resources of metals needed to produce them,
- Negative impact on the environment.

For inorganic dyes, the most commonly used group is the ruthenium polypyrides, the most efficient of which is the N719 dye with the efficiency of 11.18%. As for organic dyes, effective representative is a natural spinach dye with an efficiency of 4%, artificially synthesized coumarin derivative with a yield of 7.7%, and the indolent dye D140 with a yield of 8.0%

There are two ways to improve the performance of dyes;

- Applying several layers using dyes with different light absorption [6]
- Structural modifications of existing dyes [7]

3.1 Simultaneous Use of Several Layers

An important modification to discuss in the case of dyes used in DSSC solutions is the ability to use several types of them simultaneously. The combination of many dyes with light absorption of different lengths allows, to maximize the results achieved by the cells. This modification is primarily used for organic dyes, which is justified by the need to replace costly and environmentally in organic dyes. The effectiveness of simultaneous use of dyes such as TT1 (3.52%) and JK2 (7.08) has already been confirmed. They are characterized by light absorption by 400–550 nm for JK2 and 690 nm for TT1. The result of the combination of these solutions was a cell with an efficiency of 7.74%. It is also possible to combine more layers of dye, however, this solution is only in the laboratory phase. In order to use several types of dyes, it is necessary to use protections that limit their interaction with each other. A solution that allows such an operation is to use an additional layer so that the dye part of the cell accepts the form: TiO_2/Dye 1/Al_2O_3/Dye 2.

3.2 Structural Modifications

Most studies involving DSSC cells focus on organic dyes. This is primarily justified by the cost of materials, production costs and the environmental impact of inorganic dyes. Organic dyes are cheap and do not adversely affect the environment, but their durability leaves a lot to be desired. The solution focused on in the research presented in Article 7 is structural modification. Artificial organic dyes are still cheaper than their inorganic counterparts and at the same time their life span is longer. The article presents two potential structural modifications of indoline dye. The modifications shown in article 7 show greater susceptibility to electrolyte regeneration. The efficiencies achieved by the presented solutions are shown in Table 1. This table also adds a breakdown due to the electrolyte used for regeneration where E1 is iodine electrolyte and E2 is cobalt electrolyte.

Table 1 Summary of results achieved for each of modifications due to electrolyte used. (XS45 and SX46 are modified dyes, XS47 is a dye before modification)

Dye	J_{sc} (mA cm^{-2})	V_{oc} (mV)	FF	η (%)
XS45/E1	14.8	686	0.68	6.90
XS45/E2	13.0	800	0.66	6.86
XS46/E1	13.3	640	0.69	5.87
XS46/E2	11.4	750	0.66	5.64
XS47/E1	13.5	676	0.68	6.20
XS47/E2	11.5	770	0.67	5.93

Table 2 Effectiveness of DSSC cells with ionic electrolytes

Electrolyte	Dye	η (%)
HMII, I_2, et al.	N719	5.0
I_2 and NMBI in MPII	Z907	6.0
I_2, GuSCN, TBP in PMII and EMINCS (13:7, v/v)	K19, DPA	6.3
EMII, I_2, LiI, TBP in EMITFSA	N3	4.5 (0.45 cm^2) 2.7 (69 cm^2)

4 Electrolytes—Possibilities

They are the part that decides on the vitality and efficiency of the DSSC cells. The purpose of the electrolyte is to regenerate the working dye, replenishing the lost electrons. There are three main types of electrolytes:

- Liquid electrolytes [1],
- Solid electrodes,
- Gel electrolytes (semi-solid quasi-solid) [8].

Liquid electrolytes are divided by the solvent used in them, which can be an organic solvent or various types of ionic solutions. The advantages of organic solvent solutions include high efficiency, ease of cell design (use in the cell and manufacture), efficient exchange of electrons. Representatives include nitriles: acetonitrile, valeronitrile, and esters: ethylene carbonate, propylene carbonate. The most commonly used solutions in DSSC cell technology are organic solutions containing I^{3-}/I^{-} redox pair. However, they are not devoid of defects which include their low stability, problems with their sealing in applied solutions as well as their leaks due to changes occurring in the structure of organic solvent. The second group of solvents is ionic solutions that exhibit significantly better thermal and chemical stability than organic solutions. However, they also have their drawbacks. The most important of these is their high viscosity which prevents the efficient transport of I^{3-} ions and affects the efficient regeneration of the dye. Solid electrolytes have been developed to eliminate the most important defects characteristic of their liquid counterparts, namely leaks. Through the use of solid electrolytes it is possible to increase the life of the cell. However, their poor performance makes them not widely used in the production of DSSC cells. Gel electrolytes are a solution finding more and more followers. They are characterized by high thermal stability, high ionic conductivity and low vapor pressure, which is responsible for potential leaks. They are obtained by the use of some polymers, low weight gels or silica nanoparticles as an additive for standard ionic electrolytes. This allows the electrolyte to be compacted while maintaining the molecular structure of the entire solution.

Comparing solutions 1 and 3 shown in Tables, we can see that the use of the additive also positively influences the efficiency of the cell. In case of solution 4, the efficiency of the cell after the electrolyte modification decreased significantly.

5 Cathode—Possibilities

The cathode is an important element of the DSSC, which, when combined with the anode, forms an arrangement in which electrons circulate and thus electric energy flows in a circuit. The most commonly used solution that researchers present in papers about solar cells (of each type of solar cells) is platinum plate, Pt. This solution is the most effective and at the same time resistant to the corrosive properties of the electrolytes. The most important advantage of new type cells, such as DSSC cells is their low cost of production. Production of this type of link should therefore be connected with the use of the cheapest possible materials and technological solutions. The Pt plate is an extremely expensive element, so it is contradictory to the concept of a cheap cell.

There are many choices available for cheap replacement of Pt. The best of them seems to be the use of a carbon sooted plate applied to the glass substrate FTO. The efficiency of the cell and its operating parameters depends on the thickness of the carbon black used in this solution. According to the information provided in the article 8, with increasing thickness of the carbon black used, the fill factor (FF) is increased from 46 to 72%, the current in the circuit (Jsc, mA cm^{-2}) does not change

Table 3 Electrolyte cell performance after application of the additive indicated in the table

Electrolyte	Additive	Dye	Efficiency
HMII, I_2, et al.	Low molecular weight gel	N719	5.01
I_2 and NMBI in MPII	Silica nanoparticles	Z907	6
I_2, GuSCN, TBP in PMII and EMINCS (13:7, v/v)	Low molecular weight gel	K19, DPA	6.1
EMII, I_2, LiI, TBP in EMITFSA	PVDF-HFP	N3	3.8 (0.45 cm^2) 2.4 (69 cm^2)

Table 4 Cell performance depending on the thickness of the carbon black [8]

Thickness (μm)	Jsc (mA cm^{-2})	Voc (mV)	FF (%)	η (%)
14.47	16.8	790	68.5	9.1
9.79	16.8	770	64.6	8.4
4.73	16.9	760	64.1	8.2
3.09	16.5	769	59.3	7.5
2.14	16.2	772	55.2	6.9
0.85	16.2	769	46.3	5.8

Table 5 Cell characteristics according to the cathode used

Modified counterelectrode	Jsc (mA cm^{-2})	V_{oc} (V)	FF (%)	η (%)
Graphen and Carbon Black coated FTO glass	11.34	0.82	71	6.67
Activated carbon coated FTO glass	7.93	0.8	61	3.89
PEDOT coated AU with FTO glass	2.6	0.68	51	0.93
PEDOT coated Au/FTO glass	2.5	0.36	54	0.5
Polyvinyl pyrrolidone capped Platinum coated ITO glass	10.5	0.66	41	2.84
Platinum Coated ITO glass Pt coated FTO glass	17.73	0.84	75	11.1
Carbon Black (thickness 14.47 μm) FTO glass coated stainless steel with TiO_2	16.8	0.79	68	9.1
graphene/PEDOT/PET	12.6	0.77	58	6.26

while a voltage of the open circuit is slightly decreasing (Voc, mV). Table 4 lists the cell parameters according to the thickness of the applied layer [9, 10].

Another solution, also based on carbon black is to cover it with a layer of metallic substrate. This is a low cost solution, but for the proper functioning of the cathode it is necessary to use metals completely or very corrosion resistant (stainless steel use is possible). Polymers and their compounds with carbon are another alternative. Examples of polymers whose uses have been described in the literature may be poly-3,4-ethylenedioxythiophene (PEDOT) with dopant p-toluenesulfonate (PEDOT-TsO) or polystyrenesulfonate (PEDOT-PSS). There are also combinations of polymers with carbon black. Examples of cathode solutions are given in Table 5 [9].

6 Summary

Proposed improvements may be considered beneficial or defective depending on the aspect by which we analyze them. In the case of the presented anode modifications, the best solution seems to be the use of graphene and silver nanoparticles as

Table 6 Selected solutions for modifying DSSC cells

Example	J_{SC} (mA cm^{-2})	V_{oc} (V)	FF	PCE (%)
Anode				
P25/0.01-GTMs/AgNWs	15.05	0.756	0.652	7.42
Cathode				
Carbon Black (thickness 14.47 µm) FTO glass coated stainless steel with TiO_2	16.8	0.79	0.68	9.1
Dye				
YD2-o-C8/Y123	–	–	–	12.3
XS45/E1	14.8	686	0.68	6.90
Elektrolite				
I_2, GuSCN, TBP in PMII and EMINCS (13:7, v/v)	–	–	–	6.3

an additive for the currently used TiO_2. The use of such refinements can translate into increased energy production, while its introduction does not lead to an increase in environmental burden.

In the case of Dyes, both solutions appear to be beneficial. Theoretically, it is possible to apply them simultaneously, however, such studies have not yet been carried out. The use of several structurally modified natural dyes that are characterized by light absorption of different lengths should translate into increased efficiency of the DSSC cells at the same time should not adversely affect the environment. Dyes that undergo structural modification, are organic dyes which, upon expiry of their useful life, will decompose. Solutions that involve electrolytes can be analyzed in two ways. The ionic (organic) electrolytes have the smallest impact on the environment. On the other hand, there are gel solutions using organic substances which are used to prolong the life of the entire device. It is therefore important to consider whether we are aiming for a long, trouble-free work or the greatest possible reduction of the environmental impact. By analyzing Tables 2 and 3, it can be seen that the introduction of a thickener that transforms fluid electrolyte into a gel, in the majority of solutions positively affects their efficiency. The exception is the 4 solution in which after adding the additive the efficiency of the cell falls. The DSSC-type cell is characterized by far less efficiency than its silicon counterpart. This technology can gain popularity among consumers only if its price is low enough. Technicians dealing with DSSC cells should therefore look for solutions that will be as low in cost as possible. In the case of the solutions presented in the article their use decreases the efficiency of the cell in various degrees. However, comparing the prices of the proposed modifications and the price of platinum, which has so far been used to manufacture cathode plates, these solutions are becoming more important. Table 6 shows the best solutions for specific DSSC elements.

7 Conclusions

Many techniques for optimizing and maximizing the effectiveness of dye cells exists. All of them should strive to minimize the impact of solar cells on the environment (both during production and decommissioning). The efficiency of the cells can be increased by using more expensive materials, although this should result in a significant increase in the efficiency of the cell. If the performance is not significantly increased, then considering the cost-effectiveness of DSSC solution it can gain larger popularity. It should also be noted that despite the numerous modifications described, no one has proposed or described an attempt to introduce several of them simultaneously. It is important to consider whether the introduction of some of these will result in synergy and thus maximize the efficiency of the whole solution.

Aknowledgements The studies presented in this article was conducted within the project GEKON2/O4/266475/6/2015 “Isothermal and refrigeration photovoltaic car body” funded by the National Centre for Research and Development.

References

1. Khan, M.Z.H., Al-Mamun, M.R., Halder, P.K., Aziz, M.A.: Performance improvement of modified dye-sensitized solar cells. Renew. Sustain. Energ. Rev. **71**, (2017)
2. Yan, H., Wang, J., Feng, B., Duan, K., Weng, J.: Graphene and Ag nanowires co-modified photoanodes for high-efficiency dye-sensitized solar cells. Sol. Energy **122**, 966–975 (2015). https://doi.org/10.1016/j.solener.2015.10.026
3. Amiria, O., Salavati-Niasaria, M., Farangib, M., Mazaheric, M., Bagheri, S.: Stable plasmonic-improved dye sensitized solar cells by silver nanoparticles between titanium dioxide layers. Electrochim. Acta. **152**, (2015)
4. Park, K., Zhang, Q., Garcia, B.B., Zhou, X., Jeong, Y.-H., Cao, G.: Effect of an ultrathin TiO (2) layer coated on submicrometer-sized ZnO nanocrystallite aggregates by atomic layer deposition on the performance of dye-sensitized solar cells. Adv. Mater. **22**, 2329–2332 (2010). https://doi.org/10.1002/adma.200903219
5. Kim, J.T., Lee, S.H., Han, Y.S.: Enhanced power conversion efficiency of dye-sensitized solar cells with Li2 SiO3-modified photoelectrode. Appl. Surf. Sci. **333**, 134–140 (2015). https://doi.org/10.1016/j.apsusc.2015.01.227
6. Gong, J., Sumathy, K., Qiao, Q., Zhou Z.: Review on dye-sensitized solar cells (DSSCs): advanced techniques and research trends. Renew. Sustain. Energ. Rev. **68**(1), (2017)
7. Wang, L., Liang, M., Zhang, Y., Cheng, F., Wang, X., Sun, Z., et al.: Influence of donor and bridgestructure in D-A–π–A indolinedyes on the photovoltaicproperties of dyesensitizedsolarcellsemployingiodine/cobaltelectrolyte. Dye Pigment **101**, 270–279 (2014). https://doi.org/10.1016/j.dyepig.2013.10.016
8. Kong, F.-T., Dai, S.-Y., Wang, K.-J.: Review of recent progress in dye-sensitized solar cells. Adv. Optoelectron. **2007**, 1–13 (2007). https://doi.org/10.1155/2007/75384

9. Murakami, T.N., Grätzel, M.: Counterelectrodes for DSC: application of functionalmaterials as catalysts. Inorg. Chim. Acta **361**, 572–580 (2008). https://doi.org/10.1016/j.ica.2007.09.025
10. Ramasamy, E., Lee, W.J., Lee, D.Y., Song, J.S.: Nanocarbon counterelectrode for dye sensitized solar cells. Appl. Phys. Lett. **90**, 173103 (2007). https://doi.org/10.1063/1.2731495

Effectiveness of the Hydrogen Production, Storage and Utilization Chain

Wojciech Kostowski, Sebastian Lepszy, Władysław Uthke, Mariusz Chromik, Arkadiusz Wierciński, Marek Foltynowicz and Tomasz Stendera

Abstract The paper evaluates the effectiveness of a power-to-gas hydrogen chain, comprising the production, storage and utilization sections. The production section is based on alkaline electrolyzers producing about 18.6 kg hydrogen per MWh supplied electric energy derived from renewable (wind) sources. Next, hydrogen is transported to an underground storage facility (UGF), assuming that the pressure of the produced hydrogen is sufficient to provide its transportation to the storage site. Energy demand required for hydrogen compression to the UGF is accounted for, and the maximum level of hydrogen losses is evaluated. Finally, three options for hydrogen utilization are considered: (1) hydrogen is co-fired in a gas turbine, (2) it is supplied to hydrogen vehicles, (3) it is used for process purposes replacing the existing production based on steam methane reforming. Moreover, energy effects related to the replaced oxygen production are optionally taken into account. It has been shown that the choice of a scenario (co-firing//vehicles/process application) and, to a lesser degree, the possibility of using the generated oxygen strongly affects the overall process performance which may vary between low values of 20% (energy generation), 70–80% for process application (replacement of steam methane reforming) and more than 90% for vehicle application (replacement of diesel fuel). In conclusion, the process may provide excellent energy performance for dedicated hydrogen users, and a less favorable yet still considerable option for energy storage for renewable sources.

Keywords Hydrogen · Energy storage · Salt cavern · Power to gas

---

W. Kostowski (✉) · S. Lepszy
Faculty of Power and Envirionmental Engineering, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland
e-mail: wojciech.kostowski@polsl.pl

W. Uthke · M. Chromik
Chemkop sp. z o.o, Wybickiego 7, 31-261 Kraków, Poland

A. Wierciński · M. Foltynowicz · T. Stendera
Grupa Lotos S.A, Elbląska 135, 80-718 Gdańsk, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_31

1 Introduction

The share of renewable energy in the World's electricity production has been constantly increasing over the past several years. A significant part of renewable energy sources (RES) is provided by wind and solar energy. Although these sources generate no local CO_2 emissions, their availability is highly dependent on unstable solar and weather conditions. Accordingly, production of electricity becomes variable in an unpredictable manner which is a challenge [1] for the management of power supply and demand (see Fig. 1). Therefore, the development of energy market with high share of RES also requires the use of new strategies for energy storage.

This paper reports a project registered under the acronym HESTOR related with the production, storage and utilization of hydrogen, basically originating from renewable resources. The project has been carried out under the leadership of LOTOS Group SA—a major Polish oil refinery. The company is currently using hydrogen for its process purposes, i.e. for hydrocracking and hydrodesulphurization. Accordingly, it is reasonable to install wind power capacity in the proximity of the refinery and to generate hydrogen, whose major part can be used within the plant. However, due to the strongly variable flux of hydrogen originating from wind power it is also required to consider large-scale hydrogen storage in an underground cavern. Moreover, alternative options of hydrogen utilization are also considered in the project.

The aim of this paper is to analyze and explain the energy flow across the entire hydrogen chain, starting from electricity derived from RES, and ending at various points of hydrogen utilization. In particular, the objective of the work is to define and calculate the energy efficiency of the process.

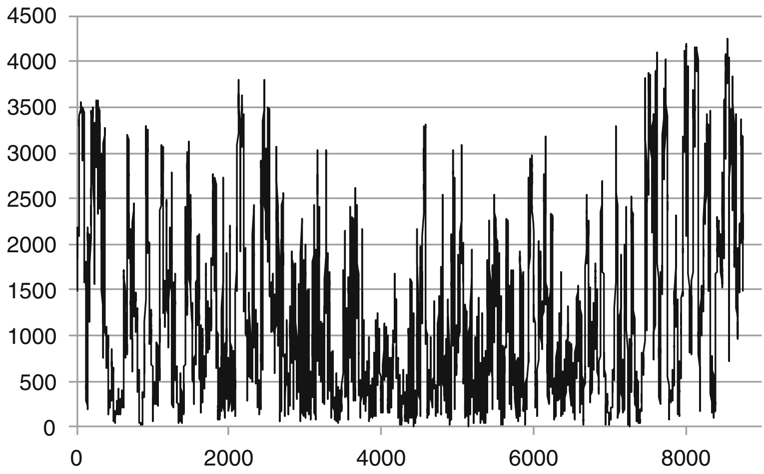


Fig. 1 Generation of wind power in Poland, 2015. Data provided by PSE and Grupa Lotos SA

2 Technical Description

The project can be divided into sections of hydrogen production, hydrogen storage and hydrogen utilization. The first two sections are presented in Fig. 2.

The section of production is composed of a set of electrolyzers producing approximately 1 ton of hydrogen per hour. The number of electrolyzers depends on their rated power (as offered by manufacturers) and it is estimated at 50–60 stacks. The supply of electricity at the required parameters is partially done within the electrolyzer unit and partially outside of it: the electrolyzer unit includes a dedicated AC/DC converter, but the transformation from medium- to low voltage has to be done independently. The fluxes of energy across the electrolyzers are explained in Fig. 3 and they are then set in Table 1.

The formulation of Fig. 2 is related to the way of defining the electrolyzer efficiency by manufacturers. The gross flux of electricity ($E_{el,\ gross}$) supplied to the site is transformed to low voltage (400–1000 V), and the transformation losses δE_{el1} are situated outside of the electrolyzer modules. On the contrary, the AC/DC conversion losses δE_{el2} and the on-site energy consumption δE_{el3} by electrolyzer subsystems (fans, pumps) are contained within the modules. The energy output of electrolyzers is represented by the chemical energy of hydrogen, measured by its lower heating value. In the presented simplified notation, the energy balance is closed by heat losses δQ which actually contain three components: the actual heat losses to the environment, the physical enthalpy of hot products leaving the

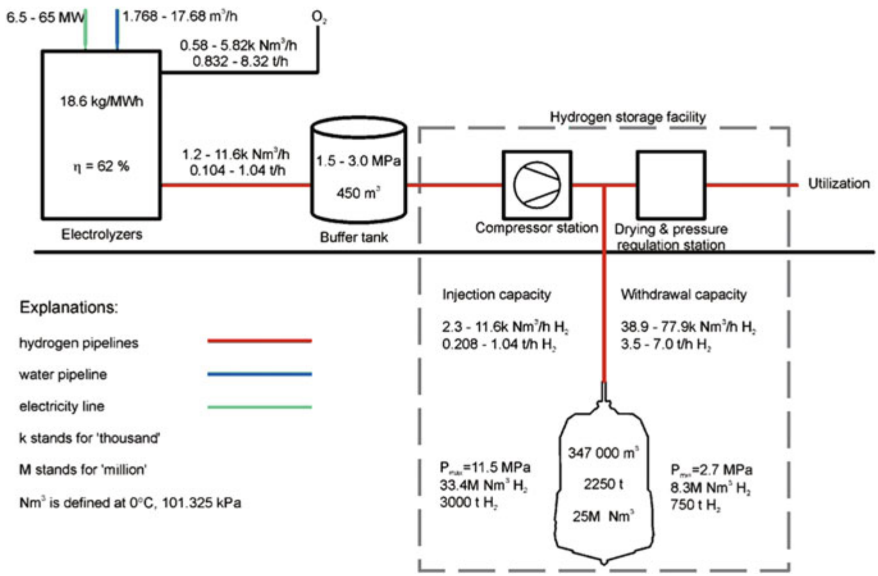


Fig. 2 Hydrogen production and storage for the HESTOR project. Data are given for the storage location B (see Table 2)

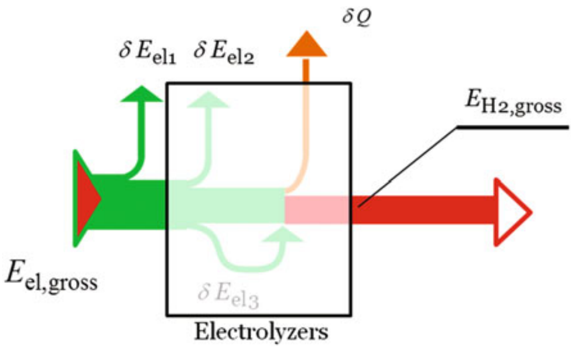


Fig. 3 A simplified representation of energy fluxes across the electrolyzer module

Table 1 Key fluxes of energy and materials across the electrolyzers

	Energy flow		Mass flow
	Absolute	Relative	
Electricity supply, MV (gross)	54,280 kW	101%	–
Electricity supply, LV (net)	53,740 kW	100%	–
Water supply	–	–	2.482 kg/s
Hydrogen production (LHV)	33,317 kW	62%	0.278 kg/s
Oxygen production	–	–	2.205 kg/s

electrolyzer (and lost in later stages) as well as the evaporation enthalpy of water which is assumed not to be recovered in the later stage of the hydrogen utilization.

It should be added that the production section is supported by a local buffer tank aimed at equalization of production profile for variable supply conditions. This buffer tank (presented in Fig. 2) is neglected in further considerations.

The section of storage is based on underground storage caverns in two alternative locations. The hydrogen storage cavern in the finally chosen location will be constructed by leaching a naturally gastight salt deposit, leaving the required protective zones around the generated cavern (shelves, pillars).

The cavern will have a cylindrical shape with a dome in its upper part. The widened section of the wellbore between the dome and the last cemented casing will form the neck of the cavern. The cone-shaped lower part of the cavern will be filled with insoluble particles.

The shape of the cavern provides a long-term mechanical stability: the dome eliminates tensile stress while the neck shifts the variable stresses away from the junction with the last cemented casing (LCC).

For the purpose of the reported project, two locations of salt caverns were considered. The location A is foreseen to provide hydrogen for technological purposes. The location B will provide hydrogen for electricity generation. Key parameters of both caverns are given in Table 2. It may be seen that the maximum working capacity results from the difference of quantity stored at maximum and minimum operating pressure.

Table 2 Underground hydrogen storage caverns considered in the HESTOR project

Location	A	B
Geometric volume (m^3)	101,000	347,000
Max. cavern pressure (MPa)	16.0	11.5
Min. operating pressure (MPa)	3.7	2.7
Max. quantity of gas stored (Mg H_2)	1190	3000
Max. working storage capacity (Mg H_2)	900	2250
Diameter of the LCC (mm)	244.5	244.5
Depth of the casing shoe (m)	1015	725

Once the cavern construction and the final tightness test are terminated, the final process equipment will be installed. The main elements of the equipment are: the inner production string, a permanent packer, the downhole safety valve and the wellhead. The inner production string is hanged on the wellhead and in its lower end it is connected with the LCC by a permanent packer.

The tubing-casing annulus between the LCC and the production string will be filled by the packer fluid. A downhole safety valve will be installed inside the inner production string below the packer.

The underground storage facility is equipped with a set of compressor unit with three stages of reciprocating compressors. The operation of hydrogen compressor station designed within the reported project was studied by Witkowski et al. [2], they concluded that the specific energy consumption for hydrogen compression between 2.0 and 10.0 MPa is 2745 kJ/kg. Accordingly, for the purpose of the present paper location B (characterized by a slightly higher maximum pressure) was selected as an example and a conservative figure of 3000 kJ/kg was assumed.

Since the electrolyzers can provide hydrogen at 3.0 MPa and due to the proximity of the production, storage and utilization sites (<50 km), it is assumed that no transmission compressors need to be installed along the hydrogen transmission pipelines.

The utilization of hydrogen is considered for the following purposes:

- electricity generation in peak demand hours;
- fuelling hydrogen vehicles;
- industrial use in the refinery of Grupa Lotos SA

These purposes can be seen as an alternative (i.e. one of them is selected), or a mix of them can be used according to the future conditions in the local energy market.

In the case of electricity generation, it is assumed that hydrogen will be combusted in a dedicated turbine. However, a possible co-firing of hydrogen with natural gas is also an option. The assumed gas turbine efficiency is 35%, both for hydrogen, natural gas or co-firing application. However, in general the efficiency may be fuel-dependent.

In the case of transport applications, hydrogen can be distributed to passenger vehicles or buses by means of a dedicated filling station. For the purpose of this paper, a passenger car Toyota Mirai consuming 1.0 kg H_2 per 100 km was assumed for the analysis. In this case, a conventional fuel consumption is avoided.

Finally, hydrogen can be used within the Grupa Lotos SA oil refinery for technological purposes, replacing the existing hydrogen production by steam methane reforming.

Moreover, it should be reminded that **oxygen** produced by the electrolyzers is available. If the project implementation succeeds with an option of oxygen utilization, then the conventional production in an air separation unit is avoided as well. Otherwise, the production of oxygen has no energy or economic value.

3 Methodology

The key task of the present paper is to provide a methodology for defining the energy efficiency of the proposed project, accounting for all possible scenarios. For complex processes, defining the efficiency is, to some extent, arbitrary since the definition represents a ratio of selected fluxes called 'product' to selected fluxes representing the 'fuel' [3]:

$$\eta = \frac{\dot{E}_{\text{product}}}{\dot{E}_{\text{fuel}}} \tag{1}$$

It should be stressed that the term 'fuel' refers to energy streams of any type driving the process (i.e. not necessarily in agreement with the common sense of the word). The arbitrary sense of the generic definition (1) is related e.g. to the method of accounting the system's in-house consumption, which may either be subtracted from the product (as it is done in conventional power plants) or it may be added to the fuel. In the present project, the in-house consumption has been subtracted from the product.

Moreover, it is not straightforward to define the product for all utilization scenarios. For the case of energy generation it is convenient to assume that the product is represented by electricity generated at the end of the entire chain. However, for the case of hydrogen vehicles it is not possible to practically quantify the mechanical energy generated in the vehicle. In the case of process applications in the refinery (hydrocracking, hydrodesulphurization) the effect of hydrogen utilization would require a very complex analyses related with the quality of the refined fuels. Accordingly, for the case of vehicles and process applications, the substituted flux of energy used in reference process was assumed to be the product of the process:

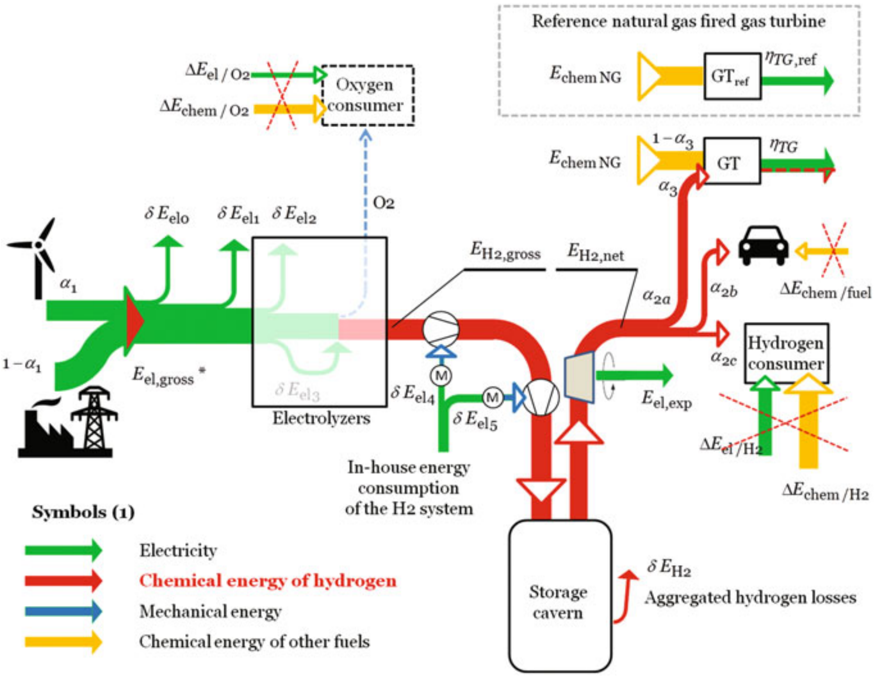


Fig. 4 A simplified representation of energy fluxes across the Hestor project

$$\dot{E}_{\text{product}} = \begin{cases} N_{el} & \text{for energy purposes} \\ \dot{E}_{\text{substituted}} & \text{for transport/process purposes} \end{cases} \quad (2)$$

The presented consideration are explained in Fig. 4 which comprises the entire chain of the HESTOR project.

The energy flow across the project may be explained as follows: some part of electricity (α_1) derives from renewable sources, while the remaining part ($1 - \alpha_1$) derives from fossil/nuclear fuels. This share has no importance unless a cumulative energy demand is studied. Then, energy is transmitted from the site of generation to electrolyzers suffering some losses $\delta E_{el0.}$ Then, energy is transformed to low voltage with transformation losses δE_{el1}. As already explained, AC/DC conversion losses and the in-house electricity consumption is included in the electrolyzer module (i.e. hidden in the value of its LHV efficiency). The generated hydrogen has the chemical energy $E_{H2,\ gross}$. It is then transported to the storage cavern, and then withdrawn. In general, energy may be required for hydrogen transmission (compressor station consuming δE_{el4}) and for hydrogen injection to the cavern (δE_{el4}). However, while withdrawing the hydrogen from the cavern some energy can theoretically be recovered in an expander ($E_{el,\ exp}$). In this case, the energy generated in the expander would contribute to the overall product of the system.

Possible losses of hydrogen from the system due to diffusion, failures or technological procedures are represented by the term δE_{H2}, symbolically aggregated to the storage cavern.

Next, three directions of hydrogen utilization (energy/transport/process) are represented by three distribution coefficients α_{2a}, α_{2b}, and α_{2c}, describing the share of hydrogen supplied to each of these sectors. In the further text, only the 'pure' utilization scenarios are considered (i.e. one of the coefficient is 100%), however, mixed scenarios are also of interest.

In the case of energy use, hydrogen may be co-fired with natural gas (or other fuel). In this case, only some part α_3 of the generated electricity should be attributed to hydrogen, and the remaining part $(1-\alpha_3)$ is generated from other sources (not contributing to the process product). The reference turbine fuelled with natural gas only may be considered if the efficiency of the turbine varies between the two fuels.

In the case of hydrogen vehicles, the flux of energy supplied with hydrogen replaces the flux of fossil fuels (petrol/diesel oil) delivered to a conventional vehicle.

In the case of process utilization, the flux of hydrogen energy replaces the same flux of hydrogen which otherwise would be produced by steam methane reforming. Accordingly, energy consumption burdening the SMR process can be attributed to the product of the HESTOR system.

Similarly, if oxygen utilization is considered, then the avoided energy consumption in a conventional air separation unit (ASU) can be attributed to the system product.

Unless a cumulative evaluation is needed, it is not necessary to distinguish between fossil fuel and electricity consumption in the replaced SMR/ASU processes. It is sufficient to indicate the total figure of energy consumption.

Assumptions done for the evaluation of the system efficiency are set in Table 3.

As it can be seen in Table 3, the choice of the reference (replaced) processes of diesel vehicles/steam methane reforming/air separation unit may affect the results, and therefore the results presented in the present paper should be understood as an example rather than a generally valid figures.

A comment should be added on hydrogen losses. In order to quantify the losses, it has been assumed that due to a construction failure, a rupture occurs in the cement annulus leading from the underground storage cavern to the surface. An equivalent diameter of the rupture was set to 1 mm, and then an adiabatic flow model according to [4] was applied. The channel length was set to 725 m and the downhole pressure to 11.5 MPa. It was found that the maximum outflow to the ambient air corresponds to less than 1 Nm^3/h of hydrogen, posing no hazard to the environment, and leading to a loss of 0.1% of the stored volume if the leakage continues during one year. Actually, it can be assumed that all possible failure scenarios will have an even lesser impact.

Table 3 Assumptions for the system efficiency evaluation of the HESTOR project

Parameter	Assumption/ value	Comments
Electrolyzer type	Alkaline	BAT 2017
Electrolyzer efficiency (LHV)	62%	
Spec. energy consumption for H_2 compression	3000 kJ/kg	[2]
Spec. energy consumption for H_2 transmission	0 kJ/kg	<50 km, electrolyzer @3 MPa
Energy recovery (H_2 expanders)	0 kJ/kg	not profitable
Hydrogen losses (maximum level)	0.1%	adiabatic flow model for 1 mm diameter of rupture [4]
Gas turbine efficiency	35%	244.5
Hydrogen consumption/vehicle	1.0 kg/ 100 km 119.9 MJ/ 100 km	Toyota Mirai, power 114 kW
Fuel consumption, replaced equivalent vehicle	5.1 dm^3/ 100 km 182.0 MJ/ 100 km	Opel Astra Astra 2.0 diesel power 118 kW
Replaced energy consumption (diesel/H_2)	1.518 kJ/kJ	=182/119.9
Replaced energy consumption for H_2	146.5 MJ/kg	SMR [5]
Replaced energy consumption for O_2	1.285 MJ/kg	Conventional ASU [6]

4 Results, Discussion and Conclusions

Results of the process efficiency obtained for the presented assumptions are shown in Table 4.

As it can be seen, the lowest process efficiency is obtained for the scenario of pure electricity generation, where hydrogen is not used for other purposes. In this case, the power-to-gas-to-power chain yields a figure of approximately 20% efficiency.

The remaining scenarios yield a much higher efficiency, which actually results from the fact that hydrogen production in the considered alkaline electrolyzer is

Table 4 Efficiency of the HESTOR project for pure scenarios

Purpose of H_2 utilization	Efficiency	
	Without O_2 utilization (%)	With O_2 utilization (%)
Electricity generation	19.9	25.1
Hydrogen vehicles	91.5	96.7
Process application (refinery)	73.4	78.6

more efficient than the SMR process. Similarly, the fuel-cell based Toyota Mirai consumes less energy than the considered vehicle of equivalent power. Accordingly, the overall value of efficiency is above the efficiency of the electrolyzer.

In all three cases, the option of oxygen utilization provides an improvement of the process efficiency by approximately 5% points.

5 Conclusions

It has been demonstrated that the efficiency of hydrogen-based energy storage systems may be extremely variable depending on the final purpose of hydrogen utilization. For the case of energy generation (i.e. power-to-gas-to-power), the overall efficiency is low since it is basically a product of the electrolyzer and the gas turbine efficiencies. However, the system may be economically viable if the operator is able to acquire electricity at very low prices (or at no cost from own renewable sources), and then to sell it in peak hours. The sell-to-buy ratio of prices should exceed 5 in this case.

The energy generation system can potentially be improved (in terms of energy efficiency) by applying fuel cells instead of a gas turbine. This option is likely to develop in the future as the problems of part-load operation of fuel cells as well as their high investment cost still need to be addressed.

Regarding the alternative options of hydrogen utilization, it is demonstrated that the considered scenarios of hydrogen vehicles or process application are both very attractive in terms of energy. Their application can thus only be limited by market issues (vehicles) or economic issues (process application), since a sufficient yearly operation time of the invested equipment must be ensured.

The presented energy analysis represents a first approach to the topic. The questions of cumulative/LCA evaluation, energy evaluation as well as the operational analysis related to the yearly load/production curves and the availability of the storage facility should be addressed in incoming publications.

Acknowledgements The work has been carried out within the project ‘Hydrogen energy storage in salt caverns’, No. GEKON1/O2/214140/23/2015, supported by the National Centre of Research and Development and by the National Fund of Environmental Projection and Water Management of the Republic of Poland.

References

1. Bartela Ł., Dubiel K., Kotowicz J.: Impact of the technical and economic conditions on construction of energy storage systems. In: Proceedings of the 6th Scientific and Technical Conference ENERGETYKA GAZOWA 2016, vol. II, pp. 25–31. ITC Press, Gliwice (2016). (in Polish)
2. Witkowski A, Rusin A, Majkut M, Stolecka K.: Comprehensive analysis of hydrogen compression and pipeline transportation from thermodynamics and safety aspects. Energy, (in press) Available online 26 May 2017. https://doi.org/10.1016/j.energy.2017.05.141
3. Tribus, M., Evans, R.B.: A contribution to the theory of thermoeconomics. Technical report, 546 Report No. 62–63; Department of Engineering, UCLA: Los Angeles, CA, USA (1962)
4. Kostowski, W.J, Skorek, J.: Real gas flow simulation in damaged distribution pipelines. Energy **45**(1), 481–488 (2012). ISSN 0360-5442. http://dx.doi.org/10.1016/j.energy.2012.02.076
5. Sanchez, R.A., Riboldi, L., Jakobsen, H.A.: Numerical modelling and simulation of hydrogen production via four different chemical reforming processes: process performance and energy requirements. Can. J. Chem. Eng. **95**, 880–901 (2017). https://doi.org/10.1002/cjce.22758
6. Aneke, M., Wang, M.: Potential for improving the energy efficiency of cryogenic air separation unit (ASU) using binary heat recovery cycles. Appl. Therm. Eng. **81**, 223–231 (2015). https://doi.org/10.1016/j.applthermaleng.2015.02.034

The Simulation of Temperature Distribution in a Ground Heat Exchanger—GHE Using the Autodesk CFD Simulation Program

Jan Giełżecki and Tomasz Jakubowski

Abstract The simulation of the temperature distribution in the ground heat exchanger was carried out using Autodesk Inventor and CFD Simulation programs. The "Inventor" program has built a ground geometry model of a heat exchanger based on an existing exchanger. CFD Simulation analyzes the effect of structures on airflow in two-phase (air-stone) air and bed temperature distribution. The program defines the materials that comprise the building, defines the boundary conditions and the initial operation of the ground heat exchanger. In order to optimize the work of the deposit, multi-variable scenarios with different initial parameters were designed: changing the temperature and speed of the air supplied to the exchanger. The section planes have been defined for visualization of air velocity vectors and additional cross-sectional planes with temperature field distributions. The obtained results of the temperature fields from the multivariant simulation were compared with the actual temperature distribution. The actual temperature distribution was obtained from the GHE digital temperature gauges installed at the time of assembly.

Keywords Ground heat exchanger · Rock bed thermal storage
Simulation research CFD

J. Giełżecki (✉) · T. Jakubowski
Faculty of Production and Power Engineering, University of Agriculture
in Krakowul, Balicka Nr 116, 30-149 Krakow, Poland
e-mail: jan.gielzecki@ur.krakow.pl

T. Jakubowski
e-mail: tomasz.jakubowski@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_32

1 Introduction

The construction of the GHE is designed as a natural bed of clean, rinsed gravel, located in soil. The air flowing through the gravel depends on the season of year, cooled down, warmed up, dried, or humidified and (always) filtered. The direct contact with the surrounding subsoil facilitates rapid regeneration of the gravel bed [1].

This article explores the possibilities of using commercially available Autodesk engineering software in CFG simulations using an example of air flow simulation and temperature distribution in GHE.

The "Inventor" program makes it easy to build a geometric model of a tested device and then simulate any process related to fluid flow, heat flow, motion in a CFD program.

2 The Actual Ground Heat Exchanger and Its Geometric Model

The dimensions of the bed and the location of the measuring points are shown in Fig. 1.

Figure 2 shows:

A manifold pipe supplying air from the bed to the system of supply and exhaust ventilation of the object,

B collective pipe draws air from the drainage pipe system C, which receives air from the bed,

D pipes ϕ250 connected to the outside air intake coupled to the E ϕ125 polyethylene drainage pipes of hard polyethylene with 6 oval holes per circumference every 1.5 cm along the pipe.

An example of actual temperature distribution is shown in Figs. 3 and 4.

3 CFD Simulation

In some analyses the actual flow geometry may contain a large number of holes or obstructions. For example, baffles are used in many electronics packages and often have hundreds of holes through which the air must pass. To model each and every hole would be tedious, expensive and unnecessary [2, 3].

In order to simplify and shorten the calculation time, two-phase (stone-air) and drainage pipes were modeled as filters.

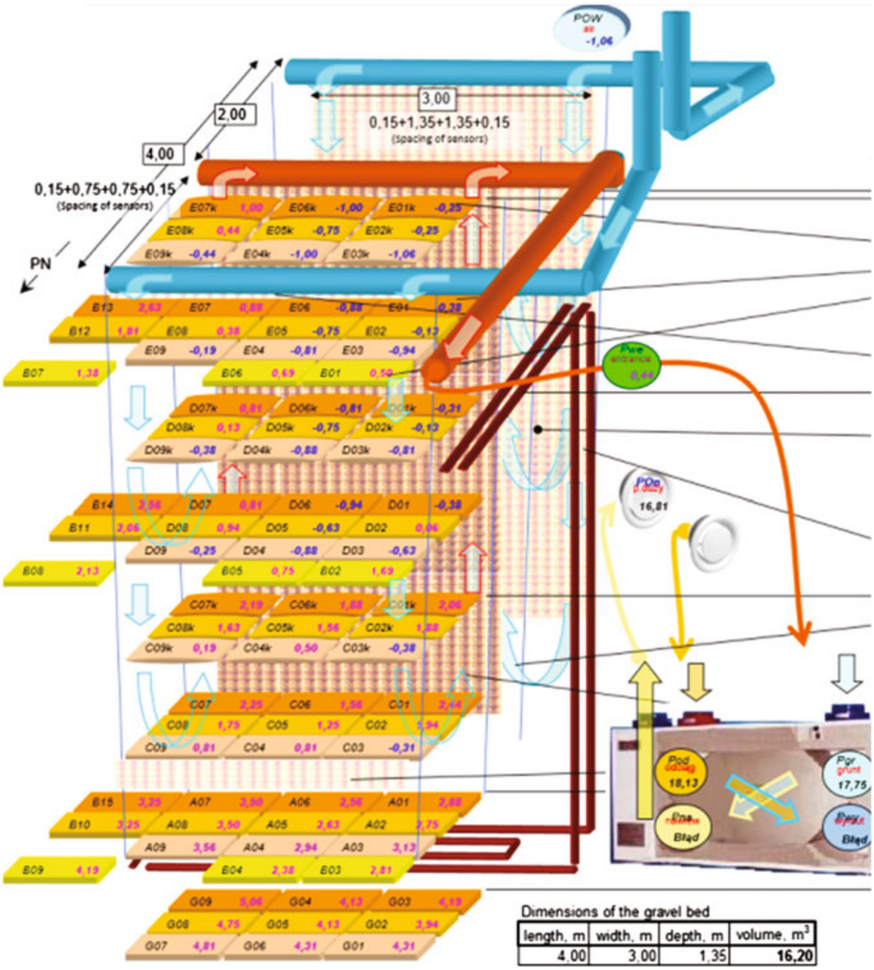
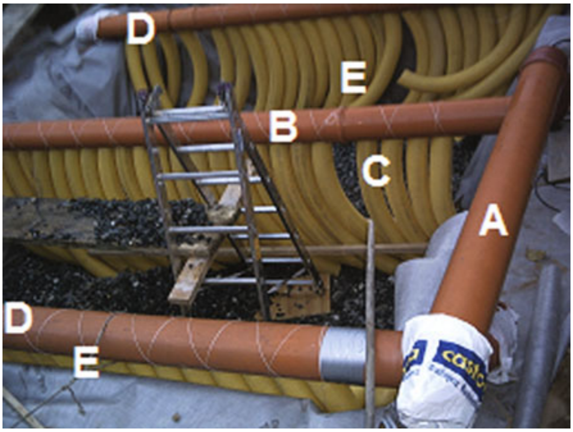


Fig. 1 Arrangement of temperature measurement points in GHE

Fig. 2 The arrangement of distribution, gathering and collected pipes



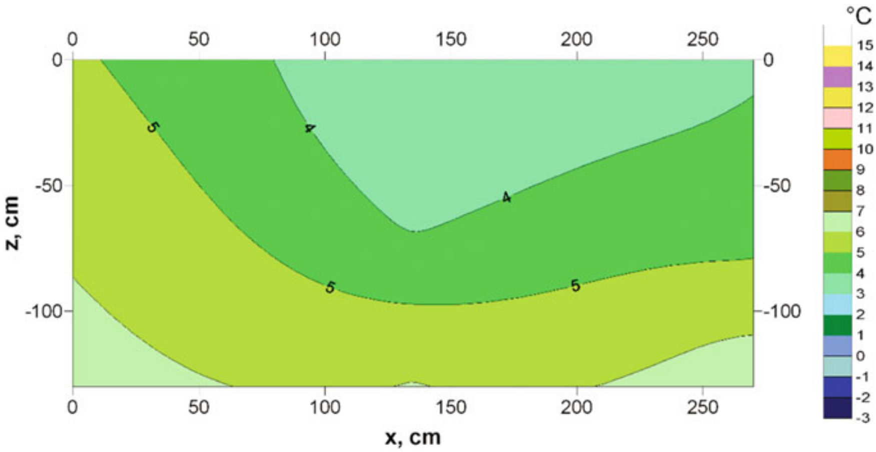


Fig. 3 Exemplary real temperature distribution in vertical section

3.1 Geometric Parameters of Bed Filling Ground Heat Exchangers (GHE)

During the construction of the GHE a gravel sample was left, which parameters are shown in Table 1.

Calculation of key parameters of real deposit based on theoretical—experimental formulas from literature [5].

The key parameter for filling the bed is its porosity

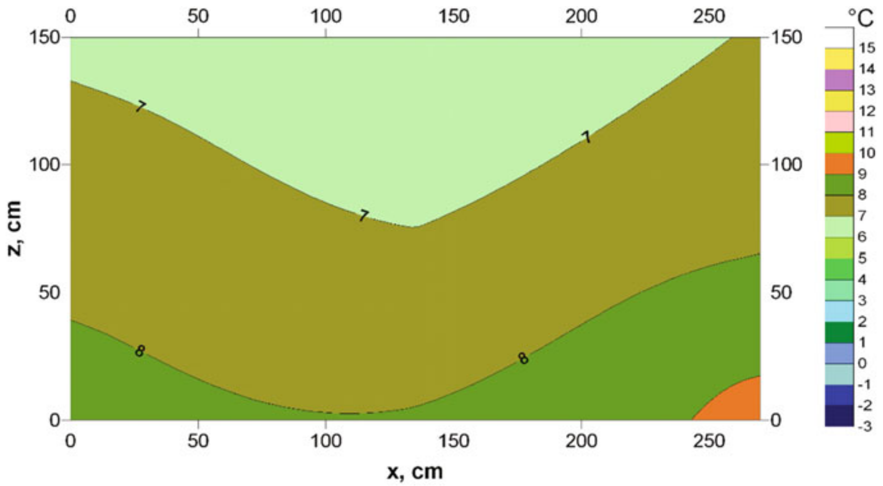


Fig. 4 Exemplary real temperature distribution in horizontal section

Table 1 Physical data on the gravel sample

Total weight of the sample	Amount of stone in the sample	The bulk volume of the sample	Total volume of grain filling the bed
kg	pcs.	V_b, m^3	V_g, m^3
26.5	1950	20.5×10^{-3}	11.15×10^{-3}

$$\emptyset = 1 - \frac{V_g}{V_b}, m^3/m^3 \tag{1}$$

where:

V_b the bulk volume of the sample, m^3,
V_g total volume of grain filling of the bed, m^3.

The substitute bed heat transfer coefficient λ_s can be calculated from the formula:

$$\frac{\lambda_s}{\lambda_a} = \left(\frac{\lambda_g}{\lambda_a}\right)^{0.280 - 0.757\log\phi - 0.057\log\left(\frac{\lambda_s}{\lambda_a}\right)} \tag{2}$$

where:

λ_s substitute bed heat transfer coefficient,
λ_a air heat transfer coefficient,
λ_g heat transfer coefficient of the material used to fill the bed.

The heat transfer coefficient for air was adopted λ_a = 2.563e−05 0.025 W m^{-1} K^{-1} and to fill the bed λ_s = 1.291 W m^{-1} K^{-1}.

Table 2 Perforation of PVC-U pipes according to PN-C-89221: 1998/Az1: 2004 [4]

Pipe ϕ (mm)	Slot width (mm)	Slot length (mm)
50	0.8	4.5
65–200	1.2	4.5
100–200	1.5	5.0

Table 3 Boundary conditions and initial simulations

Perforation of drainage pipes (m^2/m^2)	Outdoor temperature (°C)	Air velocity of aspiration from the bed (m/s)	The initial temperature of the bed (°C)
0.012	−20 to 30 krok 5	2	10
0.012	−20 to 30 krok 5	3	10
0.012	−20 to 30 krok 5	4	10
0.012	−20 to 30 krok 5	5	10
0.0051	−20 to 30 krok 5	2	10
0.0051	−20 to 30 krok 5	3	10
0.0051	−20 to 30 krok 5	4	10
0.0051	−20 to 30 krok 5	5	10

Perforated corrugated pipes made of PVC-U used in the construction of GHE are produced in different sizes of perforation gaps. The inlet slots are evenly distributed throughout the periphery of the pipe and have a large total surface area of 20–47 cm 2 per 1 m of pipeline. PVC-U 50–200 mm pipes have perforations according to PN-C-89221 and slots are cut in between recesses Table 2.

3.2 *Multivariate Calculation Scenarios with Different Initial Parameters*

The summary of the simulations, quantities, boundary and initial parameters are presented in Table 3.

The key material used in the model is shown in Tables 4, 5, 6, 7, 8 and 9 in Autodesk CFD 2018. Environment: 101,325 Pa, outdoor temperature from scenario.

Figures 4, 5, 6, 7, 8 and 9 depict a bed geometry model, initial and boundary conditions, an exemplary bed temperature distribution and flow pattern.

Table 4 Properties for air (fixed)

Density	Viscosity	Conductivity	Specific heat	Cp/Cv	Emissivity
1.20473e+03	1.817e−05	2.563e−02	1.004	1.4	1
kg m^{-3}	Pa s	W m^{-1} K^{-1}	kj kg^{-1} K^{-1}	–	–
Equation of state	Const.	Const.	Const.	Const.	Const.

Table 5 Properties for insulation (expanded polystyrene—fixed)

Density	xyz—conductivity	Specific heat	Emissivity
2.5e +02	2.5e−02	1.4	0.8
kg m^{-3}	W^{-1} K^{-1}	kJ kg^{-1} K^{-1}	–
Const.	Const.	Const.	Const.

Table 6 Properties for PVC (fixed)

Density	xyz—conductivity	Specific heat	Emissivity
1.4e +03	2.5e−01	1.25	0.92
kg m^{-3}	W m^{-1} K^{-1}	kJ kg^{-1} K^{-1}	–
Const.	Const.	Const.	Const.

Table 7 Properties for soil (dry clay—fixed)

Density	xyz—conductivity	Specific heat	Emissivity
1.6e +03	2.5e−01	0.89	0.92
kg m^{-3}	W m^{-1} K^{-1}	kJ kg^{-1} K^{-1}	–
Const.	Const.	Const.	Const.

Table 8 Properties for resistant pipes (variable)

xyz—conductivity	Through flow K
2.5e−02	0.012
W m^{-1} K^{-1}	–
Const.	Free area ratio

Table 9 Properties for Resistant stone (variable)

xyz—conductivity	Through flow K
1.444e−01	4.56e−01
W m^{-1} K^{-1}	–
Const.	Free area ratio

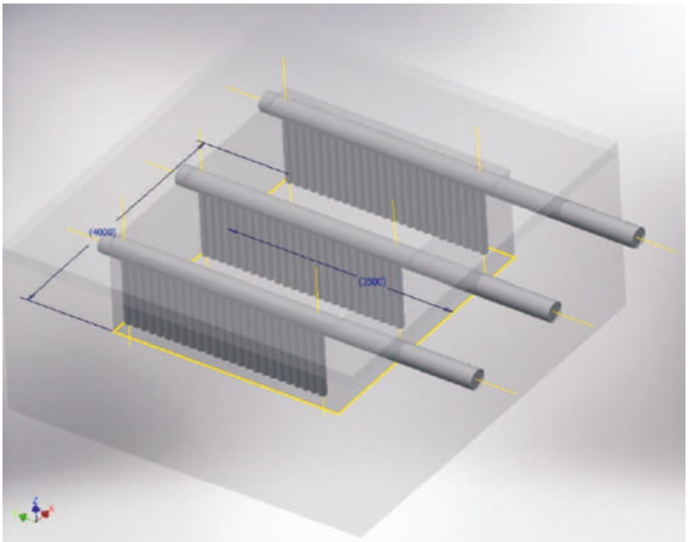


Fig. 5 The "Inventor" program has built a ground geometry model of a heat exchanger based on an existing exchanger

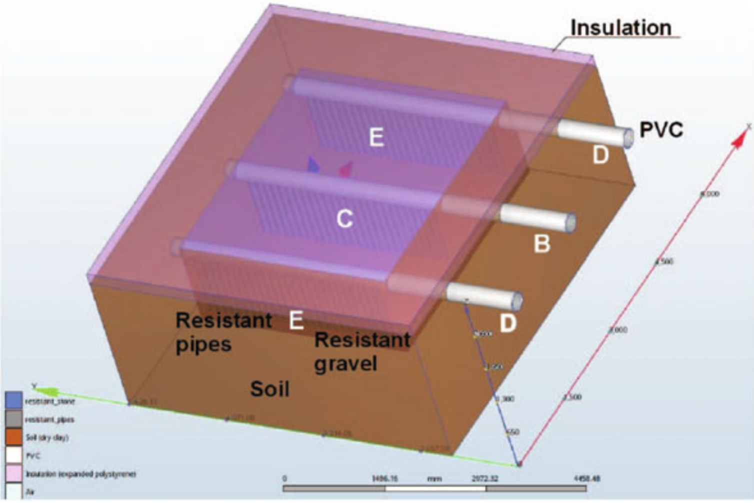


Fig. 6 Determination of boundary conditions and initial conditions in a CFD program. In order to simplify and shorten the calculation time, two-phase (stone-air) and drainage pipes were modeled as filters

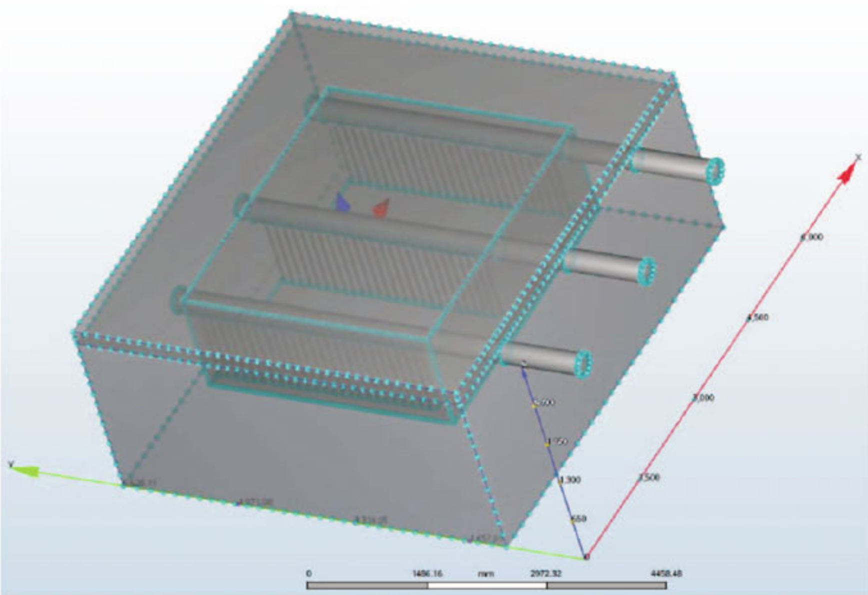


Fig. 7 Finite element: 558,494 total nodes, 517,760 fluid nodes, 40,734 solid nodes 2,997,861 total elements, 2,711,833 fluid elements 286,028

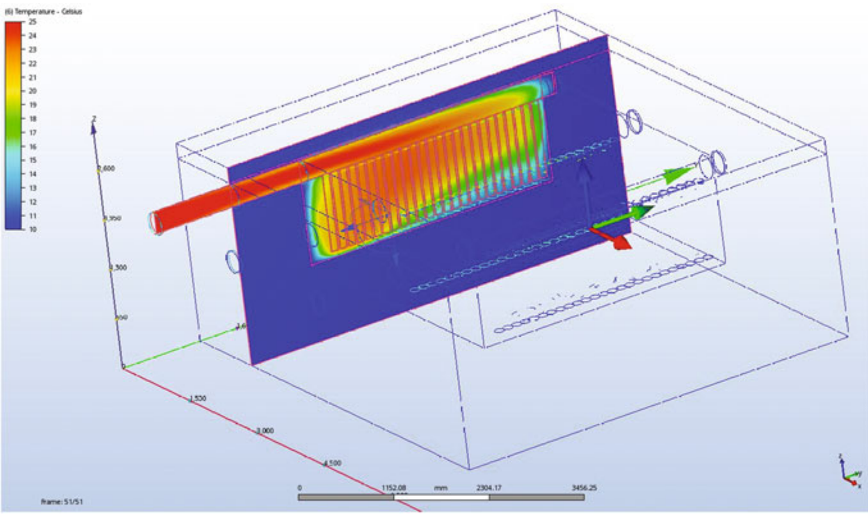


Fig. 8 Exemplary simulated temperature distribution in vertical section

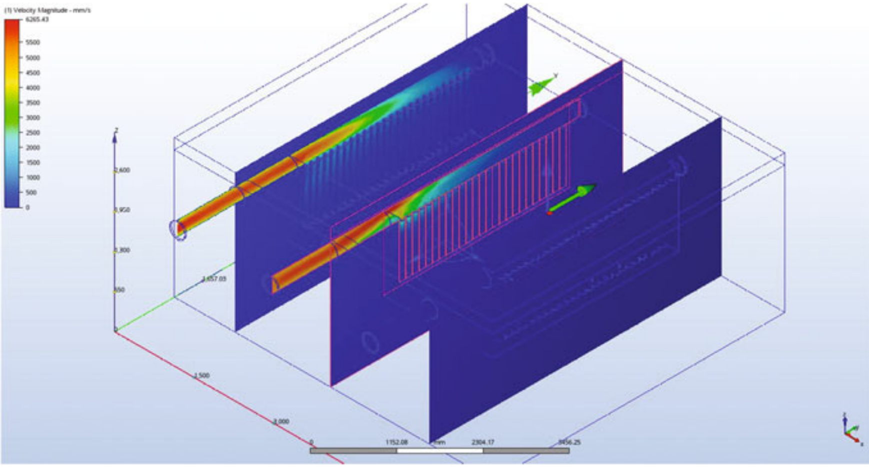


Fig. 9 Exemplary simulated air flow in the GHE field

4 Conclusions

- Strong influence of outside temperature on bed temperature was observed. At the intake of air from the intake at low outdoor temperatures (at several degrees below zero) there were negative temperatures at one third of the bed dimensions in all directions in the bed.
- The temperature in the underlying soil under the bed shows a slight trend of temperature changes during the heating or cooling period.
- Cooling of the bed is particularly noticeable at the top, indicating a deeper flow of air through the shortest path from the intake to the intake tube.
- In the vertical sections of the temperature fields the largest temperature gradient was observed at the inlet of the air intake from the bed.
- The best compatibility of simulation calculations for temperature distribution is obtained after full recovery of GHE (about 90%).
- Simulation calculations provide an opportunity to observe the air flow in the bed.
- Real-field measurements and simulation calculations show uneven flow and heat reception.
- The air distribution pipes should be redesigned by grading the number of holes depending on the distance from the intake.
- Differentiated zone granulation of the bed filling would allow more uniform airflow.

References

1. http://taniaklima.pl/tk/eng/
2. https://knowledge.autodesk.com/support/cfd/learn-explore/caas/CloudHelp/cloudhelp/2014/ENU/SimCFD/files/GUID-BCF33737-497B-47B8-867B-5DF174A7F9D1-htm.html
3. Bhutta, M.M.A., Hayat, N., Bashir, M.H., Khan, A.R., Ahmad, K.N., Khan, S.: CFD applications in various heat exchangers design: a review. Appl. Thermal Eng. **32**, 1–12 (2012)
4. PN-C-89221:1998/Az1:2004, Rury z tworzyw sztucznych – Rury drenarskie karbowane z niezmiękczonego poli(chlorku winylu) (PVC-U)
5. Smolec, W.: Fototermiczna konwersja energii słonecznej. Wydawnictwo Naukowe PWN, Warszawa (2000)

Torrefaction of the Black Lilac (*Sambucus nigra* L.) as an Example of Biocoal Production from Garden Maintenance Waste

Krystian Butlewski, Wojciech Golimowski, Weronika Gracz, Damian Marcinkowski, Maciej Waliński and Jacek Podleski

Abstract The paper presents the conversion of the black lilac (*Sambucus nigra* L.), which is an example of garden plant residues coming from garden maintenance works into valuable energy carriers by using torrefaction technology. A laboratory reactor was built for the torrefaction process, which allowed black lilac chips to be roasted at a temperature ranging from 250 to 300 °C for several dozen minutes. The black lilac's properties and structure were investigated before and after material torrefaction to identify the effect of this process on the plant. The average higher heating value (HHV) of the raw black lilac increased from 17.2 to 24.0 MJ/kg after torrefaction. The average mass yield amounted to 39–65%, while the energy yield amounted to 58–96%. The moisture of the black lilac after cutting and grinding was up to 50%, while after torrefaction it did not exceed 4%. Analysis using a scanning electron microscope and an optical microscope revealed the black lilac's fibrous and annular structure with spherical inclusions, which changed following the torrefaction process into a flatter, more even structure with fewer inclusions. Elementary analysis revealed a significant decrease in the O/C ratio as a result of the

K. Butlewski (✉) · W. Golimowski · W. Gracz
D. Marcinkowski · M. Waliński · J. Podleski
Institute of Technology and Life Sciences, Ul. Biskupińska 67,
60-463 Poznań, Poland
e-mail: k.butlewski@itp.edu.pl

W. Golimowski
e-mail: w.golimowski@itp.edu.pl

W. Gracz
e-mail: w.gracz@itp.edu.pl

D. Marcinkowski
e-mail: d.marcinkowski@itp.edu.pl

M. Waliński
e-mail: m.walinski@itp.edu.pl

J. Podleski
e-mail: j.podleski@itp.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_33

torrefaction process. It was also found that the spherical inclusions were composed to a high degree of Ca, Al or Si elements. TGA analysis showed high volatile matter content in the raw black lilac, which decreased significantly after torrefaction. The study shows that torrefaction technology is a valuable process for the production of biocoal from garden maintenance residues.

Keywords Torrefaction · Biomass · Garden residues

1 Introduction

Torrefaction is the thermochemical process used to improve the quality of biomass fuel, which can be used for co-firing with coal [1] or for production of pellets or briquettes [2–5]. The torrefied biomass can also be used as quality improved biomass for the gasification process [6–9]. The parameters of torrefaction process are temperature and time duration. The biomass is subjected to the heat at the temperature in the range between 200 and 300 °C for about tens of minutes. Torrefaction process runs in a minimum oxygen presence. In testing units nitrogen or argon are used to remove air from the reactor. During the process of torrefaction biomass molecular composition undergo various changes. Extractives degrading and volatilizing at 100–250 °C, hemicellulose begin to degrade and volatilize at 200 °C with complete degradation at around 245 °C. Lignin starts to undergo small changes at 200–270 °C, while cellulose is not affected by the torrefaction process because it starts to change the molecular composition from temperature about 350 °C.

Lignocellulosic biomass consists of cellulose, lignin and hemicellulose compounds. Cellulose compound contains high amount of carbon and highly contributes to the energy content included in a lignocellulosic biomass. The chemical structure of cellulose contains a linear polymer chain and micro-fibrils circled by amorphous cellulose. Lignin is a complex of various polymer structure with phenyl-propane and aromatic rings. The lignin in a lignocellulose biomass binds cellulose and hemicellulose structures. Hemicellulose contains multiple monosaccharides with short branches.

The mechanism of the thermal treatment during the torrefaction process includes decarboxylation, dehydration, decarbonylation, demethoxylation, intermolecular derangement, condensation and aromatization reactions.

Torrefaction is a very promising technique for developing a new quality material, which can replace the extensively used coal for energy generation with the aim of reducing the greenhouse gases emission. The process is still not well recognized and more scientific work have to be carried out in order to find out more fundamental knowledge of the process, which will lead to the efficient production of torrefied biomass from various feedstock.

In this work torrefaction process of the Black Lillac (*Sambucus nigra* L.), as an example of the biomass coming from the garden maintenance work, has been analyzed.

2 Experimental

2.1 Experimental Setup for Torrefaction

An experimental torrefaction set-up designed and built at the Institute of Technology and Life Sciences is shown in Fig. 1. The torrefaction system consists of an electrically heated oven (1), in which the reactor (2) is subjected to heat transferred from the surrounding air within the oven. The reactor is made of stainless steel and is covered by a lid with a hole to let volatile products flow out from the container (reactor). The biomass is fully packed inside the container to minimize the amount of air present in the reactor. In the middle of the reactor, a thermocouple (5) is placed to measure the temperature of the torrefied biomass. The temperature inside the oven is controlled by the thermocouple (4) placed inside the oven. The solid, liquid and gaseous products are separated during torrefaction. Volatile products flows through a pipe (6) to a condenser (7) in which they are separated into condensable and non-condensable fractions. The condenser is cooled through a closed water circulation (8). The condensable fractions are collected in the glass tank (9), while the non-condensable parts flow through a pipe (10) and are collected in a flexible bag (11). The solid part remains in the reactor and is taken out of it after the torrefaction process is completed. The process is controlled and monitored via a control unit (12) equipped with a date storage unit (13) and a screen (14).

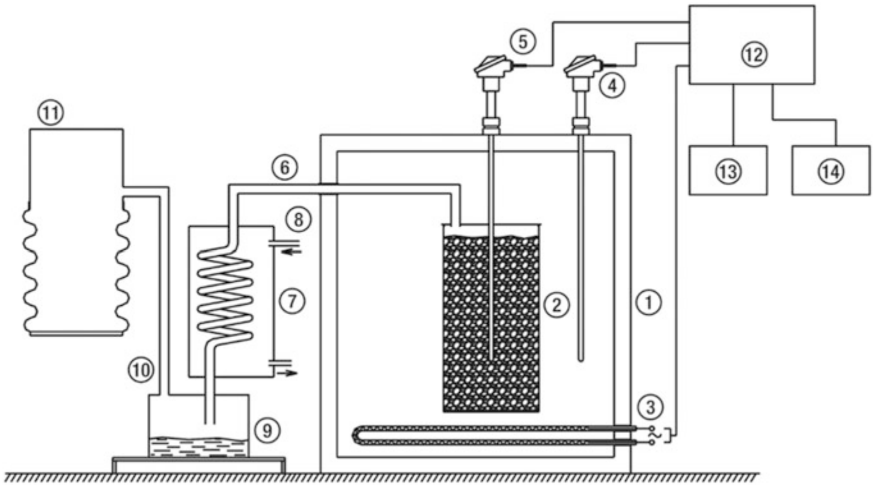


Fig. 1 Schematic diagram of the torrefaction set-up. 1—Electric furnace, 2—Reactor with material for torrefaction, 3—Electric heater, 4—Thermocouple, 5—Thermocouple, 6—Torgas flowing pipe, 7—Condenser, 8—Cooling water in and out, 9—Condensed liquid, 10—Exhaust gas pipe, 11—Non-condensable collection tank, 12—Control unit, 13—Data storage unit, 14—Screen

Fig. 2 Raw black lilac chips after the plant had been cut and shredded

2.2 Material

The experiments were run for the black lilac (*Sambucus nigra* L.) which is one of the typical plants obtained from garden maintenance work. The black lilac grew in a garden and there were several plants which could have been between one and ten years old. The plants were cut using a chainsaw then crushed into chips (Fig. 2) using a garden shredder. These chips were packed into sacks and transported to the testing laboratory.

2.3 Biomass Analysis and Procedure

2.3.1 Mass and Energy Yield

The mass and energy yields describe how much mass and energy remains in the solid fraction of biomass after the torrefaction process. The mass yield is defined by Eq. (1), while the energy yield is defined by Eq. (2)

$$Y_m = \frac{mass\ of\ torrefied\ solid\ fraction}{mass\ of\ initial\ biomass} \tag{1}$$

$$Y_e = Y_m \frac{HHV\ of\ torrefied\ solid\ fraction}{HHV\ of\ initial\ biomass} \tag{2}$$

where HHV stands for higher heating value and is expressed in MJ kg^{-1}

An important parameter for the torrefaction process is the biomass energy density increment, which is defined by Eq. (3). It describes torrefaction's impact on the biomass energy content with respect to the unit of mass.

$$E_d = \frac{HHV\ of\ torrefied\ solid\ fraction}{HHV\ of\ initial\ biomass} \quad (3)$$

3 Results and Discussion

3.1 Torrefaction Process Recording

Torrefaction parameters, including temperature and mass change, were recorded. A sample of these is shown in Fig. 3. Temperature was measured by a thermocouple placed in the middle of reactor, while the mass of the condensed liquid was measured using an electronic balance. Since the thermal conductivity of biomass is very low, the process was stopped when the temperature inside the reactor reached the desired value.

The temperature changes inside the reactor can be divided into three stages. During the first the biomass is heated up relatively quickly to a temperature of approx. 100 °C. In the second stage biomass is heated slowly, which takes place from 100 °C to about 250 °C. This is related to the vaporization of free and physically bound water contained in the biomass and the release of volatile

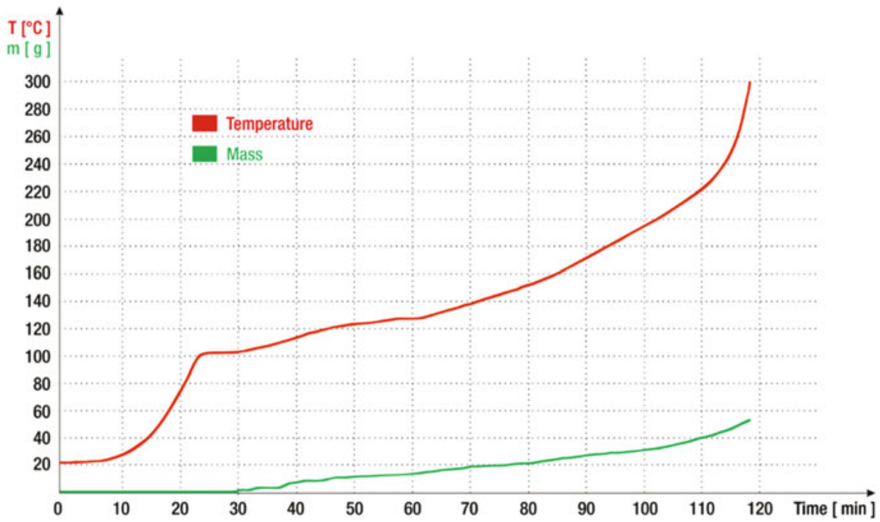


Fig. 3 The temperature changes inside the reactor and condensed liquid mass changes during the torrefaction process of black lilac

Fig. 4 Torrefied black lilac chip

hydrocarbon fractions. A rapid temperature increase above 250 °C occurs due to hemicellulose degradation and volatilization. Condensed liquid appears when the biomass reaches about 100 °C and increases steadily to about 250 °C. This phenomena is related to the condensation process of water and hydrocarbon vaporing. When the biomass reaches 250 °C, the mass condensation increases due to the intensive process of hemicellulose degradation and volatilization. The torrefied black lilac chips are shown in Fig. 4.

3.2 Microscopic Observation

Optical microscopic observation revealed changes appearing on the biomass surface due to the torrefaction process. The surface changed from rough and uneven to flatter and more even, as shown in Fig. 5.

3.3 Ultimate Analysis and Higher Heating Value

The parameters showing the effect of torrefaction on some black lilac properties including oxygen and carbon content, higher heating values (HHV), mass and energy yields are presented in Table 1. Torrefaction significantly affects the HHV values, as well as the oxygen and carbon content of this plant. The average HHV value increased from 17.2 to 24.0 MJ/kg. The carbon content increased by 79%

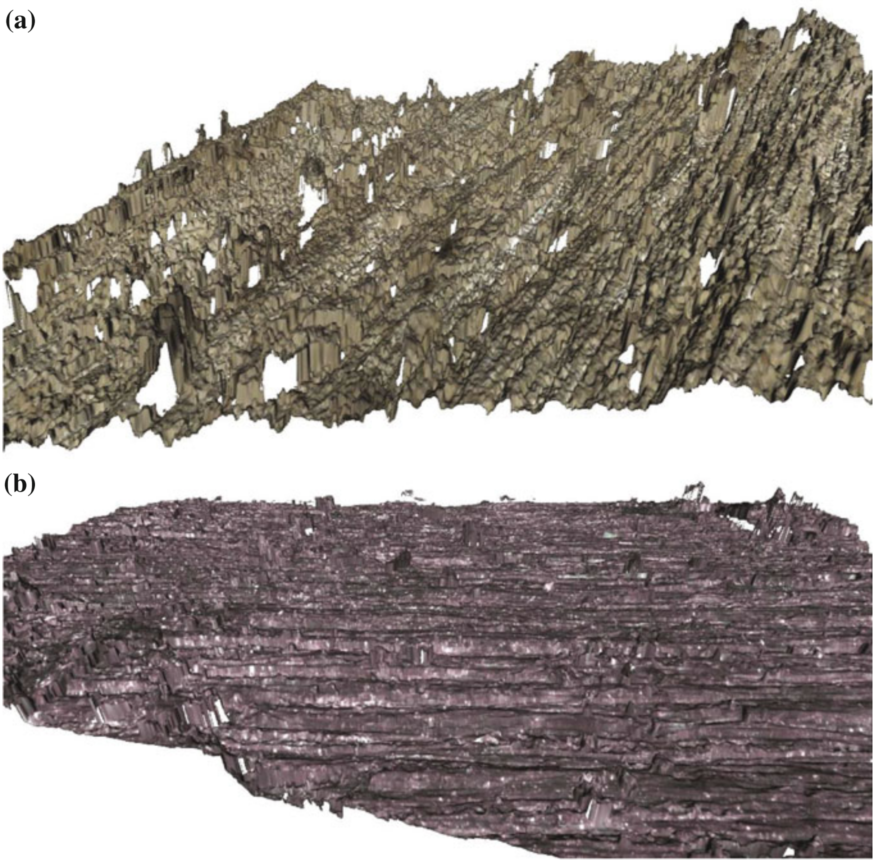


Fig. 5 Optical microscopic pictures of the black lilac **a** before torrefaction, **b** after torrefaction

Table 1 Effect of torrefaction on the chosen material's parameters

Samples of black lilac	HHV (MJ/kg)	Ultimate analysis (wt%, db)		Mass yield (%)	Energy yield (%)
		Carbon	Oxygen		
Raw material	17.4	29	57	39–65	58–96
Torrefied	24.0	52	37		

from 29 to 52 wt%, while the oxygen content decreased by 35% from 57 to 37 wt%. For coal the lowest carbon content is about 60% and the highest oxygen content is about 30% [10]. Carbon and oxygen contents after the torrefaction process of black lilac changes as shown in Fig. 6.

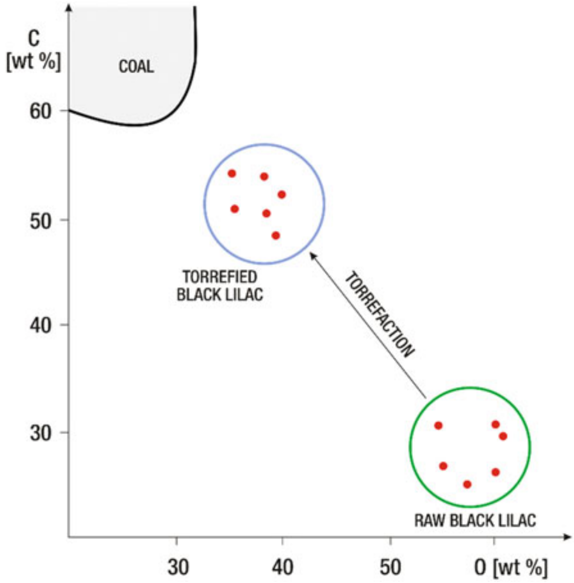


Fig. 6 Carbon versus Oxygen content before and after torrefaction in black lilac

3.4 TGA Analysis

Thermogravimetric analysis revealed changes caused by the torrefaction process in the material composition. The samples for raw and torrefied black lilac are shown in Fig. 7. In the raw material for the sample weight 6.49 mg, moisture, fixed carbon and volatile matters amounting to 6.82, 14.75 and 74.60% were recorded respectively. The torrefaction process changed the composition of black lilac by increasing the fixed carbon to 48.26%, decreasing the moisture content to 2.66% and volatile matters to 44.70%.

3.5 SEM Observation

Two types of structure composition were observed. The dominant one was fiber, as shown in Fig. 8. There are also many inclusions in the raw material visible in the picture as white spots. An analysis of their composition showed that they mainly comprise calcium, silicon and aluminium compounds. After the torrefaction process, the amount of these compounds decreases. In torrefied material fibers are

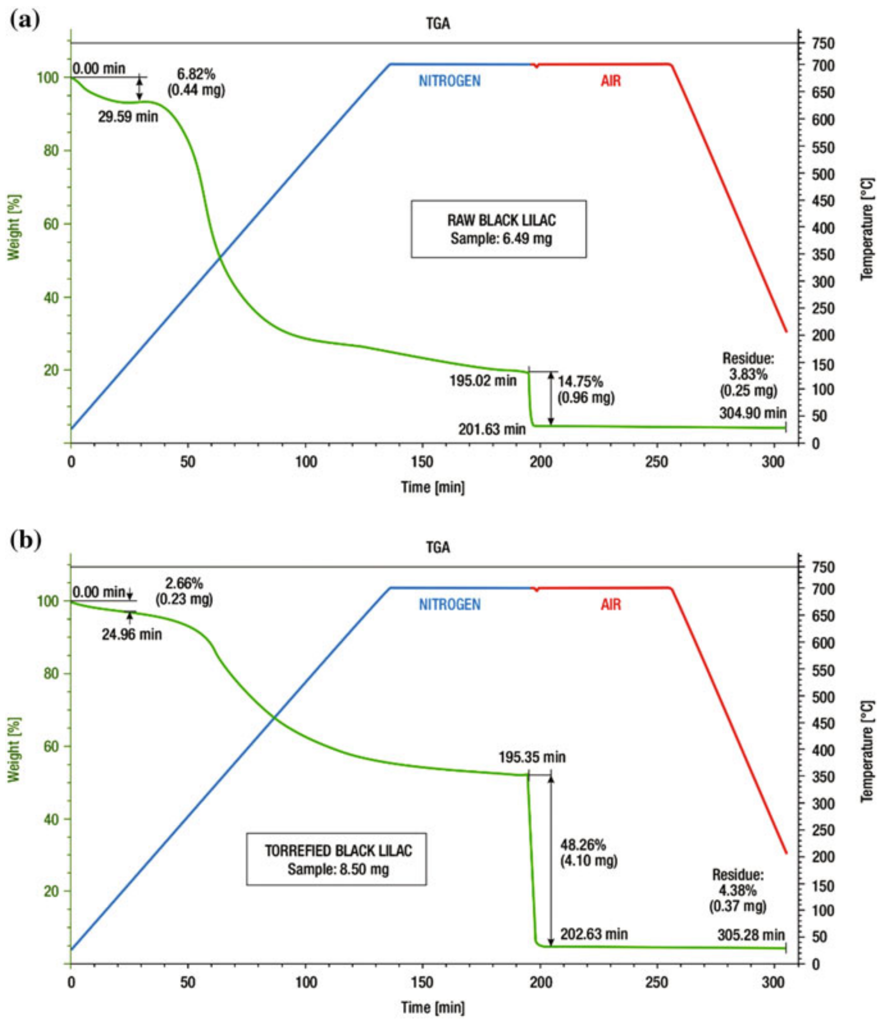


Fig. 7 Thermogravimetric analysis for **a** raw black lilac, **b** torrefied black lilac

expended due to volatiles being released from the material [11]. The second type of structure observed in the material is annular. After the torrefaction process, this type of structure becomes more flat and regular, as shown in Fig. 9. Like the previous structure, there are also more inclusions in the structure of the raw material than in the torrefied one. Some cracks are also seen on the picture of the torrefied material, which can be caused by volatiles being released from the lower layers of the material.

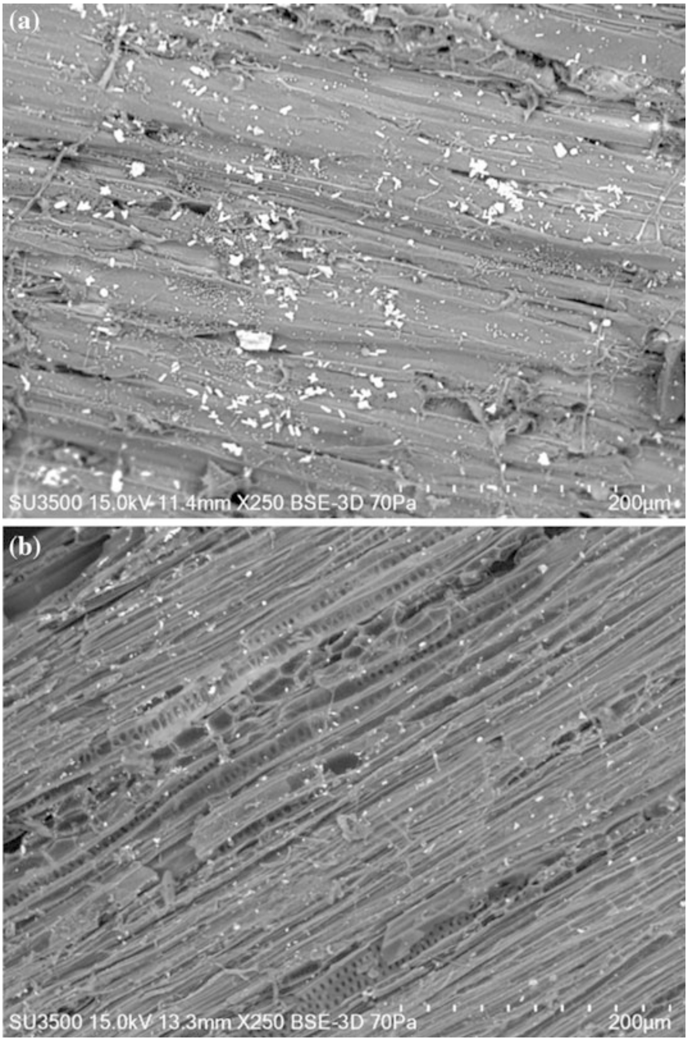


Fig. 8 SEM pictures of black lilac part of fiber structure **a** raw material, **b** torrefied material

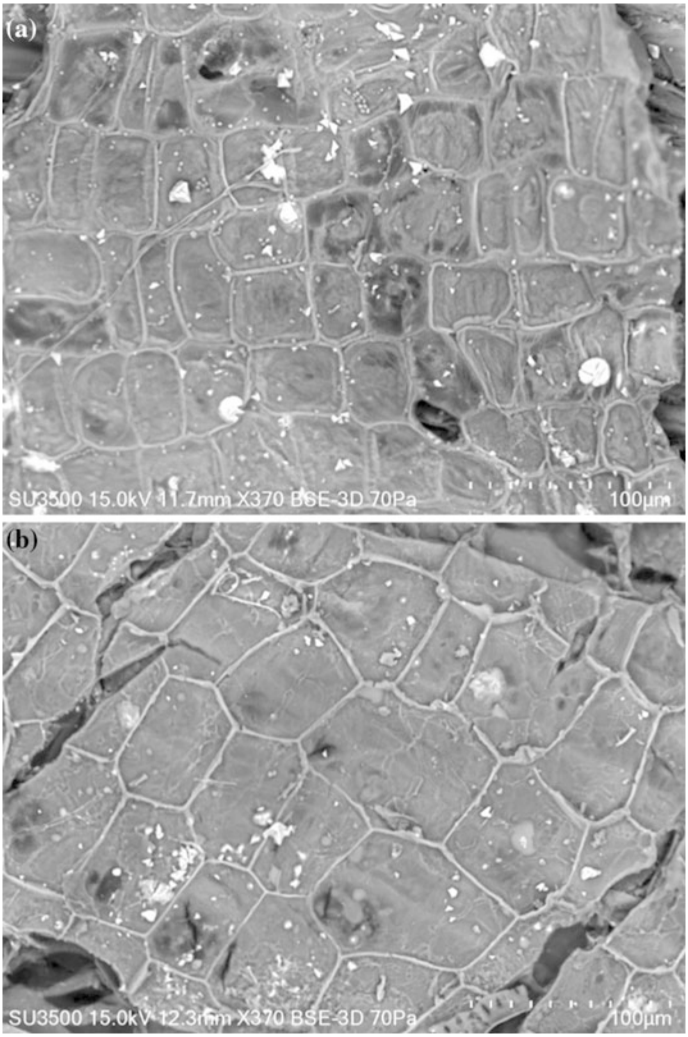


Fig. 9 SEM pictures of black lilac part of annular structure **a** raw material, **b** torrefied material

4 Conclusion

Torrefaction of garden maintenance residues showed that changes in this kind of biomass were very positive for their further energy processing. The Higher Heating Value (HHV) increased from 17.4 to 24.0 MJ/kg, the carbon-to-oxygen relation changed from 0.51 to 1.4 and the fixed carbon content increased from 14.7 to 48.3%. The surface of black lilac changed from rough and uneven to flatter and more even one after the torrefaction process. SEM observation revealed the fiber and annular structure with many inclusions containing mainly calcium, silicon and aluminium compounds. After the torrefaction process, more fibers and fewer inclusions were seen on the surface. Moreover, cracks in the annular part of the torrefied surface were observed. The torrefaction process of the black lilac, which is an example of garden maintenance residues, improved the material properties with respect to the properties appropriate for biomass firing, co-firing or gasification, making this material closer to hard coal.

References

1. Madanayake, B.N., Gan, S., Eastwick, C., Ng, H.K.: Biomass as an energy source in coal co-firing and its feasibility enhancement via pre-treatment techniques. Fuel Process. Technol. **159**, 287–305 (2017)
2. Van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, P.J.: Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenerg. **35**, 3748–3762 (2011)
3. Nunes, L.J.R., Matias, J.C.O., Catalao, J.P.S.: A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renew. Sustain. Energy Rev. **40**, 153–160 (2014)
4. Cremers, M., Koppejan, J., Middelkamp, J., Witkamp, J., Sokhansanj, S., Melin, S., Madrali, S.: Status overview of torrefaction technologies. In: IEA Bioenergy Task 32: Biomass Combustion and Cofiring (2015)
5. Rudolfoon, M., Boren, E., Pommer, L., Nordin, A., Lestander, T.A.: Combined effects of torrefaction and palletization parameters on the quality of pellets produced from torrefied biomass. Appl. Energy **191**, 414–424 (2017)
6. Weiland, F., Nordwaeger, M., Olofsson, I., Wiinikka, H., Nordin, A.: Entrained flow gasification of torrefied wood residues. Fuel Process. Technol. **125**, 51–58 (2014)
7. Xue, G., Kwapinska, M., Kwapinski, W., Czajka, K.M., Kennedy, J., Leahy, J.J.: Impact of torrefaction on properties of *Miscanthus giganteus* relevant to gasification. Fuel **121**, 189–197 (2014)
8. Woytiuk, K., Campbell, W., Gerspacher, R., Evitts, R.W., Phoenix, A.: The effect of torrefaction on syngas quality metrics from fluidized bed gasification of SRC willow. Renew. Energy **101**, 409–416 (2017)
9. Butlewski, K.: Combined biomass gasification and anaerobic digestion for the synergic effect in power production for the local application. Papers of the 24th European Biomass Conference, Amsterdam, The Netherlands, 884–885 (2016)
10. Mateli, S., Rahman, N.A., Idris, S.S., Yaacob, N., Alias, A.B.: Lignocellulosic biomass solid fuel properties enhancement via torrefaction. In: 4th International Conference on Process Engineering and Advanced Materials. Proc. Eng. 148, 671–678 (2016)
11. Wilk, M., Magdziarz, A., Kalemba, I.: Characterisation of renewable fuels torrefaction process with different instrumental techniques. Energy **87**, 259–269 (2015)

Harmful Environmental Impact of the Production Process of Photovoltaic Panels—A Review

Marcin Landrat, Krzysztof Pikoń and Magdalena Bogacka

Abstract Until recently, the main disadvantage of photovoltaics was the fact that from the perspective of ecology, it was more harmful than helping—the building of the cells required far more energy than they could generate. Although in a local scale it may have made sense and allowed to produce pure energy in a certain place, in the global perspective the balance was definitely negative. At present popular trend is promoted to use as a source of energy photovoltaic modules, but little is said about the harmful effects on the environment and human life of the production process of the PV cells. In the article, based on the available literature, the production process of silicon and tellurium-cadmium cells was analyzed. The production process has been described, with particular emphasis on the hazardous substances used in cell production, as well as by the toxic by-products of these processes. The type of environmental and human toxicity has been demonstrated and the possible ways of limiting this impact have been reviewed.

Keywords Photovoltaics · Silicon cells · Cadmium telluride cells
Manufacturing process · Recycling · Toxic products

1 Introduction

Solar energy is a vital part of the global trend towards clean, renewable energy. Over the last dozen or so years, the number of photovoltaic panels installed has been increasing on an unprecedented scale. Currently, attention is paid to potential

M. Landrat (✉) · K. Pikoń · M. Bogacka
Department of Technologies and Installations for Waste Management,
Silesian University of Technology, Konarskiego 18A, 44-100 Gliwice, Poland
e-mail: marcin.landrat@polsl.pl

K. Pikoń
e-mail: krzysztof.pikon@polsl.pl

M. Bogacka
e-mail: magdalena.bogacka@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_34

hazards and consequences of increasing the production of photovoltaic cells. In addition, it is disturbing that the largest production of cells is located in countries such as China or India, where production costs are the lowest, but at the same time the enforcement of environmental legislation is low. With the increase in production, the issue has so far been marginalized with regard to the management or disposal of waste such as the end-of-life modules. This type of waste is regulated by new European and domestic regulations.

In 2012, the revised Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment was adopted [1, 2], and it introduced a new categorization of equipment (change from 10 to 6 categories). For the first time, the photovoltaic panels have been included in electrical and electronic equipment (as equipment for the generation of electric currents), and thus fall within the scope of the directive. So far, due to the large share of glass panels (75%) in the design, they were classified as glass waste and usually landfilled [3]. In addition to the minimum collection and recovery rates for end-of-life equipment being determined, the responsibilities of the manufacturer were also specified, which include [4]:

- saving of raw materials,
- limiting the content of hazardous substances,
- designing of equipment in such a way so as to facilitate its disassembly.

Recycling of the end-of-life product should be considered already at the production stage [5, 6]. In this phase, the main objective is to reduce the over-exploitation of natural resources and the emission of waste from production into the environment as well as to minimize energy consumption in manufacturing processes and to take these factors into account when developing the production technology.

Photovoltaic modules often contain toxic substances which may cause problems throughout the entire life cycle of a product. The use of toxic substances in the production of PV modules poses a threat to the environment and to the workers involved in the production process, and significantly increases the cost of end-of-life cells disposal.

2 Toxic Substances Used in the Production of PV Cells

Analysis of manufacture has shown that the production of photovoltaic cells is a complex process that uses a number of chemical compounds whose uncontrolled release into the environment remains inert for the manufacturing process. Today, the photovoltaic industry is struggling with two major problems. The growing market and the increasing product demand force manufactures to constantly increase their production capacity while reducing the manufacturing costs and, thereby, increasing the negative impact of the production on the environment [7–9]. It is estimated that half of the world's PV cell production is made in China and Taiwan [10].

2.1 Silicon Cells

Currently, monocrystalline, polycrystalline or amorphous silicon-based cells account for about 90% of the market [10]. Silicon for the cells production is most commonly obtained as a result of the reduction of quartzite by carbon in arc furnaces. In this way, apart from silicon, carbon monoxide is formed, which is highly toxic to humans. The silicon produced, also known as metallurgical silicon, requires further purification because it is contaminated by the following elements: iron, aluminium, calcium, manganese, titanium, magnesium, nickel, chromium, copper, phosphorus, and boron. The reaction of metallurgical silicon with hydrochloric acid removes iron, aluminium, and boron. The process takes place at 300 °C, in the presence of a catalyst such as copper. In order to further purify the silicon, the Siemens process takes place at 1100 °C and therefore requires huge amounts of energy. After the process, polycrystalline silicon is obtained, and its purity may reach 99.99999%. Monocrystalline silicon is obtained from polycrystalline silicon. In the case of monocrystalline silicon, one of the threats is the process of cutting and preparing of the so-called silicon wafers [11]. As a result of this process, waste silicon is produced in the form of dust (kerf), the amount of which may reach up to 50% by weight of the chemical material to be treated [12]. The waste produced poses a risk primarily to the workers; therefore, it is recommended to use dust masks and set exposure limits to maintain a low level of dustiness. The figure presents the production process of photovoltaic cells based on silicone (Fig. 1).

In the production of thin-film silicon (most commonly used today), a highly explosive silane gas is used. In addition, silicon tetrachloride is a by-product of silane and trichloride silane production process. It is a highly toxic substance that causes skin and respiratory system burns and eye irritation. Silicon tetrachloride may be reused in silane production; however, it has to take place under strict control due to its extreme toxic properties.

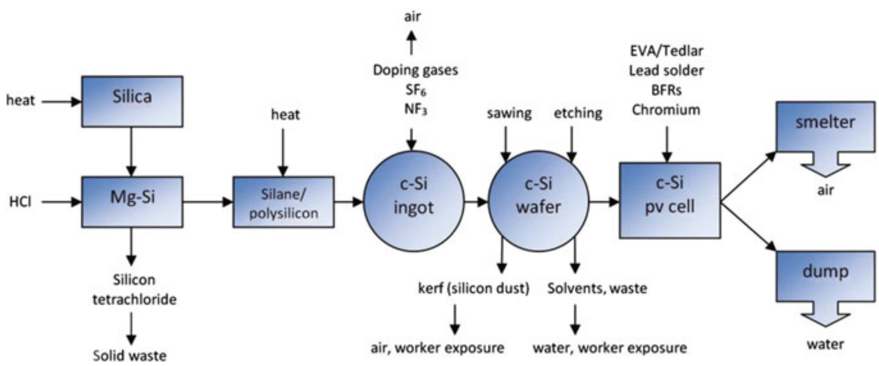


Fig. 1 Production process of photovoltaic cells based on silicone [13]

Sulphur hexafluoride is used to clean the reactors which serve in the cell production process. In the context of the greenhouse effect, this compound is 22,000 times more potent than CO_2 [14]. It is therefore necessary to find a replacement for this compound, so that the effect of reducing greenhouse gas emissions through the use of photovoltaic modules was not weakened by the use of highly "greenhouse" gases in the manufacture of these modules. Other substances that require special handling and disposal procedures while producing the crystalline silicon include [13, 15, 16]:

- sodium hydroxide used to remove scratches from silicon wafer surfaces (for this purpose, also potassium hydroxide is used); both substances are highly corrosive to the eyes, lungs, and skin,
- highly corrosive chemical compounds used for cleaning semiconductor materials (hydrochloric acid, nitric acid, sulphuric acid, hydrogen fluoride),
- toxic phosphine (PH_3) or arsine (AsH_3)—these gases are used in the doping of the semiconductor material; however, phosphorus trichloride, boron bromide, and boron trichloride are also used,
- isopropyl alcohol used to clean crystalline silicon wafers,
- lead used for brazing copper-based tape wires as well as in lead-based printing pastes,
- small amounts of silver and aluminium used for electrical contacts.

2.2 *Cadmium Telluride Cells (CdTe)*

The introduction of new cell types reduces the costs by using smaller amounts of semiconductor materials. These are the thin-film cells which may be used on glass, metal, or plastic substrates.

Already many years ago, it was discovered that silicon is a substance that exhibits semiconductor properties. Another compound that exhibits such properties is cadmium telluride. It has a regular crystal structure. Cadmium telluride has a favourable absorption coefficient. It is not necessary to apply a thick layer of this substance to a photovoltaic plate. Owing to this, cadmium telluride cells belong to the group of thin-film cells. The cadmium telluride cell consists of two thin layers: cadmium telluride (CdTe) and cadmium sulphide (CdS). Cadmium is a by-product of the zinc extraction and smelting process [17]. Much rarer tellurium, on the other hand, is obtained in the copper, lead, or gold production process. The figure presents the production process of photovoltaic cells based on cadmium telluride (Fig. 2).

Cadmium telluride cells are manufactured in the electrical insulation process whereby the manufacturer is able to apply a thin layer of semiconductor material onto glass or plastic [18]. Using a solution of cadmium sulphate or cadmium chloride mixed with tellurium dioxide, a thin CdTe layer is applied to the surface of the material. Potential threat is generated by the water used in the process, that is

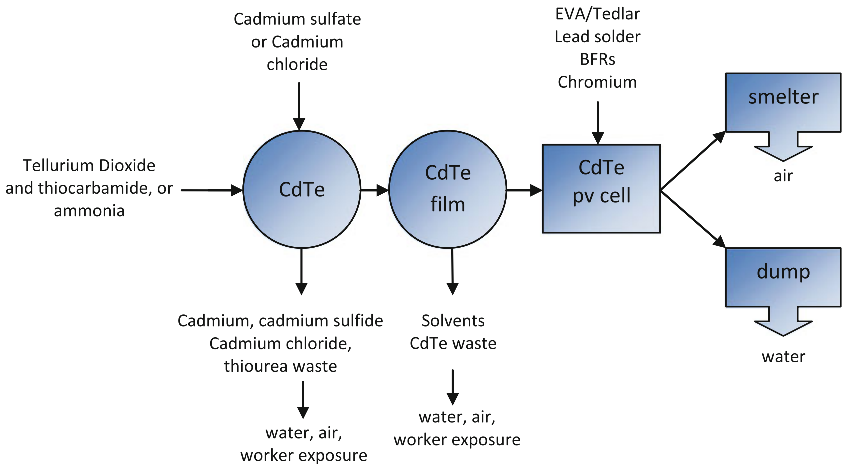


Fig. 2 Production process of photovoltaic cells based on cadmium telluride [13]

contaminated with cadmium. A CdS layer is typically formed by heating the cell surface and applying a mixture of cadmium sulphate, thiourea, and ammonia. Other methods are less common; however, in each case, cadmium compounds are recycled into the process. Unfortunately, this is not 100% feasible, and some of them are released into sewage and air. In this way, the highly toxic cadmium, cadmium sulphide, cadmium chloride, and thiourea may cause many serious illnesses in people who are employed in the thin-film cells manufacturing process. The remaining hazardous compounds used in the production include molybdenum, nickel, tellurium, and tin.

3 Prevention of the Negative Impact of Photovoltaic Cells Production on Humans and the Environment

As shown above, silicon-based technologies as well as many new ones use toxic, explosive or potentially carcinogenic substances, such as cadmium or selenium. Other materials also being used are the products of modern nanotechnology [19]. Despite their widespread use, new physico-chemical properties have been emerging that pose new challenges for the protection of the employees, consumers, and, ultimately, the environment.

Some manufacturers refrain from using dangerous components; however, in the case of thin-film cells, they are often unable to eliminate, for example, metals that are their primary constituent. For instance, CdTe cell manufacturers are not able to give up the use of cadmium [20]. The toxicity of a module may be reduced by using zinc sulphide (ZnS) instead of cadmium sulphide (CdS). Nonetheless, it is not always possible.

The challenges faced by manufacturers of photovoltaic cells (not just silicon- or cadmium-telluride-based) are primarily aimed at eliminating the most toxic chemical compounds used in their production process [16]. These include:

- withdrawal from or restriction of use of substances considered to be highly toxic, including cadmium, lead, mercury, brominated flame retardants, and chromium,
- developing new methods for the production of crystalline silicon so as to eliminate the use of trichlorosilane (the reduction of pure trichlorosilane by hydrogen is now used) [12, 21].
- withdrawal from use of sulphur hexafluoride,
- withdrawal from use of hydrogen selenide (highly toxic substance) used in the production of CIS/CIGS cells,
- withdrawal from use of arsenic (highly toxic and carcinogenic) used in the production of gallium arsenide cells,
- withdrawal from use of phosphine and arsine, toxic gases used in the production of GaAs cells [22],
- reduction of unorganized emissions of process gases into the atmosphere, including trichloroethane, acetone, ammonia, and isopropyl alcohol [21].

The development of new photovoltaic technologies to improve the efficiency and lower the production costs results in the use of new materials that, as already mentioned, may pose new risks in the production process [23]. Nowadays, various types of polymers are more and more often used in place of glass or metal as the material the cells are embedded on. In addition to the goals of improving the quality of the cells, attention should be paid to the environmental costs associated with the use of these materials [24–27]. Work is also underway to develop transparent modules based on organic cells, where the semiconductor function will be taken over by plastic produced in a liquid form to be sprayed e.g. on the glass.

Another task for the manufacturers is the development of photovoltaic technologies that take into account the susceptibility of an end-of-life module (panel) to be recycled. At present, only 10% of end-of-life PV cells are subject to recycling. Such a low level is related to the low profitability for waste processing entities and high energy consumption. The potential for post-exploitation waste management should be considered at the time of designing new technologies so that its recovery in the future is possible in an environmentally-friendly and relatively inexpensive manner [28]. The use of recycled end-of-life modules in the production of new cells, as well as the management of by-products (in particular, waste crystalline silicon) [29, 30], will significantly reduce the generation of waste and harmful emissions in the manufacturing process.

4 Conclusions

Photovoltaics does not have a negative impact on the environment, but only during operation. The production process and the stage of disposal after use have already generated a lot of harmful emissions and waste. In order for the energy generated using photovoltaic systems to be considered an environmentally-friendly source of energy, efforts should be made to limit as much as possible the negative impact of the production process both on the environment and on those employed in the plants manufacturing these systems. This can be achieved through gradual elimination of toxic substances and their replacement with less harmful ones, the introduction of new, "greener" technologies, and the reuse of end-of-life components, which fits perfectly in with the fashionable and highly promoted vision of closed-loop economy.

Acknowledgements The studies presented in this article was conducted within the project GEKON2/O4/266475/6/2015 "Isothermal and refrigeration photovoltaic car body" funded by the National Centre for Research and Development.

References

1. Dyrektywa Parlamentu Europejskiego i Rady 2012/19/UE z dnia 4 lipca 2012 r. w sprawie zużytego sprzętu elektrycznego i elektronicznego (WEEE), Dz. Urz. UE L 197/38
2. Bilimoria, S.: Renewable energy world magazine 12/2 (2013) http://www.sandtconsulting.eu/app/download/6093396/The+evolution+of+photovoltaic+waste+in+Europe.pdf. Last accessed 21 April 2017
3. Landrat, M., Pikoń, K., Bogacka, M.: Ogniwa fotowoltaiczne. Problem zagospodarowania odpadów. Przemysł Chemiczny **8**(95), 1499–1501 (2016). https://doi.org/10.15199/62.2016.8.14
4. Nowakowski, P.: Logistyka recyklingu zużytego sprzętu elektrycznego i elektronicznego od projektowania po przetwarzanie. Wydawnictwo Politechniki Śląskiej, Gliwice (2015)
5. Bogacka, M., Pikoń, K.: Best practice in environmental impact evaluation based on LCA-methodologies review. In: Geoconference on Ecology, Economics, Education and Legislation, vol. II. Book Series: International Multidisciplinary Scientific GeoConference-SGEM, pp. 101–108 (2014)
6. Klugmann-Radziemska, E., Ostrowski, P., Lewandowski, W.M., Ryms, M.: Aspekty ekologiczne i ekonomiczne recyklingu krzemowych ogniw i modułów fotowoltaicznych. Nafta Gaz **6**(481), 481–485 (2010)
7. Aman, M.M., Solangi, K.H., Hossain, M.S., Badarudin, A., Jasmon, G.B., Mokhlis, H., Bakar, A.H.K., NKazi, S.: A review of safety, health and environmental issue of solar energy system. Renew. Sustain. Energy Rev. **41**, 1190–1204 (2015)
8. https://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think. Last accessed 25 Aug 2017
9. http://www.washingtonpost.com/wp-dyn/content/article/2008/03/08/AR2008030802595.htm. Last accessed 25 Aug 2017
10. Jastrzębska, G.: Ogniwa słoneczne. Budowa, technologia i zastosowanie, WKŁ, Warszawa (2013)

11. Alsema, E.A., Nieuwlaar, E.: Energy viability of photovoltaic systems. Energy Policy **28**, 999–1010 (2000)
12. Śliwińska, A., Czaplicka-Kolorz, K.: Wybrane aspekty metodologiianalizy cyklu życia odnawialnych źródel energii. GIG (2010)
13. Toward a just and sustainable solar energy industry, a silicon valley toxics coalition, White paper, 14 Jan 2009 http://svtc.org/wp-content/uploads/Silicon_Valley_Toxics_Coalition_-_Toward_a_Just_and_Sust.pdf. Last accessed 26 Apr 2017
14. https://ec.europa.eu/clima/sites/campaign/pdf/gases_pl.pdf. Last accessed 25 Aug 2017
15. Greening photovoltaics. An the overview of the silicon valley toxics coalition's solar scorecard and industry trends. http://greenelectronicscouncil.org/wp-content/uploads/2015/10/Overview_SVTC_Scorecard_and_Industry_Trends_Oct2015.pdf Last accessed 21 April 2017
16. Fthenakis, V.M.: Prevention and Control of Accidental Releases of Hazardous Materials in PV Facilities. Prog. Photovolt. Res. Appl. **6**, 91–98 (1998)
17. Góralczyk, I., Tytko, R.: Fotowoltaika. Urządzenia, instalacje fotowoltaiczne i elektryczne. Wydawnictwo i Drukarnia Towarzystwa Słowaków w Polsce, Kraków (2015)
18. Fthenakis, V.M.: Life cycle impact analysis of cadmium in CdTe PV production. Renew. Sustain. Energy Rev. **8**, 303–334 (2004)
19. Rickerby, D.G., Morrison, M.: Nanotechnology and the environment: a European perspective. Sci. Technol. Adv. Mater. **8**, 19–24 (2007)
20. Andersson, B.A.: Materials availability for large-scale thin-film photovoltaics. Prog. Photovolt. Res. Appl. **8**, 61–76 (2000)
21. Dąbrowski, M., Frydrychowicz-Jastrzębska, G.: Nowe materiały w fotowoltaicznymprzetwarzaniu energii. Zeszyty Naukowe Politechniki poznańskiej **51**, 2–7 (2006)
22. Fthenakis, V.M., Moskowitz, P.D.: Photovoltaics: environmental, health and safety issues and perspectives. Prog. Photovolt. Res. Appl. **8**, 27–38 (2000)
23. Radziemska, E., Ostrowski, P., Janik, H., Leszkowski, K., Sielicki, P.: Research on physicochemical properties of eva copolymer for recycling of photovoltaic modules. Proc. ECOpole **4**(1), 187–192 (2010)
24. Raju, F.: Recycling of polymers. Wiley-VCH, Weinheim (2017)
25. Goodship, V.: Introduction to Plastics Recycling. Smithers Rapra Technology Limited, Shawbury (2007)
26. Kijeński, J., Błędzki, A.K., Jeziórska, R.: Odzysk i recykling materiałów polimerowych. Wydawnictwo Naukowe PWN, Warszawa (2011)
27. Greene, J.P.: Sustainable plastics. Wiley, Hoboken (2014)
28. McDonald, N.C., Pearce, J.M.: Producer responsibility and recycling solar photovoltaic modules. Energy Policy **38**, 7041–7047 (2010)
29. Mueller, A., Schlenker, S., Wambach, K.: Recycling of silicon. Environmental footprints and economics. In: 23rd European Photovoltaic Solar Energy Conference and Exhibition pp. 1066–1070, Valencia, Spain (2008)
30. Radziemska, E., Ostrowski, P.: Utilization of silicon powder, recovered in the PV cell's production and recycling processes. Proc. ECOpole **3**(1), 191–197 (2009)

Experimental Studies on Energy Crops Torrefaction Process Using Batch Reactor to Estimate Torrefaction Temperature and Residence Time

Szymon Szufa, Łukasz Adrian, Piotr Piersa, Zdzisława Romanowska-Duda, Mieczysław Grzesik, Artur Cebula and Sebastian Kowalczyk

Abstract Biomass of agricultural origin has the biggest potential from all kind of renewable energy sources in Poland because it provide continuous electricity generation, and is the only widespread source of renewable heat. In this paper an installation with a batch reactor was used to conductor experimental tests on three different energy plants by means of the torrefaction process: willow, Pennsylvanian mallow, and Jerusalem artichokes. Those energy plants were growing ion low-grade soils, which are abundant in Poland. Torrefaction or simply roasting of

S. Szufa (✉)
Biomass Training Research, Szarych Szeregów str. 25a/14, 45-286 Opole, Poland
e-mail: szufa.szymon@interia.pl

Ł. Adrian
Eko-Look, Lokajskiego str. 1A, Sieradz, Poland
e-mail: lukasz.adrian@eko-look.pl

P. Piersa
APS-Ekoinnowacje Sp. z o.o, Dubois str. 114/116 loc.0.04, 93-465 Łódź, Poland
e-mail: piotr.piersa@aps-ekoinnowacje.pl

Z. Romanowska-Duda
Laboratory of Plant Ecophysiology, Faculty of Biology and Environmental Protection, University of Lodz, Banacha str. 12/16, 90-131 Łódź, Poland
e-mail: romano@biol.uni.lodz.pl

M. Grzesik
Research Institute of Horticulture, Konstytucji 3 Maja str. 1/3, 96-100 Skierniewice, Poland
e-mail: mieczyslaw.grzesik@inhort.pl

A. Cebula
Faculty of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawła II 37A19, 31-864 Kraków, Poland
e-mail: acebula@pk.edu.pl

S. Kowalczyk
ENSYS S.C, Śliwiny 37, 83-110 Śliwiny, Poland
e-mail: office@ensys.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_35

biomass is a thermal degradation of biomass structures by heating it a inert gas atmosphere like nitrogen under atmospheric pressure. This process removes low weight organic volatile components and moisture as well as depolymerises the long polysaccharide chains of biomass. To build up a demonstration plant for torrefaction process of energy crops plants the information concerning the specific temperature of caring the carbonization process for specific type of fuel and residence time should be provided in order to obtain the best C/H ratio in fuel, which is responsible for High Heating Value, carbonization level and best physico-chemical properties as a new fuel for energy production.

Keywords Torrefaction · Energyplants · Biomass · Temperature Willow

1 Introduction

Torrefaction is a thermal pre-treatment process (thermo-chemical conversion without oxidants in inert gas atmosphere) carried out in a temperature range of 200 to 270 °C and in a residence time of 15 to 30 min [1–3]. The process removes low weight organic volatile components and moisture and also depolymerises the long polysaccharide chains of biomass [4].

The biomass fuels acquired from energy plants have a high moisture content that causes storage complications such as self-heating, biological degradation, and lower energy densities. It is a bulkier fuel (with poorer transportation and handling characteristics), and more tenacious (the fibrous nature of biomass makes it difficult to reduce it to small homogeneous particles). The biomass properties mentioned above have negative impacts during energy thermal conversion such as gasification system design limitations and lower combustion and co-firing efficiencies [5].

Torrefaction involves additional energy expenditure that needs to be accounted for in order for biomass to achieve properties similar to coal. Apart from improving fuel properties such as its high heating value (HHV), torrefaction makes it possible to store treated biomass longer than raw biomass and reduces the costs of its transportation and storage [6].

Torrefaction temperatures which influence process and product properties have been investigated for various types of unprocessed biomass. Ramos-Carmona et al. tested patula pine [7]. Tests were carried out in a laboratory furnace in temperature range of 200–300 °C, with 30 min of residence time. For hydrophobicity and moisture uptake, the authors suggest optimum temperatures of 285, 270, 275 °C at a residence time of 45 min for willow, oat, and poultry litter respectively [8].

Previous work indicates that biomass weight loss from 25 to 35% leads to the highest energy density concentration of torrefaction products with a process temperature above 200 °C [9–11].

Bridgeman et al. [12] performed torrefied Willow combustion analysis and compared the results with hard coal and lignite. The combustion process was performed within a bubbling fluidised bed combustor. There were found very low emission levels of SO_2 during the combustion of torrefied willow. However, higher NO_x emissions were observed, which were caused by an increase of fuel-N in the torrefied fuel [12].

The aim of the experiment was to determine the optimum parameters of the torrefaction process. Amongst others, the most important and valuable were the torrefaction process temperature and residence time. These parameters are crucial in the design of industrial biomass torrefaction installations. In addition, the parameters have a direct influence on fuel energy density and as consequence determine installation economic viability. In this investigation, the authors examined the torrefaction process of three types of energyplants: willow, Pennsylvanian mallow, and Jerusalem artichokes. The choice of crop was dictated by the following arguments: the selected crops grow in low-grade soils and have an expected high caloric value.

In this work detailed analyses of the torrefaction process using a batch reactor were performed. Using the torrefaction process, energy plants were investigated to obtain an optimal torrefaction process temperature, residence time and fuel characteristic.

2 Experimental Work

The experimental work concentrated on three types of biomass: willow, Pennsylvanian mallow, and Jerusalem artichokes. A batch reactor was used to obtain the optimal mass to energy loss ratio (highest caloric value). The energy plants torrefaction process was performed using a specially designed and dedicated installation with a batch reactor for torrefaction under an inert gas atmosphere—technical nitrogen.

2.1 Preparation of Biomass Samples

The biomass samples were pre-treated before the experiments, the biomass was separated from foreign bodies and clean from contamination chopped and ground to reach the appropriate geometric dimensions. The plants were cut into sections of 2 to 4 cm, ground and then sieved on a special automatic screen and dried in an electric oven at 110 °C for 4 h. Then the samples were tightly closed and sent for technical and elemental analysis.

The samples were subjected to elemental and technical analysis. The content of the elements carbon, hydrogen, nitrogen and sulphur were determined and the volatility, moisture content, ash, combustion heat and calorific values were determined (the same analysis was performed after the torrefaction process). The weight of the samples was determined before and after the drying process and the results were used to determine the moisture content.

In each experiment, the dried biomass was divided into three separate samples of 20 g and each of them was evenly distributed on three horizontal screens of a reactor metal structure with different perforations made of acid-proof steel.

Only selected samples were analysed because, as a result of previous studies, a too high weight loss of more than 35% results in a very high degree of carbonization and high energy loss. The reverse is achieved with a mass loss below 25% which too low, and the biomass in the end is not fully roasted (it is not fragile and still has a high degree of moisture absorption and low calorific value).

2.2 Batch Reactor and Torrefaction Process

The installation was designed and constructed in such a way that it can conduct a thermal-chemical process of fuel crops with a size of 2–4 cm (see Fig. 1).

Dried samples of biomass were uniformly distributed on perforated screens covered with brass protective grids to keep the bed from fluidising and roasting. The screens (14) with three samples were placed inside the reactor (15). A brass mesh (14) prevented biomass elements from escape and fluidizing. The flow control system for the instantaneous nitrogen heater (5) and the temperature and flow

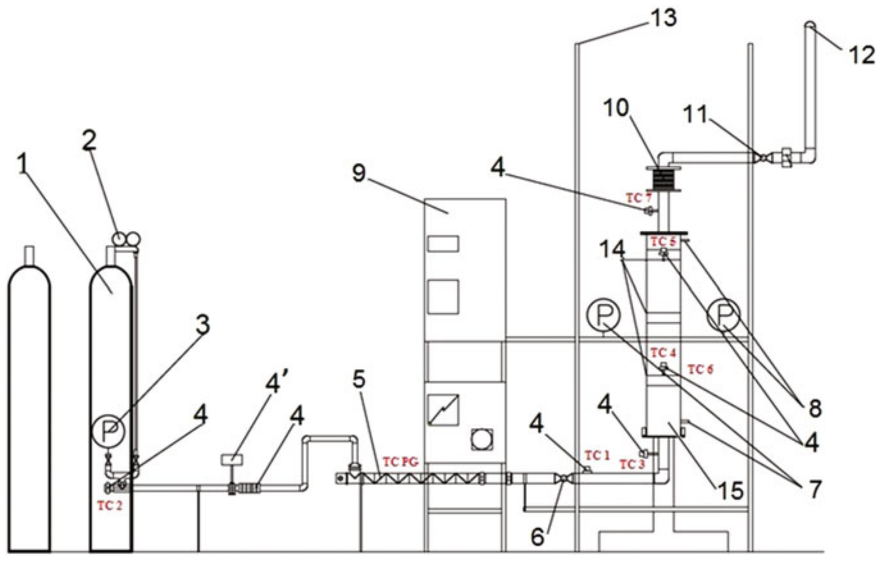


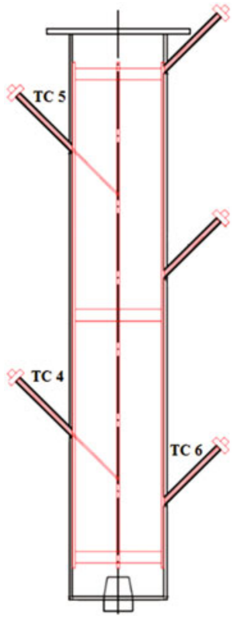
Fig. 1 Diagram of a batch reactor for the torrefaction of biomass: (1) bottle with nitrogen (2) extension valve (3) manometer (4) thermocouple (4') calorimetric flowmeter (5) electric heater (6) control valve (7) pressure sensor (8) manometer (9) control central (10) check valve (11) safety valve (12) outlet (13) supports (14) horizontal reactor screens (15) batch reactor

recording system was switched on. Control of the instantaneous nitrogen heater (9) that was connected to the flow heater (a system of three heaters in a special housing) designed for 230 V was started (5). The flow of nitrogen was set at a nitrogen gas reducer (2 bars represent a flow of approximately 40 l/min.) and the flow temperature was configured (the torrefaction was tested at a temperature of 230–270 °C).

Nitrogen flow was controlled by the extension valve (2). The calorimetric flowmeter (4) measured the amount of flowing gas. Control valves located at the inlet of the batch reactor as well as its outlet (8) permitted the generation of overpressure and force the appropriate flow conditions. The samples were kept in the reactor for approximately 15 min.

The hot nitrogen inside the torrefaction chamber (15) heated the energy plants and the torrefaction process took place. The energy plants underwent thermal-chemical degradation, part of the moisture contained in the biomass evaporated and torgas was produced, which consists mainly of water vapour, methane, carbon monoxide and various types of formaldehyde acids. Torgas released from biomass left the reactor (12) via a check valve to the surrounding. In the batch reactor, there were nine thermocouples (TC1-TC7) mounted in the batch reactor at an angle of 45° (according to proper measurement standards) to measure the temperature during the experiment (see Fig. 2), two nitrogen TC (TCpg and TC1) located upstream and downstream of the electric heater (5) and two pressure gauges (7 and 8) located on the inlet and outlet of the reactor to measure pressure. The entire installation was insulated with a wool-aluminum thermal shield.

Fig. 2 Cross-section of the batch reactor chambers with the thermocouple (TC) placements



When the torrefaction process was finished the installation was switched off and cooled down. One important issue was to keep a uniform temperature distribution in the batch reactor during the torrefaction process. That condition was fulfilled and the carbonisation level of the tested fuel crops was fully controlled. Another noteworthy phenomenon was the cooling stage, which for safety reasons (the possibility of burning heaters in an electric flow-through heater, nitrogen heated by a stream of technical nitrogen that could be damaged at high power and low currents) was perform to protect the heater. Torrefied biomass products were removed from the batch reactor (15). After the technical and elementary analysis was performed, the calorific value of the torrefied biomass were determined.

3 Results and Discussion

Temperature measurements and mass loss determination after the torrefaction of energy plants allowed a proper and detailed investigation of torrefaction process conditions which occur when there is a mass loss of 30% together with an energy loss of around 10% according to the literature. Table 1 summarises all research results (torrefied energy plants, optimal temperature and residence time in batch reactor to achieve 30% mass loss and 10% energy loss) of the torrefaction process of the biomass willow, Pennsylvanian mallow, and Jerusalem artichokes. The most important results of the research on the torrefaction of fuel crops using a batch reactor are the determination of the average torrefaction temperature and the energy plants residence time during which the mass loss ranged from 25 to 35%.

A high C/H ratio increase (nearly 30%) occur during torrefaction process in all kinds of torrefied samples with biomass. The main parameters describing the process are the average temperature and residence time. The residence time was measured since temperatures in the batch reactor reached 200 °C. The calorific value of torrefied biomass and untreated energy plants were analysed in a calorimeter bomb and the results are collected and presented in Table 1. It is possible to make the following comparisons. The Caloric value of Pennsylvanian mallow increases by 26% during torrefaction; the caloric value of Willow increases by 20% during torrefaction; and the caloric of Jerusalem artichokes increases by 23% during torrefaction. In addition, it was found that the most optimal process temperatures for Pennsylvanian mallow, willow and Jerusalem artichokes are 247.2, 245.0, 243. 4 °C respectively. To achieve a torrefied product with the highest caloric value of the three chosen energy crops the resident time of biomass samples in the batch reactor should be Should be about 14 min (see Table 2). The results presented in Table 2 are the most representative energy crop torrefaction conditions used in pilot and industrial scale installations.

Table 1 Experimental results: elemental analysis, technical analysis of torrefied and untreated energy plants, residence time torrefaction temperature

Biomass type	C/H	Moisture content	Ash	HHV	LHV	Mass loss	Residence time	Temperature
Pennsylvanian mallow		Analytical (%)	Dry matter (%)	Average (MJ/kg)	Average (3 samples) (MJ/kg)	%	min	°C
Untreated	7.44	14.21	8.49	18.56	17.67			
1	10.39	4.42	4.2	22.47	20.06	35.60	14	259.6
2	9.82	5.31	2.74	21.40	19.82	35.60	14	258.9
3	9.57	5.41	3.17	20.41	18.22	26.70	14	239.7
4	9.99	4.98	3.65	21.88	19.54	27.05	14	243.7
5	9.26	6.11	2.82	19.88	17.75	35.00	14	251.4
6	9.45	5.89	2.97	20.19	18.03	28.15	13	247.2
Jerusalem artichoke								
Untreated	7.17	11.23	7.12	19.79	18.67			
1	10.83	5.93	6.12	24.35	21.74	26.80	12	251.2
2	10.14	6.44	5.82	22.42	20.02	28.10	13	245.2
3	10.21	6.15	6.02	22.68	20.25	32.65	14	247.9
4	9.39	7. 72	5.11	21.26	18.98	27.50	13	242.2
5	9.76	7.14	5.46	21.92	19.57	28.95	14	243. 5
Willow								
Untreated	7.17	11.23	7.12	19.79	18.67			
1	8.68	4.12	2.92	22.31	19.92	30.15	14	245.0
2	8.98	4.05	3.01	23.48	20.96	31.50	16	240.0
3	9.09	3.93	3.2	24.02	21.45	30.40	14	244.7
4	9.53	3.78	3.46	25.10	22.41	34.15	15	243.9
Coal	15.49	2.21	9.78	32.31	28.85			

Table 2 The recommended process temperatures and residence times for selected energy plants

Energy crop	Temperature (°C)	Residence time (min)
Willow	244	15
Pennsylvanian mallow	260	14
Jerusalem artichoke	251	12

4 Conclusions and Recommendations

This paper presents the results of experimental work concerning three types of energy crops. To perform the experiments and tests a special test stand was designed and manufactured. The test stand ensured the stability of biomass torrefaction process. This meant that the nitrogen temperature inside the batch reactor was uniform and constant during the whole process and the gas flow rate was controlled. The authors determined the two most crucial parameters of the torrefaction process in the three analyses of the energy plants. The most optimal torrefaction process conditions are a temperature in a range of 245–250 °C, and a residence time in a range of 12–14 min. Precise data are presented in Table 2. These parameters could be used as a constraint in the design of torrefaction installations and also maintenance. Exceeding these values leads to a too high carbonisation of energy crops and results in a volatile loss of matter. In addition, an excess of the recommended torrefaction process temperature results in unnecessary energy and fuel and expenditure that could make the process or installation unviable.

Acknowledgements The studies presented were financed by the National Science Centre (NCN) Poland under the research program Preludium. The research and development project is entitled “Thermodynamic analysis of thermo-chemical process of degradation of biomass particles in oxygen-depleted atmosphere” (Preludium 2 Program, No. 2011/03/N/ST8/02776).

References

1. Tumuluru, J.S., et al.: A review on biomass torrefaction process and product properties for energy applications. Ind Biotechnol. **7**(5), 384–401 (2011)
2. Rejdak, M., et al.: Compaction studies of torrefied willow. J. Ecol. Eng. **18**(1), 183–192 (2017)
3. Prins, M.J.: Thermodynamic analysis of biomass gasification and torrefaction. Technische Universiteit Eindhoven (2005). https://doi.org/10.6100/IR583729
4. Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T.: Torrefaction of reed canary grass, wheat straw and willow to enhance fuel qualities and combustion properties. Fuel **87**(6), 844–856 (2011)
5. Chen, W.-H., Kuo, P.-C., Liu, S.-H., Wu, W.: Thermal characterization of oil palm fiber and eucalyptus in torrefaction. Energy **71**, 40–48 (2014)
6. Ramos-Carmona, S., et al.: Effect of torrefaction temperature on properties of patula pine. Ciencia y Tecnología **19**(1), 39–50 (2017)

7. Acharya, B., Dutta, A.: Fuel property enhancement of lignocellulosic and nonlignocellulosic biomass through torrefaction. Biomass Conv. Bioref. **6**, 139–149 (2016)
8. Basu, P., "Biomass Gasification and Pyrolysis," Academic Press, Burlington, 99 (2009)
9. Veringa, H.J., Boerrigter, H., Kiel, J.H.A.: Electricity from biomass. Energy Centre of the Netherlands, Report no. ECN-RX-04-003 (2004)
10. Szufa, S.: Thermodynamics analysis of biomass particles thermo-chemical degradation in atmosphere devoid in oxygen, research on biomass co-combustion kinetics and on biomass torrefaction products. In: 15th International Symposium Advances in Chemical and Mechanical Engineering, Proceedings 2012
11. Ramos-Carmona, S., et al.: Effect of torrefaction temperature on properties of patula pine. Cienciay Tecnología **19**(1), 39–50 (2017)
12. Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T.: Torrefaction of reed canary grass, wheat straw and willow to enhance fuel qualities and combustion properties. Fuel **87**(6), 844–856 (2011)

Oxy-fuel Combustion of Wheat Straw Pellets in a Lab-Scale Fluidized Bed Combustor

Monika Kosowska-Golachowska, Henryk Otwinowski, Krzysztof Wolski, Agnieszka Kijo-Kleczkowska, Tomasz Musiał, Katarzyna Środa and Damian Richter

Abstract This paper presents an experimental study on agro biomass pellets combustion in a circulating fluidized bed (CFB) under three oxy-fuel conditions ($21\%O_2/79\%CO_2$, $30\%O_2/70\%CO_2$ and $40\%O_2/60\%CO_2$) and air–fuel condition. The combustion of wheat straw pellets was conducted at a temperature of 850 °C in a 12 kW lab-scale CFB combustor. The main objective of this study was to investigate the combustion behaviour of wheat straw, in terms of particle temperature profiles, ignition time, volatiles combustion time and burnout time. The results of the tests show that the composition of the oxidizing atmosphere highly influences the combustion process of biomass fuels. Replacing N_2 in the combustion environment by CO_2 caused slight delay in the combustion of wheat straw pellets. The combustion process in O_2/CO_2 mixtures at 30 and 40% O_2 is faster and shorter than that at lower O_2 concentrations.

Keywords Biomass · Oxy-combustion · Agricultural residues
Pellet · CFB

M. Kosowska-Golachowska (✉) · H. Otwinowski · K. Wolski
A. Kijo-Kleczkowska · T. Musiał · K. Środa · D. Richter
Czestochowa University of Technology, Armii Krajowej 21,
42-201 Czestochowa, Poland
e-mail: kosowska@imc.pcz.czest.pl

H. Otwinowski
e-mail: otwinowski@imc.pcz.czest.pl

K. Wolski
e-mail: wolski@imc.pcz.czest.pl

A. Kijo-Kleczkowska
e-mail: kijo@imc.pcz.czest.pl

T. Musiał
e-mail: musial@imc.pcz.czest.pl

K. Środa
e-mail: katarzynasroda@imc.pcz.czest.pl

D. Richter
e-mail: richter_damian@imc.pcz.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_36

1 Introduction

Numerous countries are taking initiatives to counteract global warming by reducing their greenhouse gas emissions. The European Union has a leading role in this effort and has targets to reduce greenhouse gas emissions by 20% (from the 1990 level) to increase the share of renewable energy to 20% in its primary energy consumption and to improve energy efficiency by 20%. These three targets will be satisfied by the year 2020. Efforts to increase boiler efficiency and the use of biomass and other solid renewable fuels are consistent with these objectives.

Biomass is considered to be a carbon-neutral fuel in many countries. Its utilization in utility boilers can cause a reduction in CO_2 emissions as the biomass captures atmospheric carbon dioxide during its growth cycle. Biomass contains more volatiles and has a lower carbon content than coal does, which makes biomass a highly reactive fuel. However, raw biomass fuels have several disadvantages compared with fossil fuels, including [1–5]:

- high moisture content (maximum of 60%),
- relatively low heating value per unit volume,
- variability of quality and heating value,
- irregular shape and size,
- difficulty in controlling the rate of burning,
- rapid burning, which necessitate frequent refueling,
- difficulty in mechanizing continuous feeding,
- large volume of area required for storage,
- economic problems associated with transportation and distribution.

Several of these disadvantages are attributed to the low bulk density of biomass, especially for agricultural residues. The bulk density of loose wheat straw is approximately 18 kg/m^3 whereas the bulk density of lignite coal is approximately 700 kg/m^3. For this reason, the transport of unprocessed biomass is only feasible for distances less than approximately 200 km [6]. To improve the characteristics of biomass fuel for transportation, storage, feeding into boilers and combustion, raw biomass should be upgraded by densification and unification of size. Biomass densification, which is also known as briquetting or pelletizing of sawdust and other agro residues, has been practiced for many years in several countries. The densification of biomass has the following technical advantages [1–6]:

- low moisture content is achieved,
- the rate of combustion is comparable to the rate of fossil fuels,
- uniform combustion can be achieved,
- particulate emissions can be reduced,
- the possibility of spontaneous combustion in storage is reduced,

- stability and durability of biomass is improved,
- handling is improved,
- costs associated with the transportation and storage are reduced.

The basic problem that is frequently encountered in the use of biomass briquettes or pellets is the cost of densification. Factors that control the densification process are moisture content, particle size, form, and fibrous and non-fibrous nature, as well as lignin contents. Biomass pellets and briquettes have the potential to be a source of renewable energy if they are fabricated from sustainably harvested biomass or waste agricultural residues. For example, wheat straw represents approximately 48% of the production volume in the EU; it is the most important part of the straw-supplying arable crop [7].

Circulating fluidized bed (CFB) boilers are ideal for efficient power generation. They are capable of firing an extensive variety of solid biomass fuels in small combined heat and power plants (CHP) and large utility power plants. The well-known benefits of CFB technology, such as superior fuel flexibility, inherently low emissions and high availability can be completely utilized for this purpose. Designs of efficient subcritical boilers that fire 100% biomass are available to 600 MWe. Examples of the Advanced Bio CFB (ABC) technology include two power plants in Poland, the Konin power plant (55 MWe/154 MWth) and the Połaniec power station (205 MWe/447 MWth). Both plants fire 100% biomass including a significant share of high-demand agricultural residue [8]. Biomass residues usually have significantly lower ash content (with the exception of rice husk with 20% ash) but their ashes have a higher percentage of alkaline minerals, especially potassium. These constituents have a tendency to devolatilize during combustion and condense on tubes, especially the constituents of super heaters. These constituents also reduce the sintering temperature of ash, which causes ash deposition on the boiler's exposed surfaces [9–11].

Biomass firing coupled with oxy-fuel (oxy-biomass combustion) and CCS (carbon capture and storage) is potential 'carbon negative' technology. In oxy-fuel combustion, biomass particles are burnt in a mixture of pure oxygen and recycled flue gas. As nitrogen is eliminated from the oxidizing gas, the flue gas leaving the combustion chamber is highly enriched in CO_2, which indicates that the combustion process occurs in an O_2/CO_2 mixture. Changes in the physical properties of the combustion atmosphere will influence the ignition time and ignition temperature, the devolatilization time, the volatiles matter combustion time, the temperature distribution in a burning solid fuel and the total combustion time for a single particle and pollutant formation [12, 13].

In this paper, a 12-kW oxy-fuel CFB combustor was used to study the combustion behaviour of wheat straw pellets.

2 Experimental

2.1 Lab-Scale CFB Combustor

Oxy-biomass combustion tests were conducted in a 12-kW lab-scale CFB combustor shown schematically in Fig. 1.

The facility consists of a combustion chamber (1), a cyclone (2) a downcomer (3) and a loop seal (4). The electrically-heated rectangular combustion chamber (riser), 680 × 75 × 35 mm, is the main component of the unit. The front wall of the riser is made of transparent quartz through which the combustion process can be directly observed. Silica sand (particles smaller than 400 μm) to a mass of 0.3 kg constituted the inert bed. The gases to make up gas mixtures are supplied from cylinders (12) to a mixer (17) and then transferred via a preheater (8) directly into the combustion chamber. Flow rates of gases are controlled by valves (16) and measured by rotameters (15). During combustion tests, the superficial gas velocity was kept at a constant level of about 5 m/s. The temperature was held at 850 °C by means of microprocessor regulators (11). S-type thermocouples (T1–T3) measured the temperature at three different levels inside the combustion chamber with an accuracy of ±2 °C.

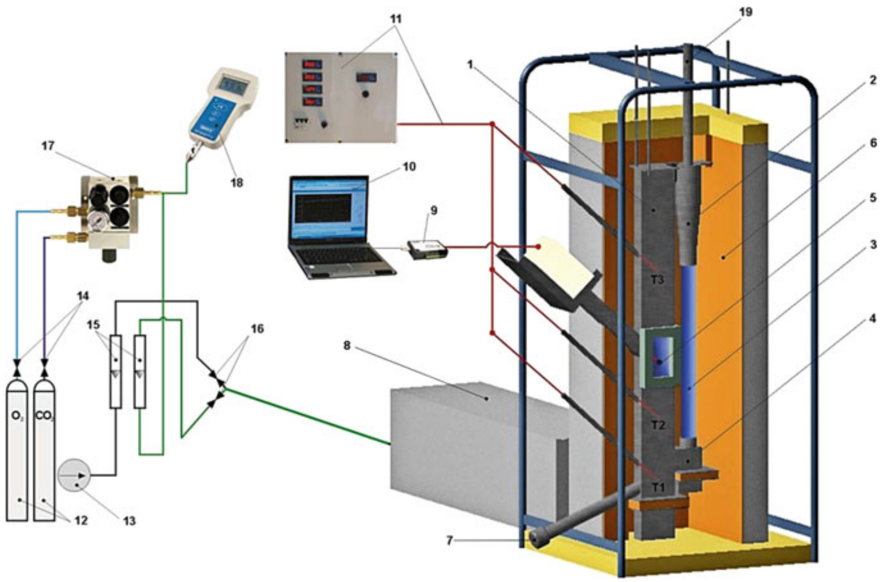


Fig. 1 Schematic of the experimental apparatus for oxy-CFB combustion [13] 1—combustion chamber, 2—cyclone, 3—downcomer, 4—loop seal, 5—biomass pellet, 6—insulation, 7—drain valve, 8—preheater, 9—card, 10—computer, 11—temperature control system, 12—gas cylinders, 13—air compressor, 14—pressure regulators, 15—rotameters, 16—valves, 17—mixer, 18—gas analyzer, 19—ventilation duct, T1–T3-S-type thermocouples

A single biomass pellet (5) was introduced into the combustion chamber and positioned stationary in the bed. To measure the temperatures in the centre and at the surface of the biomass particle a special stand was constructed. It provided a support for two S-type thermocouples. The tip of the first thermocouple was located inside the pellet, whereas the second thermocouple measured the surface temperature and served as a basket in which the biomass sample was placed. The thermocouples were connected via a card (9) to a computer (10) to record the temperature measurements. The ignition time, volatiles combustion time and burnout time were measured by a stopwatch with an accuracy of 0.1 s. The intraparticle temperature, the surface temperature, the ignition time and the volatiles combustion time were simultaneously measured. Video and digital cameras were employed to record the progress of biomass combustion.

The experiments were performed in air (base case) and mixtures of O_2/CO_2 with oxygen concentrations in the range from 21 to 40 vol%. The atmospheres were denoted as follows:

- air (base case),
- 21oxy—21%O_2/79%CO_2,
- 30oxy—30%O_2/70%CO_2,
- 40oxy—40%O_2/60%CO_2.

2.2 *Laboratory Method of Biomass Pelletization*

Figure 2 displays a flow diagram that demonstrates how the pellets were produced.

The first stage involved preliminary size reduction, which consisted of cutting the fuel into small pieces. In the second stage, the fuel was milled in a laboratory mill. In the third stage, the milled fuel was sifted by passing it through a series of standard sieves with sizes decreasing to 0.1 mm. The sifted fuel was mixed with potato starch as a binder (approximately 8% by weight) and water in the fourth stage. In the fifth stage, the mixture was compacted using a hydraulic stamping

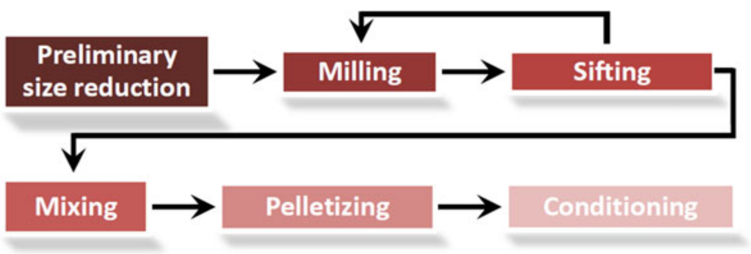


Fig. 2 Flow diagram of biomass pellet production [14]

press, which gave the pellet its spherical shape. The last stage involved conditioning the pellets to remove moisture.

2.3 Tested Biomass

In this study, 10-mm spherical biomass pellets (Fig. 3c) composed of wheat straw were employed. Pellets were produced with a density of approximately 380 kg/m^3 from loose wheat straw with bulk density of 80 kg/m^3. The biomass fuel composition is important with respect to its heat content, emission characteristics and ash-related issues during the combustion process. The proximate and ultimate analyses of the tested biomass are presented in Table 1.

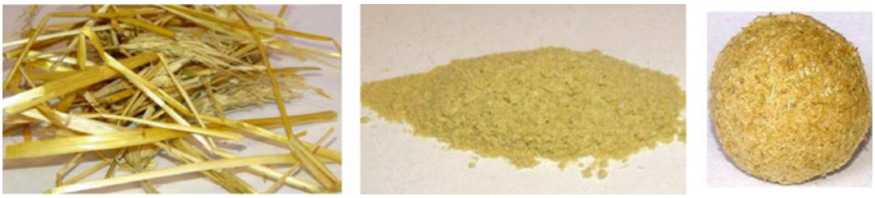


Fig. 3 Raw wheat straw (**a**), sawdust (**b**) and spherical pellet (**c**) (d = 10 mm)

Table 1 Proximate and ultimate analyses of wheat straw

Proximate analysis (dry basis)	
Moisture (wt%)	8.4
Ash (wt%)	6.1
Volatile matter (wt%)	68.3
Fixed carbon (wt%)	17.2
Higher heating value (MJ/kg)	17.84
Ultimate analysis (dry ash free basis)	
Carbon (wt%)	50.2
Hydrogen (wt%)	5.8
Nitrogen (wt%)	0.8
Sulphur (wt%)	0.08
Chlorine (wt%)	0.17
Oxygen (by difference) (wt%)	42.95

3 Results and Discussion

A single particle of solid fuel that is introduced to the combustion chamber undergoes several characteristic stages [13]:

- heating up and drying,
- devolatilization,
- ignition and combustion of volatiles,
- combustion of residual char.

Most solid fuels experience these processes; the duration of each process is dependent on the fuel type and its composition (moisture and volatile matter contents, total carbon content), the temperature in the combustion chamber, the heating rate and the oxidizing atmosphere [14]. Figure 4 shows pictures of wheat straw pellets burning in different oxidizing atmospheres. After rapid heating, the ignition of volatiles occurs. Burning volatiles form a distinctive long flame. The differences in combustion times, which are related to the composition of oxidizing atmospheres, are observed. At higher oxygen concentrations, the combustion process is more intense, and therefore, the total combustion burnout time is shorter.

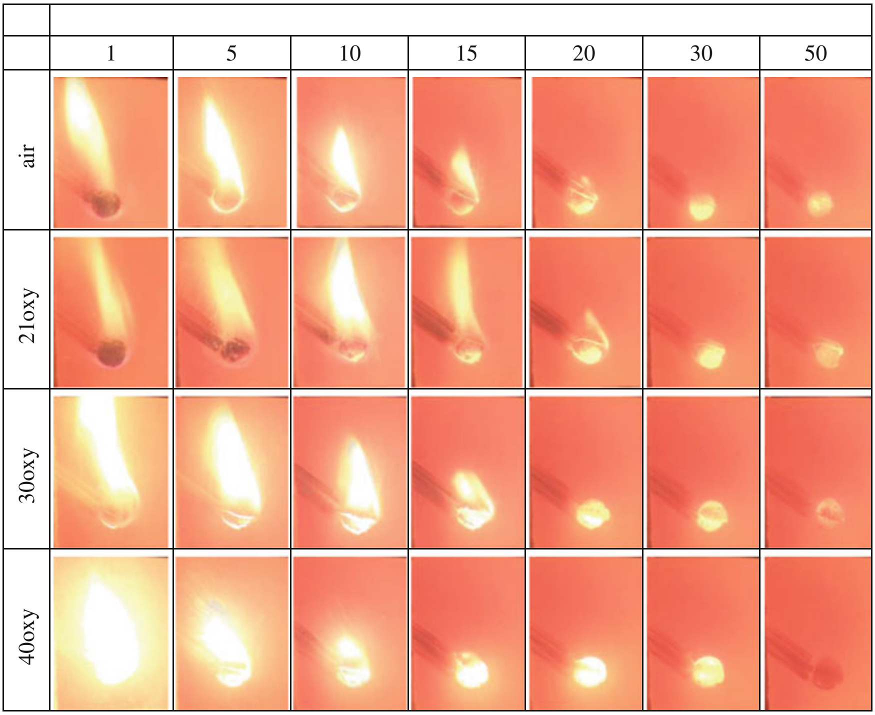


Fig. 4 Combustion of wheat straw pellets in various atmospheres at 850 °C

Ignition times for wheat straw pellets were less than 1 s in all tested atmospheres. Ignition time was characterized by the time required to achieve a visible flame.

Volatiles combustion time was the duration of the visible flame (from ignition of volatile matter to the end of combustion of the volatile matter) [13]. Devolatilization and burnout times for wheat straw pellets are shown in Fig. 5. The volatiles combustion time decreases with an increasing O_2 concentration for biomass samples. The burnout time for the tested biomass significantly decreases with an increase in oxygen concentration. The total combustion time for the wheat straw pellets in 40oxy atmosphere is approximately 42% shorter than the burnout time for combustion in air.

Figure 6 shows temperatures that were measured at the surface and in the centre of the wheat straw pellets burned at 850 °C in air. After an initial delay, the centre temperature exceeds the surface temperature and is approximately 100 °C higher during the course of combustion.

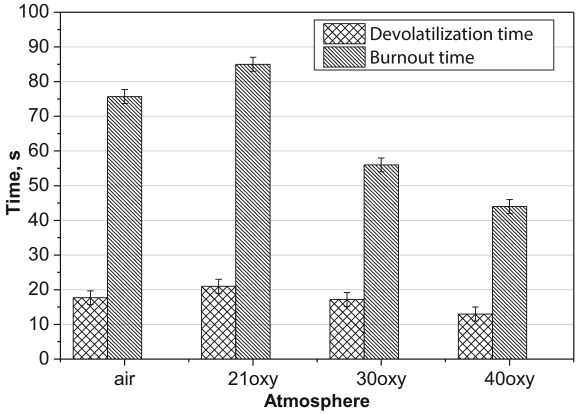


Fig. 5 Devolatilization and burnout times for wheat straw pellets burned in CFB in various atmospheres at 850 °C

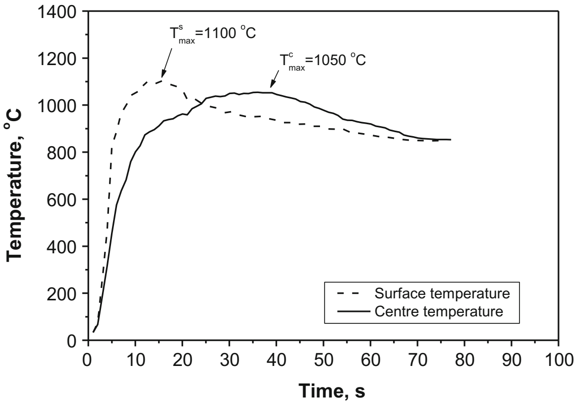


Fig. 6 Temperature profiles for wheat straw pellets burned in CFB in air at 850 °C

Lower surface temperatures can be explained by the intensive heat transfer between the burning coal particles and the bed material. When the flame approaches its point of extinction, the surface temperature attains its maximum value. This maximum value was ~1100 °C for biomass pellets. In the next stage, i.e. char combustion, the centre temperature was higher than the surface temperature. The maximum centre temperature was 1050 °C for wheat straw. When the char combustion process is completed, the surface temperature and the centre temperature decrease to a value that corresponds to the temperature in the combustion chamber.

The temperature profiles for wheat straw pellets burned in the mixture of 21oxy are shown in Fig. 7a. Combustion of pellets in a O_2/CO_2 mixture at 21% O_2 generated a centre temperature that is ~40 °C lower than the centre temperature generated for combustion in air. A higher specific heat capacity of CO_2 decreases the heating rate of the biomass sample. The diffusion coefficient of O_2 in CO_2 is smaller than the diffusion coefficient of O_2 in N_2. These two factors negatively influence the kinetics of the combustion process and are responsible for the observed decrease in the centre temperature. The char-CO_2 gasification reaction in the 79% CO_2 atmosphere is highly endothermic and may reduce the particle temperature. The combustion of wheat straw in air required slightly less time compared with combustion in an O_2/CO_2 mixture with 21 vol% O_2. Figure 7b shows the temperature measured at the surface and in the centre of the biomass pellets burned in the 30oxy atmosphere. The maximum value of the surface temperature was ~1220 °C for wheat straw. The maximum centre temperature of ~30 °C was higher than the corresponding maximum centre temperature during combustion in air. The temperature profiles for biomass pellets burned in the mixture of 40oxy are shown in Fig. 7c. The maximum surface temperature value varies from ~1100 °C for combustion in air to ~1320 °C for combustion in the mixture of $40\%O_2/60\%CO_2$. The maximum centre temperature of ~90 °C for wheat straw pellets during combustion in the 40oxy was higher than the corresponding maximum centre temperature during combustion in air.

Graphs shown in Figs. 6 and 7 can be employed to determine the total time of combustion with reasonable accuracy.

Burning biomass in CFB boilers is known to cause slagging and fouling problems due to low ash fusion temperature. These high values of particle temperature in the 40%oxy can cause slagging and fouling problems in CFB boilers. Gulyurtlu et al. [15] discovered that wood biomass can be successfully employed as biofuel without slagging and fouling problems. However, agglomerated particles of agro biomass contained high quantities of Si, Ca and K, which may melt or soften at low temperatures and form ash particles with an extensive range of compositions, shapes and sizes due to the different proportions of K_2O-CaO-SiO_2.

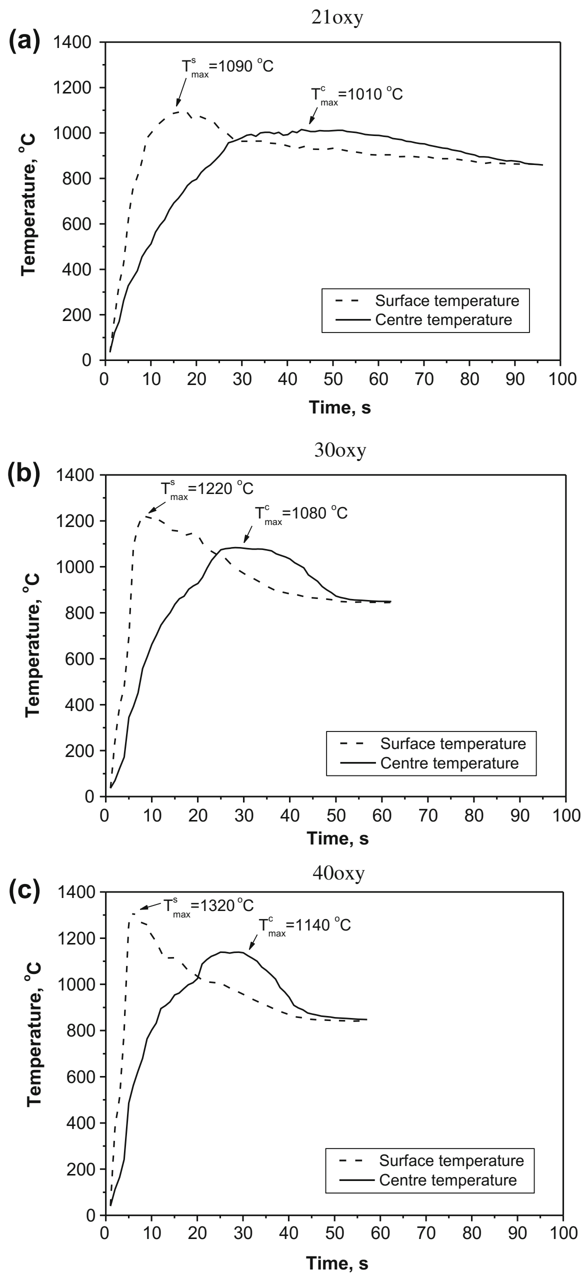


Fig. 7 Temperature profiles for wheat straw pellets burned in O_2/CO_2 atmospheres at 850 °C

4 Conclusions

Wheat straw pellets were burned in a laboratory-scale CFB combustor at 850 °C in air and in different oxy-fuel atmospheres and simulated by dry O_2/CO_2 mixtures. The results of our experimental research show that the composition of the oxidizing atmosphere highly influences the combustion process of biomass fuels. The weakest biomass pellets combustion intensities were obtained in the 21%O_2/79% CO_2 atmosphere due to lower particle temperatures, which can be attributed to the low diffusivity of oxygen in CO_2 compared with the diffusivity of oxygen in N_2 and the high volumetric heat capacity of CO_2 (compared with the volumetric heat capacity of N_2). The combustion process in O_2/CO_2 mixtures at 30 and 40% O_2 is faster than the combustion process for lower O_2 concentrations. The ignition times for wheat straw pellets were less than 1 s in all tested atmospheres. The volatiles combustion time decreases with an increasing O_2 concentration for all biomass samples tested. The average volatiles combustion time varies from 17 s in air to 14 s in 40%oxy. The burnout time significantly decreases with an increase in oxygen concentration. The burnout time in the 40%O_2/60%CO_2 mixture was approximately 42% less than the burnout time for combustion in air. The maximum surface temperature value varies from ~1100 °C for combustion in air to ~1320 °C for combustion in the mixture of 40%O_2/60%CO_2. These high particle temperature values, especially in the 40%oxy, can cause slagging and fouling problems in CFB boilers.

Acknowledgements This work was financially supported by the National Science Centre (Poland) on the basis of the decision No. DEC-2012/07/B/ST8/03730. The support is gratefully acknowledged.

References

1. Suri, A., Horio, M.: Solid biomass combustion. In: Lackner, M., Winter, F., Agarwal. A.K. (eds.) Handbook of Combustion. Solid Fuels, vol. 4, pp. 85–140. Wiley-VCH (2010)
2. Loo, S., Koppejan, J.: The Handbook of Biomass Comb. and Co-firing. Routledge (2008)
3. Obernberger, I., Thek, G.: The Pellet Handbook. The Production and Thermal Utilisation of Biomass Pellets. Routledge (2012)
4. Tutak, W., Jamrozik, A., Pyrc, M., Sobiepański, M.: A comparative study of co-combustion process of diesel-ethanol and biodiesel-ethanol blends in the direct injection diesel engine. Appl. Therm. Eng. **117**, 155–163 (2017)
5. Magdziarz, A., Wilk, M., Straka, R.: Combustion process of torrefied wood biomass. A kinetic study. J. Therm. Anal. Calorim. (127), 1339–1349 (2017)
6. Preto, F.: Strategies and techniques for combustion of agricultural biomass fuels. In: Growing the Margins Energy Conference (2007)
7. Eurostat. http://ec.europa.eu/eurostat
8. Natunen, M., Jäntti, T., Goral, D., Nuortimo, K.: First operating experiences of 55 MW_e Konin and 205 MW_e Połaniec CFB Boilers Firing 100% Biomass. PowerGen Europe (2013)

9. Magdziarz, A., Gajek, M., Nowak-Woźny, D., Wilk, M.: Mineral phase transformation of biomass ashes—experimental and thermochemical calculations. Renew. Energy (2017). https://doi.org/10.1016/j.renene.2017.05.057
10. Steenari, B.M., Lundberg, A., Pettersson, H., Wilewska-Bien, M., Andersson, D.: Investigation of ash sintering during combustion of agricultural residues and the effect of additives. Energy & Fuels **23**, 5655–5662 (2009)
11. Niu, Y., Zhu, Y., Tan, H., Hui, S., Jing, Z., Xu, W.: Investigations on biomass slagging in utility boiler: criterion numbers and slagging growth mechanisms. Fuel Process. Technol. **128**, 499–508 (2014)
12. Kosowska-Golachowska, M.: Thermal analysis and kinetics of coal during oxy-fuel combustion. J. Therm. Sci. **26**(4) (2017)
13. Kosowska-Golachowska, M., Kijo-Kleczkowska, A., Luckos, A., Wolski, K., Musiał, T.: Oxy-combustion of biomass in a circulating fluidized bed. Arch. Thermodyn. **37**(1), 17–30 (2016)
14. Kijo-Kleczkowska, A., Środa, K., Kosowska-Golachowska, M., Musiał, T., Wolski, K.: Experimental research of sewage sludge with coal and biomass co-combustion, in pellet form. Waste Manag. **53**, 165–181 (2016)
15. Gulyurtlu, I., Teixeira, P., Lopes, H., Lapa, N., Freire, M., Galhetas, M., Cabrita, I.: Prediction of slagging and fouling tendency of biomass co-firing in fluidized bed combustion. In: Werther, J., Nowak, W., Wirth, K.-M., Hartge, E.-U. (eds.) CFB-9: Circulating fluidized bed Technology IX: Proceeedings of the 9th International Conference on Circulating Fluidized Beds in conjunction with the 4th International VGB Workshop “Operating experience with Fluidized bed-firing systems”, p. 6. Hamburg, Germany, May 13–16, (2008)

Increasing the Energy Efficiency of Hybrid RES Installations Using KNX System

Sławomir Sowa

Abstract Buildings belong to the group of largest receivers of energy in the form of electricity and heat. Therefore, research and actions are needed to improve energetic performance of these objects. Renewable energy sources (RAS) help significantly reduce the use of energy from the primary sources and to reduce energy losses. In order to increase the possibilities of using these energy sources, hybrid generation system (HGS) have been introduced, which combine several technologies of obtaining electricity and heat (Paska et al. in Wiadomości Elektrotechniczne 12:3–13, 2005 [1]). These systems include small sets of cooperating units that produce electricity and heat based on different primary energy media (both renewable and non-renewable) and/or including system(s) of energy storage. The cooperation of the units is controlled and coordinated by advanced energoelectronic systems. The choice of energy sources to be applied in a particular building depends on the type and use of the building. Optimum energy system for a building should be controlled automatically, allowing full adjustment and management of the energy sources performance. Energy performance should be controlled based on the current and expected atmospheric conditions, as well as the current energy demand of the building. Data measuring, analysis and acquisition may be successfully carried out by the KNX system equipment. This equipment has an advantage of acquiring real-time data from various sensors in order to perform the necessary functions that improve the effectiveness of energy production. The KNX technology enables data storage and analysis on the energy production, its performance, profit and total energy saving. Cooperation with the elements of the building's automatic systems allow to manage the load and, as a result, increase the building's energetic performance.

Keywords Hybrid power systems · Energetic performance · KNX control

S. Sowa (✉)
Institute of Electric Power Engineering, Poznan University of Technology,
ul. Piotrowo 3A, 60-965 Poznan, Poland
e-mail: slawomir.b.sowa@doctorate.put.poznan.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_37

1 Characteristics of the Hybrid RES Systems

1.1 Hybrid Systems—Background Information

Hybrid systems are a combination of units that use different, separate power sources. The main advantage is the possibility of independent power production from various sources, such as sun, wind, earth, etc. Energy production from one of these sources, e.g. sun or wind, depends on unpredictable and unstable atmospheric conditions. As a result, the continuity of energy supplied in a required amount to a given facility cannot be guaranteed. Consequently, hybrid power systems are the right solution [1, 2]. The use of another, independent system producing energy from a different source increases stability of energy supply and energetic performance of a facility. Systems, which produce energy from various sources, need to be automatized, in order to carry out continuous monitoring of the generated power parameters and energy demand of the receivers. A very much needed possibility would be to forecast the production and use of energy based on prognoses and analyses of the previous work of the whole system. As a result, we obtain a high-performance energy production system, which focuses on the most available of the energy sources at a given time, effectively using its generative potential.

1.2 Production of Energy in the Hybrid RES Systems

Buildings may be equipped with production systems using two types of energy sources or several independent sources of renewable and conventional energy [3]. The most popular are dual-fuel systems, i.e. hybrid systems, which use two sources, e.g. wind and sun energy, to generate electricity. They are usually "on-grid" systems. Connecting the system with the external electric grid guarantees continuous power supply to the receivers, and the benefits of reduced use of energy supplied by the external operator. Such configuration also enables sending to the grid the generated energy surplus. Such a system should additionally be extended to include energy storage. Then some of the energy surplus is stored in the batteries. With this hybrid solution, in case of power shortage, energy can be sourced from the system's storage first, and only then from the grid. Such a priority of sources is beneficial, because the payment for the energy provided to the grid is usually less than the cost of buying it from the operator. Moreover, this way the power sources are diversified, which significantly improves energy security.

"Off-grid" systems, on the other hand, are applicable in locations, where connecting to the electric grid would be impossible or economically unviable. This paper focuses on systems connected to the external power grid and, optionally, are equipped with energy storage.

The systems of energy production management and control based on the current energy demand are most useful in the systems composed of several energy sources.

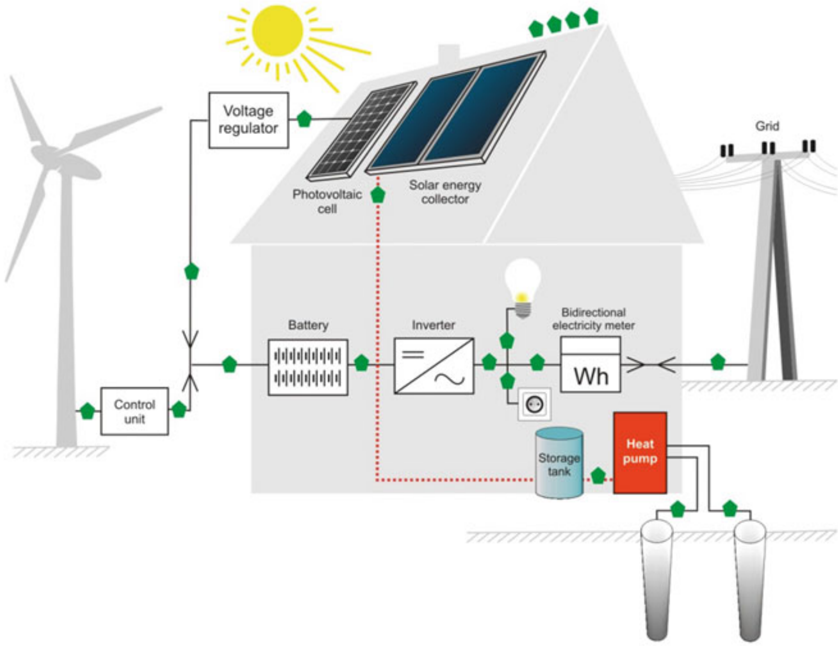


Fig. 1 Example of a hybrid installation based on RES, with elements of the KNX system and sensors (author's own project)

Generating electric energy from two sources and heat from several sources makes system control rather complex and requires advanced automation. A system of sensors and meters supervises the system, providing updates to the central unit, which controls each unit installed in the system. Figure 1 shows a multi-source hybrid system, which uses sun, wind and earth energy to produce electricity and heat.

1.3 Reliability of Hybrid Systems

The key aspect of choosing the power supply system for a facility is the reliability of supplying heat and/or electricity. RES energy supplies are highly unpredictable and unstable. Hybrid systems solve this problem, as they enable energy production from other sources. When taking into consideration renewable sources only, systems can be created that produce electricity using PV cells and wind turbines, and that produce heat using solar thermal collectors and heat pumps. With tailored, automated control and surveillance, the power system can achieve high level of reliability and independence. Electric energy generated in the PV cells, which work only during the day, provides power to the receivers when the demand is at its highest. Wind turbines generate energy which is then stored in batteries or sent to the grid. Furthermore, solar thermal collectors produce heat in the day and accumulate its surplus in the heat storage. In this system, heat pump is crucial, especially in the winter, when heat from the collectors is generated only for a short time in the day and in small amounts.

2 KNX Control System

2.1 General Characteristics of the KNX System

Modern electric installations need to meet several criteria posed by demanding users. Apart from standard properties, typical for traditional installations, they are required to provide comfort and safety of use, as well as, importantly, reduce the energy use. The solution that meets this requirement may be the KNX system. Additionally, its structure is transparent and it provides flexible installation work. KNX is a global standard of management and control of equipment and buildings. This is a dispersed system, which uses the bus cable to send information, cablegrams that control the functions of equipment and subunits [4]. All parameters of the equipment and its functions are defined and programmed by the user, so that the functioning of the system can be largely modeled. Visualization programs enable fast readout and monitoring of the equipment and sensors in the whole installation.

2.2 Implementation of the KNX System of Power Generation Control

The KNX system is most profitable with multi-source energy production systems. These include systems that generate both electricity and heat for a particular facility. By implementing this system of managing energy production from different sources, energy losses can be reduced to minimum, especially for the own purposes. For example, in this type of a system, the heat pump is powered with energy generated by PV cells. When the control procedures are well tailored, the heating system can be switched on by the heat pump when sufficient amount of energy is produced in the PV or wind turbine modules. The KNX system has a number of sensors that supervise the current power generation parameters in correlation with the target temperature and other parameters, ensuring optimum use of all the produced energy. Implementation of the KNX system includes installation of a number of sensors and elements processing the parameters measured in the whole energy producing system. Measurements should be taken, if possible, at all essential sites, devices, and elements of the energy generation, storage, processing and distribution systems. Additionally, as many data as possible should be collected on the current external conditions (weather station), current energy use and estimated energy demand. An important benefit of the KNX standard is the manual mode, with the use of sensors and controls. This solution man be useful, if the automatic system cannot make an unequivocal choice of the best option.

2.3 Algorithms of Energy Production and Usage Control

The advantage of hybrid systems of energy production is the possibility to generate energy in different weather conditions. Time of the day, season of the year and location are also significant. When generating energy from renewable sources, we cannot accurately predict the produced amounts. However, based on the analysis of publicly available data, we can estimate the amount of generated energy at a given time of the day, month and year. This is more applicable to the sun energy than to the wind energy. The most predictable is the heat production from the earth.

When developing the algorithms of controlling energy production in the RES hybrid systems, such data need to be correlated with the data on energy demand. Energy usage forecasts help manage the energy sources in a more effective way. The purpose is to ensure maximum use of the RES energy with minimum use of energy from the external supplier. The control system should be programmed to prioritize the RES energy. When this energy is not sufficient, conventional sources of heat should be used or, in case of electricity, the external supply from the grid.

The designed concept project of hybrid power source control is shown in Fig. 2. The control system uses the KNX system to supervise, control, join circuit and acquire data. The performance parameters of the grid, devices and other elements are monitored by sensors, detectors and KNX standard compatible sensors. Controlling particular circuit and devices is done with the use of KNX performers such as: actors, makers. All data is sent by the bus to the central data server with software for real-time visualization of the system parameters and system management. After the control system processes the data based on the defined algorithms, the executive elements are regulated, which determine the functions of each device and each control and executive element. This way, we can decide to switch off the circuits of the installation that are not in use. Appropriately designed algorithm will prevent the water heater from switching on, when the system receives information that the weather conditions are appropriate to obtain energy from the sun thermal collector. The whole system can additionally be extended to include conventional heat sources. Then the applied automatics will also control switching on and off the gas boiler and adjusting its power.

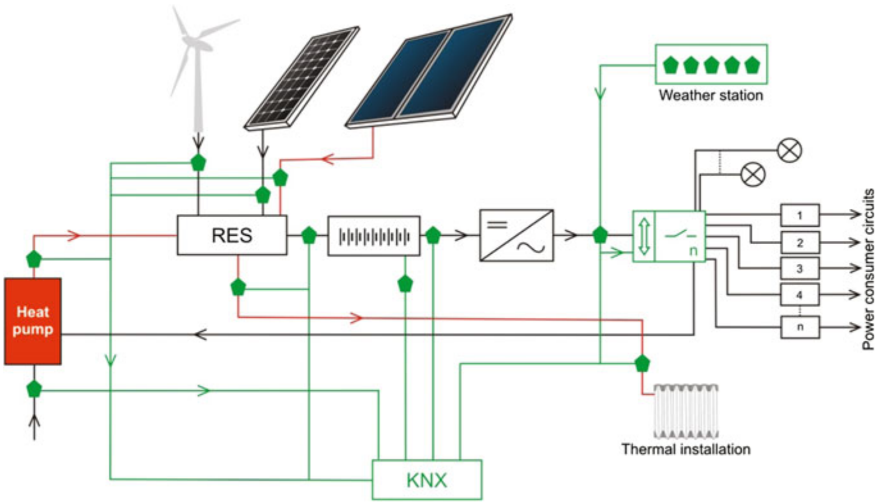


Fig. 2 General concept of hybrid power source control using the KNX system (author's own project)

3 Energy Performance of Facilities

3.1 The Term Energy Performance

The energy performance and renewable energy together constitute the main pillars of the sustainable energy policy [5]. There are numerous standards and directives on energy performance of facilities. One of them provides that until the end of year 2020, all new buildings should have a near to zero use of energy.

There are many ways of securing the energy performance. A popular solution is to provide thermal isolation of the buildings, which helps reduce the amount of supplied energy and reduce the power of the installed energy sources. The energy demand of facilities include the need for electricity, heat and cold. The renewable energy and energy storage helps reduce the use of primary energy and reduce the energy losses.

3.2 Increased Energy Performance with the Use of KNX System Based Solutions

The KNX system can be applied in many areas of automatics and construction technique, as well as the industry. My studies show that when implementing the KNX system based solutions for controlling lights in a school, we can save between 35 and 48% energy. The rate of energy saving depends on the introduced control variant and the use of dedicated elements. The KNX standard ensures compatibility with the majority of transducers on the market, as well as energy measuring systems and typical sensors of the environmental parameters and equipment functions. The data from sensors provide complete and accurate knowledge on the energy production, its performance, profit and total energy saving. The data on the functional parameters and amounts of the generated energy are sent to the central unit in real-time. The KNX system is coupled with the building's automatics, which controls the majority of electric devices in the facility, such as lighting, heating, shutters, fans, air conditioning, etc. Communication with the elements of the building's automatics and control elements enables the control of electricity and heat loads of the building. Combining the data on the generated energy (electricity and heat) with the data on the energy demand makes it possible to design the energy policy for the facility. All data gathered, both on the production and use of energy, we can implement appropriate control algorithms, which improve the energy performance.

It should be noted that it is possible to extend the structure of control and monitoring in the KNX system. The intelligent KNX systems have the capability to control the executive elements, which in turn control the functioning of all devices and components of a given system. This capability helps optimize the amount of generated energy in reference to its current and future demand. It also enables the control of storing its surplus for future use by the receivers. By principle, the more nodes and installation elements are monitored and controlled, the more appropriate control algorithms can be selected, so that the performance of the whole energy system can be improved.

4 Summary and Conclusions

System of hybrid power is the most effective solution to power facilities and buildings. Using only one energy source significantly limits the possibility to secure stable production and supply of energy. When independent, alternative production systems based on different energy sources are introduced in a building, power supply is much more effective.

The global KNX system integrates the capabilities of monitoring functional parameters, controlling the production sources and executive devices in the building's automatics, as well as supervising the energy use and demand. Other benefits of this control, supervision and data acquisition system is its compatibility with different sensors, monitoring of the measured parameters, system transparency and visualization software. The ability to use the collected data and appropriate control algorithms helps improve the energy performance of hybrid installations based on the renewable energy sources.

References

1. Paska, J., Sałek, M., Surma, T.: Wytwarzanie energii elektrycznej i ciepła w systemach hybrydowych. Wiadomości Elektrotechniczne **12**, 3–13 (2005). ISSN 0043-5112
2. Paska, J., Biczel, P., Kłos, M.: Hybrydowe systemy energetyczne - efektywny sposób wykorzystania pierwotnych źródeł energii. Energia odnawialna **34**, 11 (2009)
3. Stefaniak, A.: Systemy hybrydowe odnawialnych źródeł energii. Czysta Energia **11** (2013)
4. Klajn, A., Bielówka, M.: Instalacja elektryczna w systemie KNX/EIB. Centralny Ośrodek Szkolenia i Wydawnictw w Warszawie, Warszawa (2006)
5. The Twin Pillars of Sustainable Energy: Synergies between Energy Efficiency and renewable Energy Technology and Policy. Aceee.org. Last accessed 16 July 2010

Analysis of Wind Farm—Compressed Air Energy Storage Hybrid Power System

Marlena Wróbel and Jacek Kalina

Abstract This paper presents a hybrid system which consists of wind turbines and compressed air energy storage (CAES) facility. The inclusion of CAES into an existing wind farm helps to control power output of the entire plant. Due to wind farm location the considered CAES system was assumed to be a small scale with above ground air vessels. Mathematical, dynamic simulation of CAES model was performed. Conclusions on annual co-operation of CAES systems with wind turbines are presented.

Keywords Wind farm · CAES · Hybrid energy storage · Compressed air

1 Introduction

Over the last 20 years the installed capacity of wind energy in EU has systematically increased. According to data published by the European Wind Energy Association, at the end of 2013 there were 117.3 GW of installed wind energy capacity in the EU States. The leader in the production of wind energy is Germany, as well as Spain, France, Italy and Great Britain. In two years only (2012–2013) 5.535 GW of wind turbines with power of 33.73 GW were installed in Germany [1].

Based on data of the Energy Regulatory Office of Poland, in 2016 there were 5.807 GW [2] of power installed in wind farms which generated 11,694.086 GWh [3] of electric energy in 2016 year. The most of power has been installed in approx. 30 biggest wind farms located mainly in northern and central part of Poland (Fig. 1) [4]. Since 2005 the share of wind installations in total energy generation by renewable sources has increased up to 47% for 2015. Years 2011 and 2013 are a breakthrough period when wind power sector generated more electric energy than

M. Wróbel (✉) · J. Kalina
Institute of Thermal Technology, Silesian University of Technology, Gliwice, Poland
e-mail: marlena.wrobel@polsl.pl

J. Kalina
e-mail: jacek.kalina@polsl.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_38

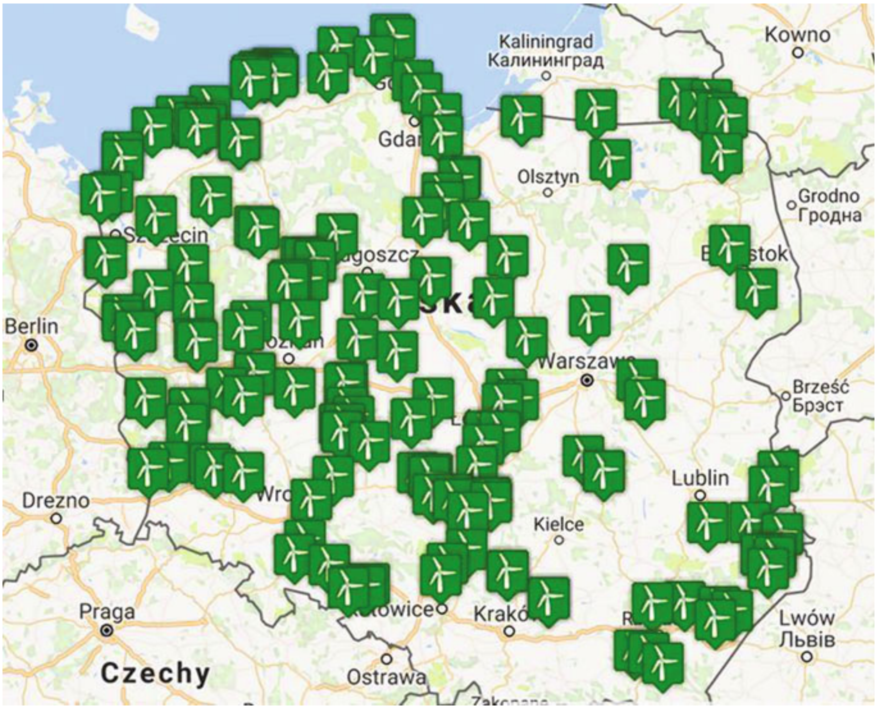


Fig. 1 Location of wind farms in Poland [15]

hydro power plants (year 2011), and system power plants co-firing biomass with other fuels (year 2013).

The characteristic feature of the electricity system is a significant variability in the demand for power supplied. It concerns both seasonal cycles as well as daily ones. The connection of additional generation sources characterized by high instability of operation additionally intensifies this phenomenon. Unfortunately wind farms fit very well in this unfavorable situation as the energy they generate depends very much on weather conditions despite great efforts put into predictions of generation profiles.

The fact that it is not possible to accurately plan energy generation from wind farms has a negative impact on the operation and, in view of currently used legal regulations, also the economics of the operation of conventional power plants. With low wind speed, the energy output in wind farms is reduced and in consequence there is a power deficit in the system. In view of the fact that the energy balance in the power system must be always offset, the deficit created should be covered by energy storage facilities such as hydroelectric peak load power station or conventional sources.

The increase of the share of wind energy in the Polish energy mix is accompanied by the reserve power to be covered. In the typical system this creates cyclicity of the operation of traditional thermal power plants. This involves cyclical power control to adjust the supply to the current demand.

However, thermal power plants running on fossil fuels are not designed to operate at variable loads. Continuous and unexpected change of the load results in operation below the nominal efficiency which in turn leads to increased fuel consumption and additional CO_2 emission. The bigger the share of wind energy, the more serious the problem with power regulation. However with significant wind speed and high generation, the output of big wind farms will not be efficiently utilized locally and it will be necessary to transmit oversupply of power to other regions of the country by the transmission network which results in energy losses. One of the ways to utilize the periodic energy surplus is to accumulate it in storage facilities making it possible to make up for the power deficits occurred in a period of adverse weather conditions.

To accumulate large volume of energy, pumped-storage systems which have the biggest (99%) share in the installed power as compared to energy storage technologies used worldwide [5]. The advantages of this technology include the possibility of storage for any length of time, short start-up time, cheap and commonly available energy carrier, low cost of energy generation, maturity of technology and long lifetime. The disadvantages, on the other hand, include the dependability on hydro geological conditions, introduction of changes in the eco system and high capital expenditure [6]. A less common technology are the Compressed Air Energy Storage installations. The main advantage of the technology is the use of a free energy carrier i.e. air. In a classical CAES installation electric energy available outside the peak is used for compressing air which is stored in an underground or ground vessels. If there is a need to generate electricity, compressed air is mixed with natural gas, burnt and expanded in a modified gas turbine thus powering the generator. In the conventional CAES system an additional fuel is introduced and therefore it should be regarded as a hybrid storage/electricity generation system [5]. Adiabatic Compressed Air Energy Storage [7] has been proposed as a much more energy effective method which eliminates the demand for fuel and combustion process in favor of the storage of heat generated during the air compression process. The accumulated heat is subsequently used for heating the air supplied to the expansion turbine. Figure 2 presents an example layout of this kind of installation.

Simulations for the ACAES plant with taking into account heat losses during heat storage showed that the round trip efficiency of the system may reach as much as 75% [8]. An important aspect for the ACAES technology is the development of an efficient procedure for heat replacement and storage. The storage agent should meet the requirement of quick absorption and giving up of heat, and the storage facility should be properly insulated [9].

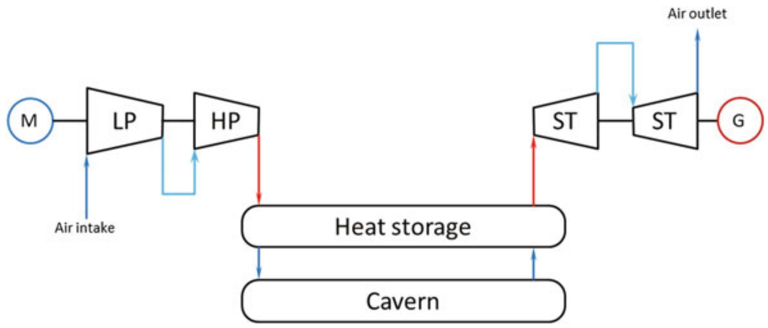


Fig. 2 Simplified operating diagram of ACAES system

2 Analyzed Case

In this paper an example of wind farm and compressed air energy storage hybrid power system was analyzed. It was assumed that the compressed air electric energy storage plant is collocated with the wind farm and the entire installation can be regarded as an integrated power station. Sizing of the storage system was based on annual variability of energy generation in wind power station which is shown on Fig. 3.

Due to the lack of an appropriate geological formations for air storage (salt cavern) the ACAES with above ground air storage vessels was assumed. The installation with above ground storage in steel vessel may be located in any place. This technology is nowadays regarded as an alternative for distributed CAES plants of up to 20 MW installed power. The ACAES plant was sized taking into account generated median of annual power which is 0.4 MW (approximate 23% of the wind farm installed power). In the studied case it was decided to use a group of steel vessels. Simplified scheme of analyzed ACAES is shown Fig. 4. The air vessels

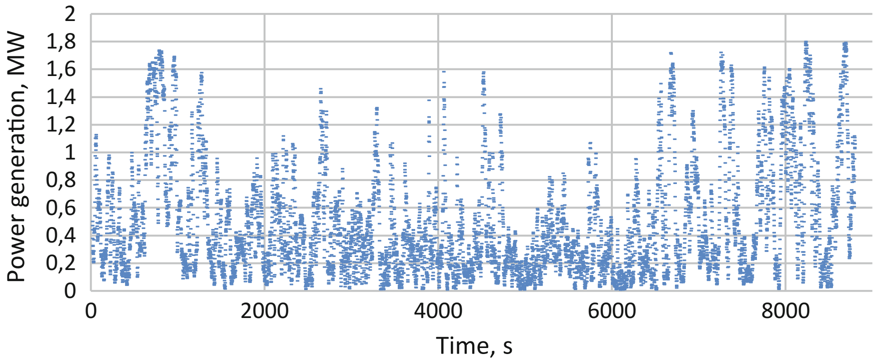


Fig. 3 Wind farm power production in every hour of the year

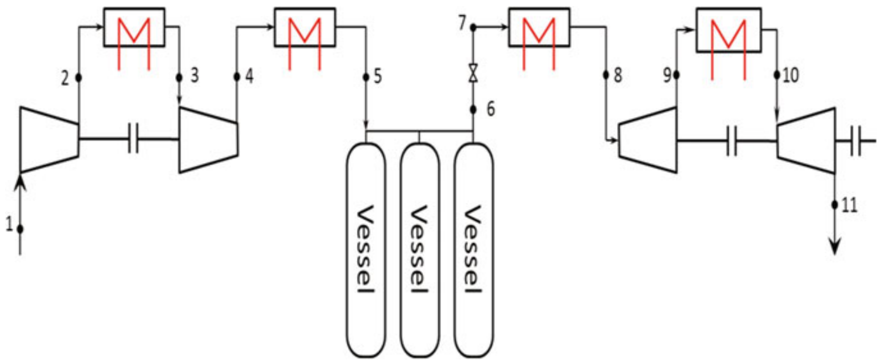


Fig. 4 Analyzed ACAES scheme

charge system consists of two stage compressor with section intercoolers. Compressed air discharge system consist of two expanders and two air heaters.

3 Thermodynamic Analysis of ACAES Plant

3.1 Assumptions

In order to determine the performance of ACAES plant preliminary dedicated dynamic model of the process was created using Matlab software. The model contains the ordinary differential equations describing processes in the ACAES system.

Basic assumptions adapted to calculations (subscripts relevant with symbols in Fig. 4).

- overall capacity of air vessels—377 m^3 in 20 vessels,
- internal compressor efficiency 85%, mechanical 95%, electrical 95% [10, 11]
- internal expander efficiency 85%, mechanical 95%, electrical 95% [10, 11]
- ambient conditions p_1 = 1 bar, T_1 = 283 K, ϕ = 0.6
- vessel inlet temperature T_2 = 323 K
- maximum pressure in vessel p_{max} = 100 bar
- minimal pressure in vessel p_{min} = 10 bar
- vessel pressure after throttling in valve 50 bar
- assumed working fluid—real gas

Pressure and temperature levels were adopted for possibility of strength of steel vessels. The analyzed ACAES plant does not show accurate representation of real operating system. In order to visualize energy storage capabilities in compressed air, an idealized model was adopted, which do not take into account turbomachinery characteristics and analysis of heat storage system.

According to the first law of thermodynamics the energy balance of compressed air storage reservoir is represented by an equation:

$$\frac{dU}{d\tau} = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \dot{Q} \quad (1)$$

where $\frac{dU}{d\tau}$ is the rate of increase in internal energy of the air inside the storage vessels. Equation (1) can be decreased as:

$$\frac{dU}{d\tau} = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \alpha A_{wall}(T_{st} - T_{wall}) \quad (2)$$

where α is the heat transfer coefficient, A_{wall} is the area of heat transfer, T_{st} and T_{wall} are the air temperature inside the vessel and the vessel wall temperature.

Equations (1) and (2) were used to create a mathematical model of the compressed air storage reservoirs. In the literature [12, 13] there are located detailed mathematical models.

3.2 Results of Modeling

Variations of selected parameters generated from modeling of air compression process in ACAES installation are shown in charts below.

During the compression cycle the installation requires 20 GJ of electricity produced by the wind plant. The vessels under pressure of 100 bar accumulate 3.8 tons of air. Figure 5 shows air mass changes in the storage installation and the quantities of energy utilized to run the compressors. In Fig. 6 variables of power provided by compressors, air pressures in storage vessels and pressure ratio in

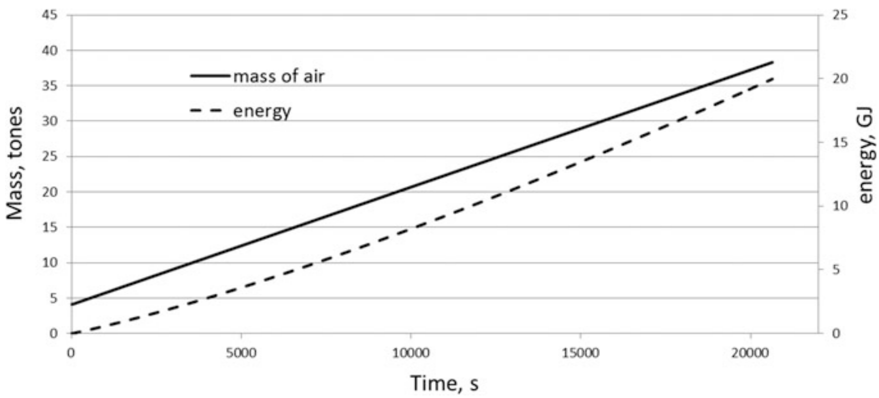


Fig. 5 Air mass and stored energy in function of time

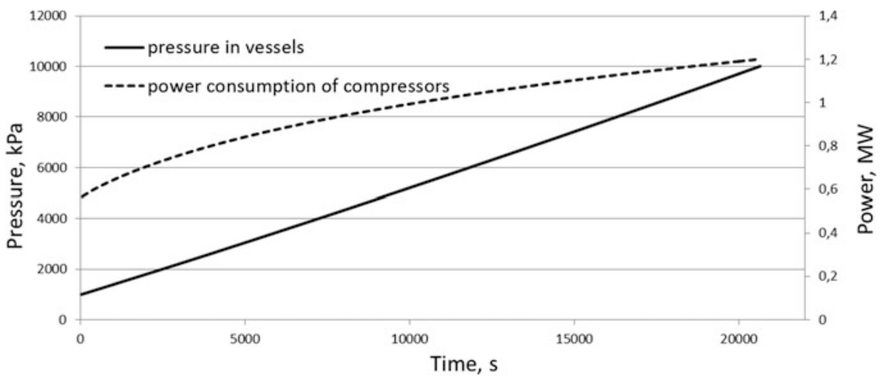


Fig. 6 Pressure and power consumption in function of time

compressor are shown. Air temperature in storage unit was shown in Fig. 7. During calculations heat losses in vessels were taken into consideration.

During the expansion cycle the ACAES system produces about 12 GJ of electricity. In Fig. 8 variations of power generated by turbine and pressure before turbine are shown as a function of time. Calculations show that the round trip efficiency of the system is 61%.

4 Cooperation of ACAES and Wind Farm

4.1 Assumptions

The co-operation of a wind farm with an energy storage system may have different objectives. For example, a purpose can be achieving the best economic results by generating energy at peak hours [14]. In this paper an aim of cooperation of wind farm and energy storage in compressed air was to minimize variations of electric power generation by the hybrid system. Adopted assumptions are shown in Fig. 9.

When median value exceeds more than 15% ACAES plant will start to charge. When power generated by wind plant decrease lower than 85% of median, ACAES system will launch air turbines in order to cover power deficiency in electrical system. If the generated power was in the area between ±15%, the ACAES system would not operate, and the wind farm itself is considered as stable. In case of overfill of air vessels or their completely depletion ACAES does not run and actual wind farm power is transferred into electricity grid. It was assumed that the ACAES will be adjusted to the required level of power by modifying the air flow. In this paper the annual cooperation of wind farm and ACAES hybrid system is calculated.

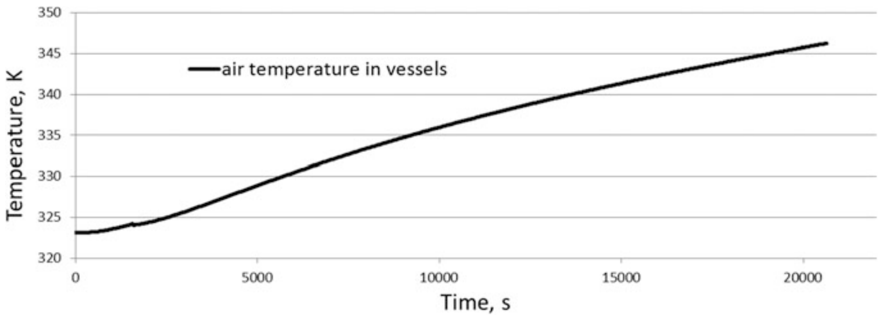


Fig. 7 Temperature of air in function of time

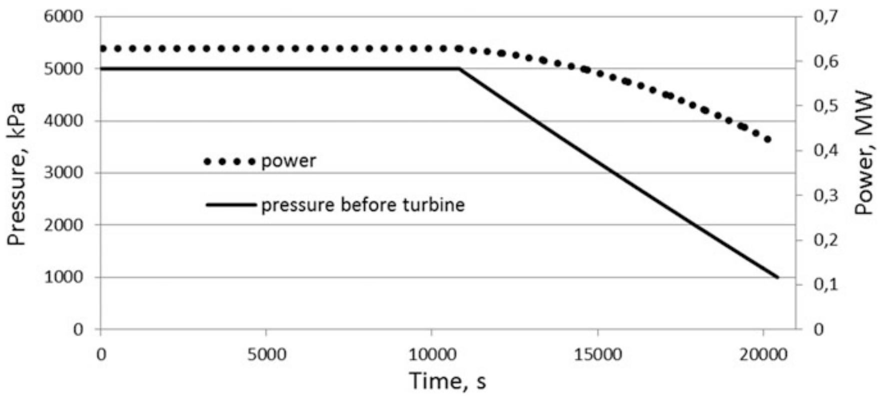


Fig. 8 Pressure before turbine and power production in function of time

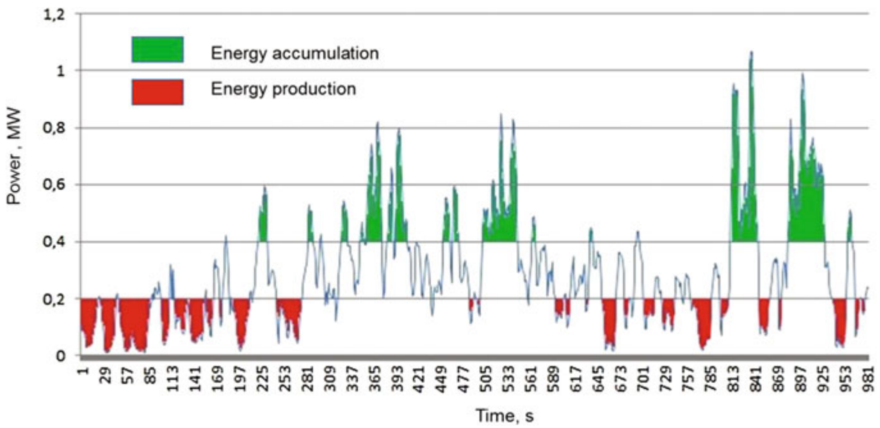


Fig. 9 Scheme illustrating the cooperation of wind farm and energy storage system

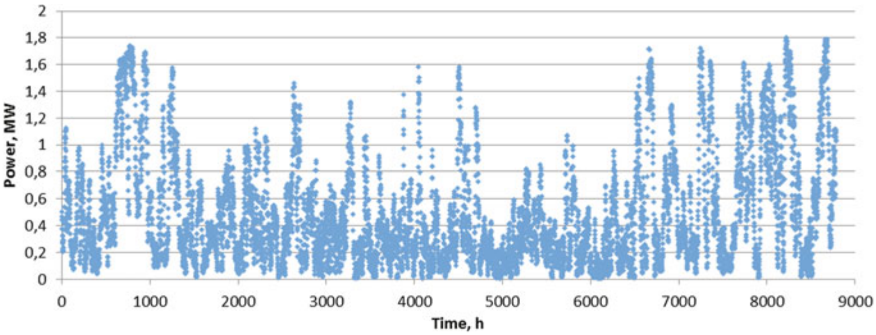


Fig. 10 Wind farm power production without ACAES

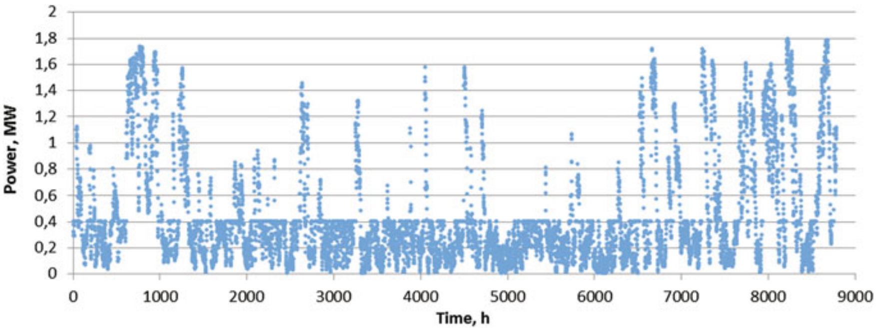


Fig. 11 Hybrid system power production

4.2 Results

Annual cooperation of analyzed hybrid installation was simulated in Matlab software. Results was demonstrated in Fig. 11 where power generated to grid is presented. Results can be compared with the chart of a independently operating wind plant which is shown in Fig. 10. Comparison of both charts presents that application of energy storage system in compressed air has reduced partial variability of generated power.

5 Conclusions

High dependence of energy production in wind farms from prevailing weather conditions has negative impact on electricity system. Cooperation of wind powered renewable source with energy storage can take positive impact on reduction of power variability delivered to the grid. The applied method of energy storage—the above ground energy storage ACAES. Has a round trip efficiency of 61%. Efficiency of energy storage can be increased by optimization of pressures and heat storage. The proposed system of energy storage has not completely reduced the variability of produced energy. However, aboveground artificial vessels allow to accumulate enough energy to generate electricity for 12 h in case of insufficient wind conditions. That allows electricity system operators to run the conventional power plants (which in Poland are mostly coal based) to maintain system stabilization, cover power deficiency and have additional positive influence for stabilization. A further assessment of combining energy storage systems with wind plants should be enhanced by hybrid system economic analysis.

References

1. The European Wind Energy Association, Building a stable future, Annual report 2013
2. URE homepage. https://www.ure.gov.pl/pl/rynki-energii/energia-elektryczna/odnawialne-zrodla-ener/4762,Odnawialne-Zrodla-Energii.html. Last accessed 15 June 2017
3. PSE homepage: http://www.pse.pl/index.php?modul=21&id_rap=24. Last accessed 15 June 2017
4. WNP homepage. http://energetyka.wnp.pl/gdzie-w-polsce-jest-najwiecej-farm-wiatrowych,186676_1_0_0.html. Last accessed 15 June 2017
5. International Electrotechnical Commission Electrical Energy Storage. ISBN 978-2-88912889-1
6. Nalepa, K.: Magazynowanie, kondycjonowanie i konwersja energii ze źródeł odnawialnych, Wydaw. Instytutu Maszyn Przepływowych PAN (2014)
7. Dzierżanowski, Ł.: Elektrownie Caes; Energia Elektryczna – nr 2-3/2011
8. Egidi, R.: Technical and Economic Analysis of Various Power Generation Resources Coupled with CAES Systems. National Energy Technology Laboratory, DOE/NETL2011/1472
9. Andris, R, Bartlett, E., Blaik, R., Bruce, S.D., Elkind, E., Intrator, J., Lim, C., Luong, D., Sawchuk, M., Smith, L., Tsu-Chin, T., Weissman, S.: 2020 Strategic Analysis Of Energy Storage In California, Nov 2011. CEC-500-2011-047
10. Szulc, A., Chou, J., Tang, L., Zeng, X.Y.: Compressed air energy storage. Analysis of Feasibility and Efficiency of Compressed Air as an Energy Storage Medium. University of Pennsylvania
11. Yao, E., Wang, H., Wang, L., Xi, G., Maarechal, F.: Thermo-economic optimization of combined cooling, heating and power system based on small-scale compressed air energy storage. Energy Convers. Manag. **188**, 377–386 (2016)
12. Peng, H., Yang, Y., Li, R., Ling, X.: Thermodynamic analysis of an improved adiabatic compressed air energy storage system. Appl. Energ. **183**, 1361–1373 (2016)
13. Wang, J., Luo, X., Krupke, C., Wang, Y., Sheng, Y, Li, J., Xu, Y., Wang, D., Miao, S., Chen, H.: Modelling study of efficiency analysis and optimisation of large-scale Adiabatic Compressed Air Energy Storage system with low-temperature thermal storage. Appl. Energy **162**, 589–600 (2016)
14. Emily, F.: Jay Apt Economics of compressed air energy storage to integrate wind power: a case study in ERCOT. Energy Policy **39**(5), 2330–2342 (2011)
15. http://www.szamsija.pl/mapa/. Last accessed 2017/06/10

Wind Power Engineering—Would a Well-Managed Investment Process Prevent Disputes Between the Local Authorities, the Investor and the Local Community?

Angelika Górczewska and Jacek Leśny

Abstract One of the phenomena connected with the development of wind power engineering includes social skepticism related with its potential environmental impact and effect on human health. One of the essential elements, enforced by legal regulations, is the requirement of public consultations, which may refute or limit public concerns. This study presents an investment process in the Kramsk commune along with the results of a questionnaire survey conducted in the local community upon the completion of the investment project. It may be concluded that one of the characteristics of conscious society is its willingness to broaden their knowledge. In such a situation, thanks to the intensive educational efforts of the local government, local residents may acquire sufficient knowledge to cease being passive recipients of information, manifesting their hostile attitude towards investors. In contrast, the may actively engage in the investment process and show positive attitudes to the development of renewable energy sources, as well as other future investment projects.

Keywords Wind power engineering · Local community · Public consultations Participation · Impact of wind turbines

A. Górczewska (✉)
Poznan University of Life Sciences, Piątkowska 94C, 60-649 Poznań, Poland
e-mail: angelikagorczewska@wp.pl

J. Leśny
Department of Meteorology, Poznan University of Life Sciences,
Piątkowska 94C, 60-649 Poznań, Poland
e-mail: jacek.lesny@up.poznan.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_39

1 Introduction

The Polish power engineering sector faces inevitable modernisation. Wind power engineering is continuously struggling with numerous barriers limiting its development. The most common causes for skepticism are connected with its potential environmental impact and effect on human health. For this reason rational localisation and reliable information on the future operations of the planned wind farm seem to be crucial for the entire investment process. The subject for this study was to discuss the key issue, i.e. social participation, in the decision-making process within the investment project. The study focuses on the significance of knowledge on the planned activities on the part of the local residents. Good practices are presented, which may potentially contribute to the success of a given investment project, related with the concept and behaviour of local communities. The in-depth analysis was conducted based on the Kramsk commune, the town of Podgór, where three wind farms were established.

2 A Review of Literature

Local communities share a set of principles related with the local traditions, as well as a certain lifestyle. The concept of sustainable development, of paramount importance for the contemporary world, should not be undermined by investments having a negative effect on social relations in the local community. Investments potentially having such an effect include construction of wind farms. In view of the progressing suburbanisation the world view of suburban residents and inhabitants of dormitory towns is rapidly changing. It is a consequence of the influx of young professionals into rural areas [1]. The task faced by the investor, i.e. persuading the local community, may be much easier if the local community does not include former urbanites. It turns out that they are the most influential residents and ones most willing to organise protests. When deciding to move to the country they associate such locations with attractive landscapes and in their opinion wind farms may have a potentially negative effect on the main factor for the decision to move out of the city [2]. From the sociological perspective the diffusion of knowledge on wind power engineering is associated with the theory of the centre and periphery developed by Shils [3]. In relation to the above-presented situation, with the increasing spatial distance from the centre to the periphery information in terms of its rational content may be distorted to a certain extent. Specific economic conditions or the actual knowledge on the planned investment project and its impact most frequently are associated with the centre, i.e. the decision-makers, such as e.g. the Commune Office. It is highly likely that comprehensive and reliable information on the subject will reach only a small group of residents (e.g. those leasing land), and not necessarily the periphery community.

An interesting phenomenon, resulting relatively often from the exclusion of the local residents from the decision-making process, is related with the NIMBY syndrome [2]. It is typically an ecological conflict. Representatives of local communities using a given space may differ in their opinions on its use from the new users, i.e. investors. Disputes occur mainly in situations, when the planned new concept for the use of this space in the opinion of residents differs from the concepts of the investor. Its negative perception results from the habits and specific mentality of the local community, particularly when the investor's true intentions or the effects of the investment are not known. The slogan *Not in My Back Yard* refers to a certain attitude of individuals or groups to investment projects, which in their opinion should not be implemented in their immediate neighbourhood. The need for a given investment is understood, but it is accepted by the local community only when it is located away from their homes. In the case when the proposed actions concern specific communities and may additionally be burdensome, they met with resistance and dissatisfaction [4]. In terms of functioning of local government we need to focus on the concept of local governance. It is based on cooperation and collaborative networks. In this sense governance has not been sufficiently adopted in Poland. Examples of enterprises executed in cooperation with local authorities implementing the principles of partnership and local governance confirm effectiveness of this management model.

According to the Polish Sociological Association [5], public consultations should comprise three elements:

- information, using which the planned enterprise is promoted,
- counselling based on the collected opinions of the local residents,
- participation, i.e. active involvement of recipients in the decision-making process.

A lack of any of the above elements or failure to conduct any public consultations may result in protests and deterioration of mutual relations.

Local residents, frequently having no specialist knowledge on actual or potential threats and hazards, oppose investments in wind power engineering based on similar projects publicised in mass media due to their misjudged site locations. The need for an information campaign is evident when analysing the situation observed when it is not launched. The first issue is to organise meetings for those interested in the utilisation of wind energy. These meetings should only focus on facts, an objective overview of advantages and possible disadvantages of a given investment project. Direct contacts with the local residents should be maintained by an unbiased specialist, preferentially somebody well-known to the local population and considered trustworthy [6]. Awareness of climate change and its consequences, as well as insight into the state's energy policy make is easier to understand the crucial aspects of a given investment, which is required when striving to satisfy the proposals for sustainable development.

3 Methods

The investigated case of a wind farm is located in the town of Podgór, the Kramsk commune. Documents indirectly connected with development orders concerning wind turbines were analysed, such as e.g. the commune's study of land use conditions and directions. A survey questionnaire was a tool used to determine the degree of public acceptance, along with opinions on the impact of the investment. The principle adopted when preparing the questionnaire was to ensure simplicity and clarity of the message. The questionnaire was addressed to residents living in areas located in the immediate vicinity of the currently operating wind turbines. The survey was conducted with the participation of 50 respondents.

4 Results

The investment process in the Kramsk commune was initiated by preliminary talks with both the local authorities and residents. The presence of an individual in the commune authorities responsible for power engineering in the commune, particularly the implementation of renewable energy sources and their promotion on the commune scale, would obviously improve the quality of these preliminary talks and would facilitate objective assessment of proposed solutions. The opinion of the Regional Directorate for Environmental Protection imposed on the investor the obligation to conduct the environmental impact assessment (EIA). The EIA procedure requires the participation of the public in the process. As a result the responsible authority, i.e. in most cases the commune head, conducts public consultations, in the course of which objections and suggestions may be voiced concerning the planned investment project. Quite often this is the most difficult step in this process. Frequently a lack of agreement as well as objections of the residents considerably prolong the investment processes. In the case of the Kramsk commune this was not the case.

The conducted questionnaire survey presents the public opinions on the wind farms operating for several years now. In the question concerning the attractiveness of the landscape with wind farms 54% respondents see positive changes in the landscape, while 36% residents claimed that they do not care about landscape. Every tenth respondent does not like changes in landscape.

The benefit most frequently indicated by the respondents was connected with generation of clean energy, followed by the economic factor, i.e. increased revenue for the commune budget thanks to taxes paid by the investor (Fig. 1). The respondents were of an opinion that investing in wind power engineering has a positive impact on the image of the commune, being perceived as more "innovative".

In the question on threats and hazards related with the operation of wind turbines the most frequent answer indicated a decrease in value of land allocated for building

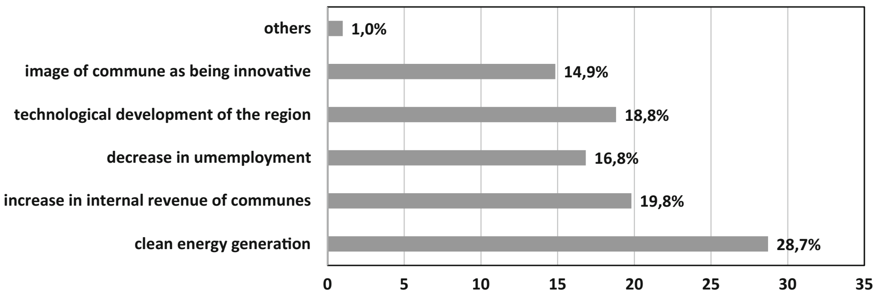
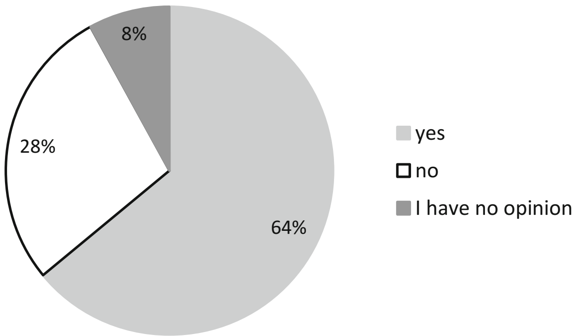


Fig. 1 Benefits from the location of a wind farm

Fig. 2 Opinions of residents on the development of renewable energy sources



development (approx. 42% respondents). This was followed by the hazard connected with noise and vibrations generated by the working turbines. This health hazard was indicated by 25% respondents. A decrease in the value of farmland was feared by 13.1% polled residents, while threat to the environment was indicated by only 11% respondents.

A total of 64% polled residents supported the use of renewable energy sources to generate energy. An opposite opinion was voiced by 28% respondents. The others, accounting for 8% polled population, were undeclared (Fig. 2).

Most residents were of an opinion that the Kramsk commune has potential for investments in wind power engineering. Another most frequently indicated alternative energy source is solar energy. Almost 17% respondents saw the potential for generation of energy from biomass. A total of 36% residents would agree to the construction of another power plant, obviously while meeting all respective standards. However, 34% all polled would oppose such a potential enterprise. The others (30%) were undeclared.

5 Discussion

Responses supplied by the polled residents reflected their educational background and confronted their knowledge with the actual subjective evaluation of the impact of the power plant (wind farm).

According to the study by the Polish Sociological Association [5], the local community would trust more a private, rather than a corporate, investor, as one who would not be anonymous and would be willing to answer all their questions. The co-called developers would face more problems in the attempts to successfully complete their investment projects, as they are considered to be interested mainly in constructing the wind farm and selling it at the earliest possible date. Being focused on reaping rapid profits they rarely have time to spare for the local community. In the Kramsk commune it was the former situation, when the primary objective of the investor was to generate and sell clean energy. For the local residents the investor was not an anonymous entity. In relation to the NIMBY syndrome in the Kramsk commune the residents seem to be relatively open-minded as far as new technologies are concerned, and after the investment proposal was publicized they voiced no major objections and did not perceive any significant threats. No serious objections were presented and no protests were organized.

This suggests that a local community understanding the need for a systematic increase in the utilization of renewable energy sources does not express envy towards individuals receiving financial profits from lease. The residents are aware that such investments are beneficial for the whole society in view of the consequences of unlimited exploitation of fossil fuels. For this reason it is crucial to ensure rational and considerate actions of the authorities in terms of the economic aspects of such investments. Positive attitudes towards investments and the actions of the local government may be expected when benefits will be experienced not only by land lessors, but a vast majority of the local population. Interesting relations were observed by Pedersen [7] in the course of studies on the impact of wind farms e.g. in terms of sleep disorders in residents living in the vicinity of wind farms. Several such cases showed that the individuals receiving financial profits from the location of a wind farm (e.g. lessors of land for the investment development) experienced no negative impact. What is of interest, such individuals lived on plots located at closer distances from the wind turbines than the residents complaining about insomnia despite a greater distance of their homes from the wind farm. In the Kramsk commune the theory of the centre and periphery was not fully confirmed, similarly as the supposition that only newcomers—former urbanites exhibit greater knowledge and potential willingness to protest against such investments. In the village of Podgór there are no newcomers; despite that fact the residents can indicate real benefits derived from the operation of wind farms, while also being aware of potential threats and hazards. Although they feel deeply attached to their hometown, the residents find landscape with wind turbines to be attractive, treating them as an element introducing variety. It is highly likely that investors may be treated as a destructive force damaging the landscape value in areas developed as a result of suburbanization and inhabited by individuals prone to negate arguments. One of them may be connected with the statement that it was landscape that was a major factor in the decision to move to that location.

In view of rapid technological progress, focus on the development of renewable energy sources and the resulting opportunities to obtain co-financing to the installations it seems necessary e.g. to provide training and educate local officials, etc. It is a method to save commune funds instead of expenses incurred to pay external companies for training courses and programmes. Despite interest in renewable energy sources on the part of the local residents, the respondents expressed varied opinions on the implementation of new potential investment projects. Since they are well-informed concerning the utilization of alternative energy sources and is consequences, it needs to be specified what causes their concerns. This is probably connected with the loosening of the partnership network and the commune authorities being unaware of the local governance principles. It is highly likely that showing interest and caring as well as being open-minded about the residents' expectations would result in greater willingness and support for the new investment projects.

6 Conclusions

1. In the case of many local government units we may observe their lack of commitment. The commune administrative staff needs to include specialists in the field of renewable energy sources, e.g. in view of the funds allocated to co-financing for such installations. Counselling for potential customers—commune residents and diligent participation in such efforts may have an impact on the image of those institutions. Moreover, preliminary talks between investors and the local authorities, preceding the initiation of the project, would then be based on professional, reliable and objective knowledge.
2. The commune authorities as the office responsible for the obligatory document, i.e. the Study of the land use conditions and directions, should show far-reaching, open-minded thinking when identifying areas, in which preliminary analyses would suggest locations for prospective wind farms (as it was the case for the Kramsk commune).
3. Residents equipped with a certain body of knowledge are no longer passive in the course of public consultations or hostile to the investor based on hear-say or biased information provided by some mass-media. Frequently negative attitudes result from the highly publicised violations of legal regulations or misconduct during the decision-making process, leading to public protests.
4. A successful investment project, which would prove satisfactory for the three involved entities, i.e. the local government, the local community and the investor, may prove to be highly encouraging for further potential investors. The investor gains a willing and cooperative business partner in the reliable local authorities operating based on the local governance principles, the authorities

enjoy economic gains, while the local community with a positive attitude to wind farms and aware of the importance of renewable energy sources should be perceived as the greatest measure of success of the whole enterprise.

References

1. Marczak, P: Energetyka wiatrowa a społeczności lokalne [Wind Power Engineering and Local Communities]. Biuro Analiz i Dokumentacji, Kancelaria Senatu, Warszawa (2011)
2. Michałowska, E.: Syndrom NIMBY (not in my backyard) jako przykład samoorganizacji społecznej [The NIMBY syndrome as an example of social self-organization]. Proceedings of the 12th Sociological Convention, Zielona Góra (Studia Regionalne i Lokalne no. 1(31)) (2008)
3. Shils, E.: Centre and periphery. Essays in Macrosociology, Selected Papers of Edward Shils, vol. 2 (1975)
4. Drzazga, D.: Konflikty przestrzenne w realizacji strategii ekorozwoju – zarys głównych problemów [Spatial conflicts in the execution of sustainable development strategy—a overview of major problems]. In: Czaja, S. (ed.) Konflikty i współpraca w realizacji strategii ekorozwoju [Conflicts and Cooperation in the Execution of Sustainable Development Strategy], Wrocław, I-BIS (2003)
5. Polskie Towarzystwo Socjologiczne: Raport końcowy – Ewaluacja konsultacji społecznych realizowanych przy budowie elektrowni wiatrowych w Polsce [Final report—Evaluation of Public Consultations on the Construction of Wind Farms in Poland], Warszawa (2011)
6. Bednarowska, M., Gajda, J., Wróblewski, J.: Raport z badań Energia odnawialna – społeczne postrzeganie inwestycji na przykładzie gminy Sułoszowa [Research Report "Renewable Energy—Public Perception of Investments Based on the Sołoszowa Commune"], Fundacja Myśli Badawczej, Małopolska (2013)
7. Pedersen, E.: Human response to wind turbine noise. Perception, annoyance and moderating factors. Göteborg University, Göteborg. https://gupea.ub.gu.se/handle/2077/4431 (2007)
8. Resolution no. XXIV/248/12 of 28.12.2012 of the Kramsk Commune Council on amendments in the Study of land use conditions and directions for the Kramsk commune (2012)

Experimental Research and Thermographic Analysis of Heat Transfer Processes in a Heat Pipe Heat Exchanger Utilizing as a Working Fluid R134A

Łukasz Adrian, Piotr Piersa, Szymon Szufa, Artur Cebula and Sebastian Kowalczyk

Abstract This article presents the experimental results of a heat pipe heat exchanger for the lower temperature range of 15–50 °C. It is worth noting that the heat pipes, thanks to the wide temperature range and high efficiency, can soon be used in building engineering. Recognizing the processes taking place in their interior and their work is essential especially in the era of striving to reduce heat loss and avoid unnecessary energy dissipation. The goal of this work was to carry out research and analysis of heat pipes and process condition by the need to save primary energy in both civil engineering and industry. The results show the effects of phase changes for the R134A refrigerant as well as the effect of its amount on the heat and power of the heat pipe. One of the main objectives of the study is to analyze the efficiency of heat pipes for different amounts of working fluid at different temperatures in both the evaporator section (heat delivery) and the condenser section (heat transfer). The paper presents the results of research on real heat exchanger made from copper 1769 mm tube, 18 mm diameter and 1 mm wall

Ł. Adrian (✉)
Eko-Look, Lokajskiego str. 1A, Sieradz, Poland
e-mail: lukasz.adrian@eko-look.pl

P. Piersa
APS-Ekoinnowacje Sp. z o.o., Dubois str. 114/116 loc.0.04, 93-465 Łódź, Poland
e-mail: piotr.piersa@aps-ekoinnowacje.pl

S. Szufa
Biomass Training Research, Szarych Szeregów str. 25a/14, 45-286 Opole, Poland
e-mail: szufa.szymon@interia.pl

A. Cebula
Faculty of Mechanical Engineering, Cracow University of Technology,
Al. Jana Pawła II 37, A19, 31-864 Kraków, Poland
e-mail: acebula@pk.edu.pl

S. Kowalczyk
ENSYS S.C., Śliwiny 37, 83-110 Śliwiny, Poland
e-mail: office@ensys.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_40

thickness. The study involved placing a heat pipe in a tube heat exchanger in a tube to deliver and receive heat to and from a heat pipe.

Keywords Heat pipe · Heat transfer · Phase change

1 Introduction

Heat exchangers are used in different common appliances and in industry, wherever heat transport is needed. A heat pipe is one of such heat exchangers [1, 2]. Heat exchangers are required of constantly improved efficiency in regard to their heat exchange capacity, and also smaller because of the size of the devices in which they are used. A heat pipe is a device which transfers heat in a two-phase closed cycle with evaporation of a working fluid in an evaporator and its condensation in a condenser. One of the main advantages of heat pipes is their high efficiency, which enables transferring large amounts of heat at a small difference of temperatures. As evaporation is combined with convection, the effectiveness of heat reception and transport in heat pipes is much better than heat conduction in the best thermal conductors. Heat supplied to the evaporator makes the working fluid evaporate. A high temperature and properly high pressure creates a stream of steam towards the opposite, colder end of the pipe, where the vapors condense, giving off its latent heat of evaporation [1].

This article presents the experimental results of a heat pipe heat exchanger for the lower temperature range of 15–50 °C. It is worth noting that the heat pipes, thanks to the wide temperature range and high efficiency, can soon be used in building engineering. Recognizing the processes taking place in their interior and their work is essential especially in the era of striving to reduce heat loss and avoid unnecessary energy dissipation. The goal of this work was to carry out research and analysis of heat pipes and process condition by the need to save primary energy in both civil engineering and industry. The results show the effects of phase changes for the R134A refrigerant as well as the effect of its amount on the heat and power of the heat pipe. One of the main objectives of the study is to analyze the efficiency of heat pipes for different amounts of working fluid at different temperatures in both the evaporator section (heat delivery) and the condenser section (heat transfer) [3].

2 Test Stand

The stand of heat pipe was used to determine the thermal effectiveness of a heat pipe for different evaporator temperature values. The other test stand was used for preliminary tests of the heat pipe washing in a canal with the circular cross-section.

A test stand was equipped with thermal flow apparatus, which consists of ultrathermostats to feed pipe exchangers which serve the heat pipe, as well as circulating pumps and fluid coolers. The stand was also equipped with measurement equipment and data acquisition system. The test stand is shown in Fig. 1. The paper presents the results of research on heat exchanger made of copper of 1769 mm length, 18 mm diameter and 1 mm wall thickness (Fig. 2). The study involved placing a heat pipe in a tube heat exchanger in a tube to deliver and receive heat to and from a heat pipe. The cold water temperature at the inlet of the heat exchanger in the condenser section was 10 °C, while the hot water at the inlet of the heat exchanger in the evaporator section was in the range of 15–50 °C and was changed in increments of 5 °C for each subsequent measurement. Hot and cold water temperature was measure at inlets and outlets solid heat pipe temperature was measured as well as it is depicted in Fig. 1. The pressure inside the tube was controlled and measured. The evaporator and condenser temperature was measured, thermocouples placement is shown in Fig. 2.

The test stand cross-section is presented in Fig. 2. Heat pipe consist of two sections, hot water is deliver to the first section where refrigerant evaporation takes place and the second section is supplied with cold water and refrigerant changes the phase and condensate.

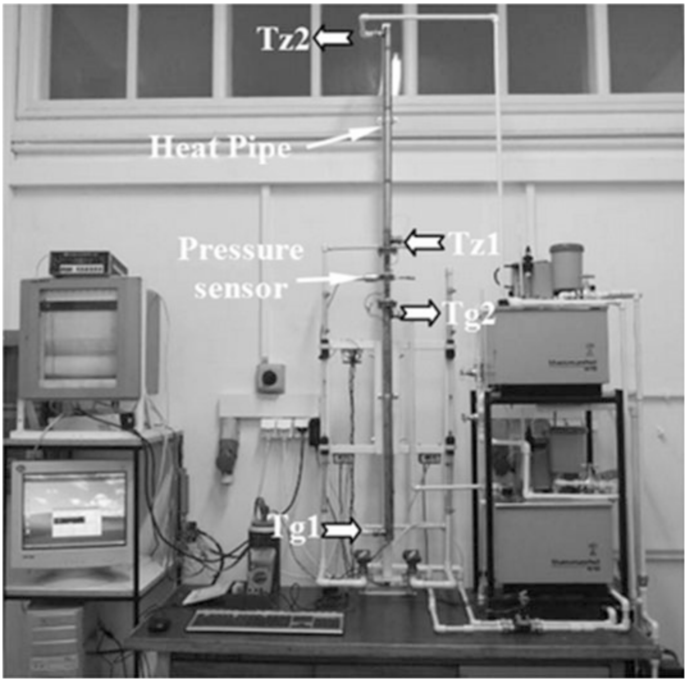


Fig. 1 The stand of heat pipe before the added insulation

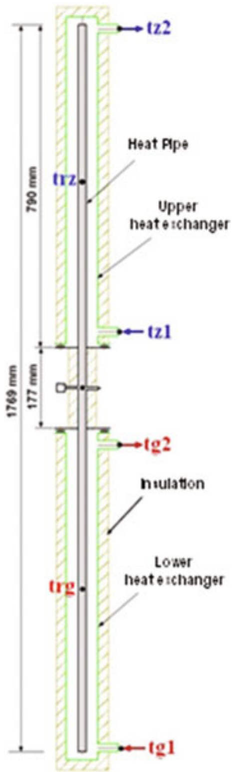


Fig. 2 Schematic of the heating pipe test stand and the thermocouple location: t_{z1}—cold water inlet, t_{z2}—cold water outlet, t_{g1}—hot water inlet, t_{g2}—hot water outlet, t_{rz}—condenser wall, t_{rg}—evaporator wall

3 Test Results

The test results on the vacuum tube in the middle proved little heat conduction through the tube walls along its axis so we can neglect. Practically unnoticeable are the differences in the water temperature at the inlet and outlet of the heat exchanger heating and cooling the heat pipe, hence the negligible values of the heat flux absorbed and delivered by the heat pipe as well as its efficiency (Fig. 3).

On Figs. 4, 5 and 6 are presented graphs for various quantities of R134A filler operating a heat pipe comparing the values of heat flux taken and donated by the heat pipe and a graph comparing the efficiency of the heat pipe.

The values of the heat flux absorbed by the evaporator are always greater than the flow of condensate from the condenser, which indicates that more heat from the refrigerant is collected than delivered. This difference is mainly due to the heat loss to the environment, for example by the isothermal portion in which the pressure sensor and the valve for filling the heat pipe are placed with the working medium.

The heat pipe operates satisfactorily at 5, 10, 20% of its volume in the temperature range tg1 15–50 °C, while filling 2.5; 30; 40% of the volume of the heat pipe operates with satisfactory efficiency in the temperature range tg1 25–50 °C.

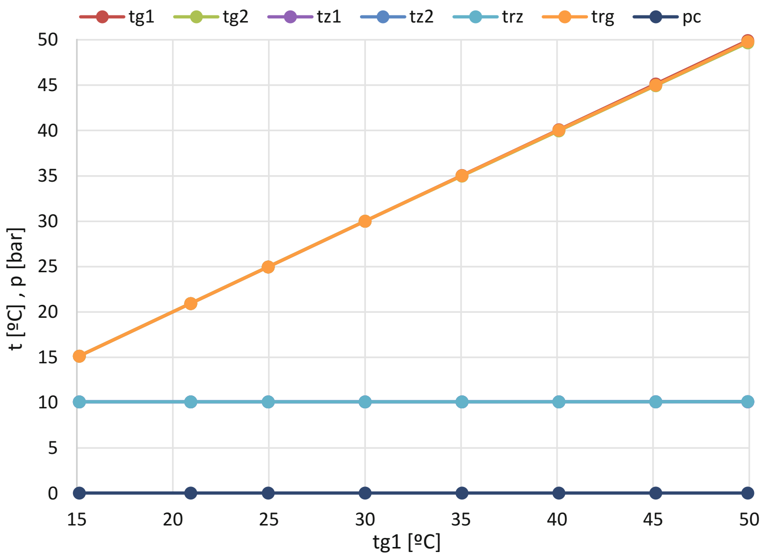


Fig. 3 Temperatures at the inlet and outlet of heat exchanger heat pipe supply with vacuum

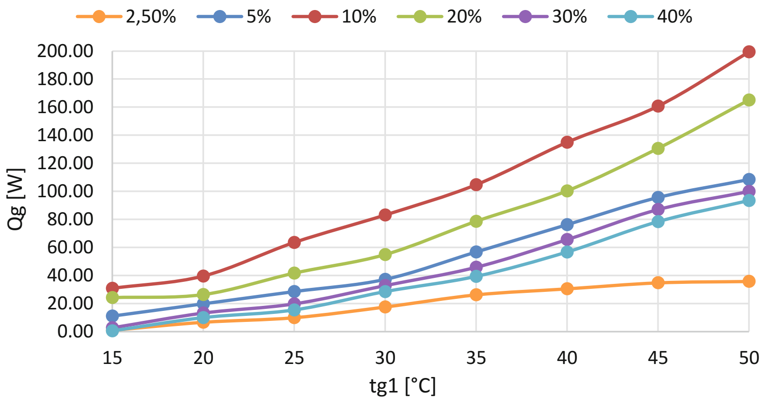


Fig. 4 Comparative graph representing the heat flux absorbed by the heat pipe for all R134A refrigerants

In all fillings, as the temperature of the inlet to the lower heat exchanger increases, the pressure in the heat pipe increases approximately linearly. The highest value of the heat flux absorbed by the evaporator and delivered by the condenser occurs when filling the heat pipe with 10% of its volume with R134A.

For filling 10% of the heat pipe at 25–50 °C, the highest efficiency was achieved at 95%. For the remaining filling in the range of the heat pipe at 25–50 °C, its

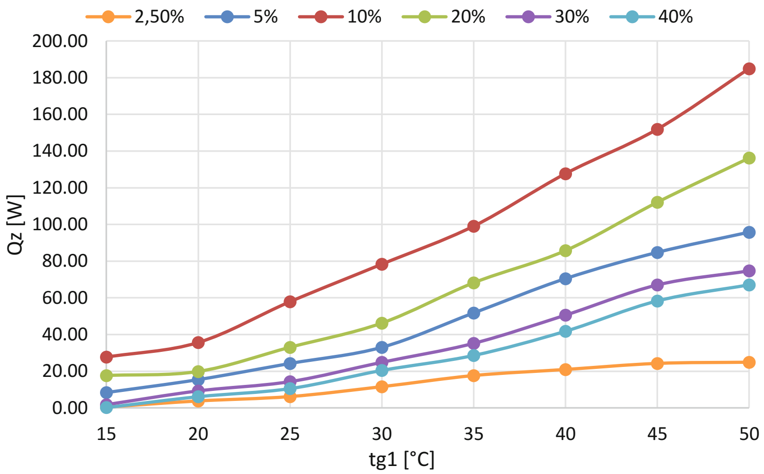


Fig. 5 Comparative graph representing the heat fluxes given by the heat pipe for all R134A refrigerants

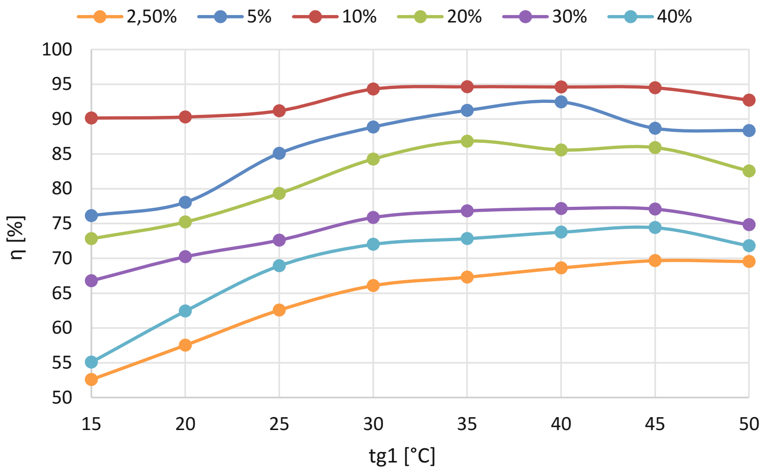


Fig. 6 Comparative graph representing the efficiency of the heat pipe for all R134A refrigerants

efficiency was also the highest. At the other end of the range, the efficiency of the heat pipe decreased. The efficiency of the heat pipe was maintained for R134A between 53 and 95%.

Because of the amount of heat transferred and the efficiency throughout the temperature range, the most effective heat pipe operation is achieved with a 10% fill of R134A.

4 Thermographic Analysis

The thermographic analysis of the heat pipe during operation was carried out on a real heat exchanger made of polycarbonate, 1769 mm long, 18 mm outside diameter and 1 mm wall thickness, the dimensions corresponding to the copper heat pipe. Both the heat pipe and the flow exchanger are made of polycarbonate because of the transparency that allows them to observe the processes occurring inside the heat pipe. The thermographic analysis was carried out with a thermal imaging camera. Figure 7 shows a thermographic analysis station with a connected polycarbonate heat pipe and thermal imagery of the heat pipe is shown during operation. The analyzed tube was filled with R134A at 10% of total volume. The hot water supply temperature of the evaporator section is tg1 = 50 °C and the cold water supply to the condenser section tz1 = 10 °C.

The thermographic analysis of the heat pipe as described above confirms the operation of the heat pipe in the analyzed temperature range. The performance of both the heat pipe and the polycarbonate feeder exchangers made it possible to observe the starting point of the evaporation of the working medium and to correlate it with the remaining test results [2, 4].

5 Conclusions and Recommendations

R134A has been used in the research because it is most commonly used in refrigeration, air conditioning and civil engineering [5]. The heat pipe was filled in 2.5; 5; 10; 20; 30; and 40% of its total volume. For safety reasons (given the operating pressure), the best factor among the tested temperature ranges is refrigerant R134A. Taking into account the type of factor and its quantitative input, the most effective was to fill the tube with R134A in the amount of 10% of the total volume of the heat pipe.

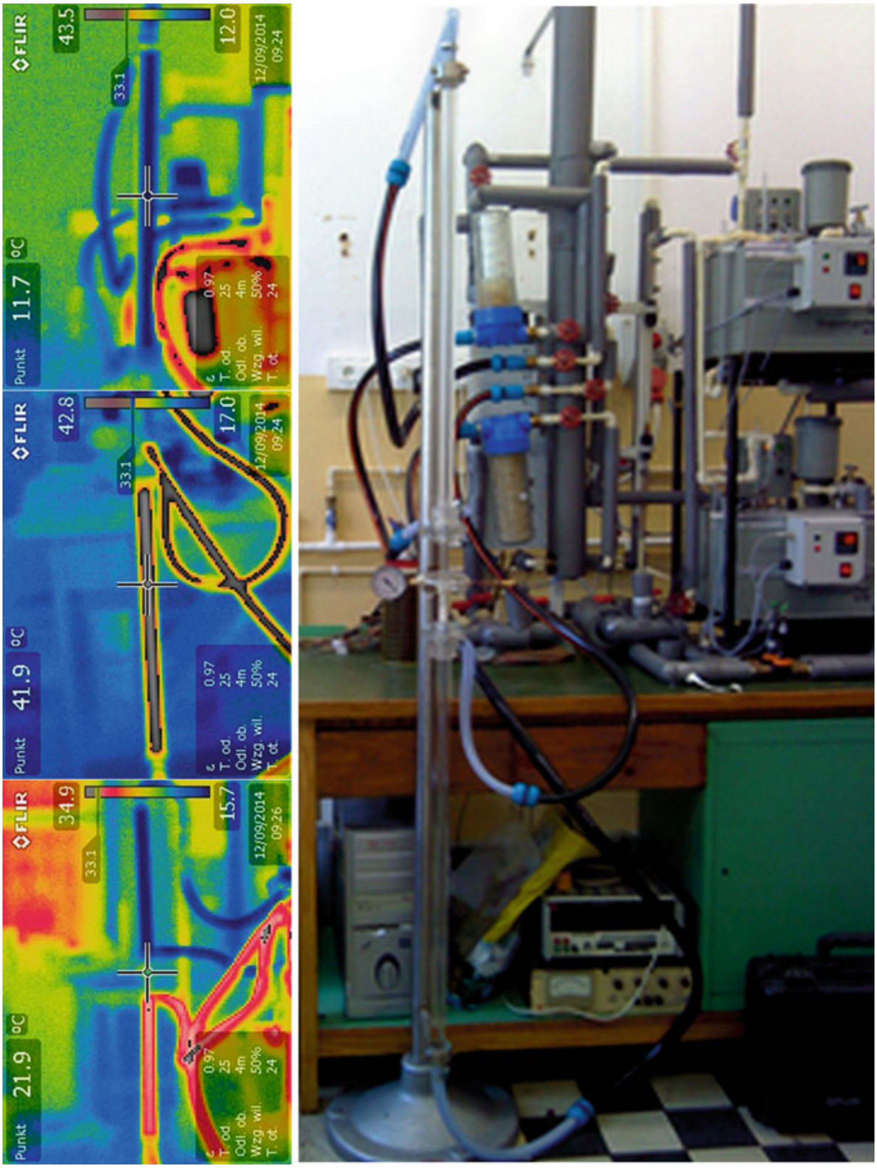


Fig. 7 Measurement stand with connected polycarbonate heat pipe

Acknowledgements The studies presented were financed by the National Science Centre (NCN) Poland under the research program Preludium II, Research and development project is entitled nr: DEC-2011/03/N/ST8/05912 pt. "Badania procesów wymiany ciepła i rozkładów pól prędkości przepływów metodą PIV oraz efektów przemian fazowych i transportu kapilarnego zachodzących w wymiennikach ciepła typu rurka ciepła".

References

1. Adrian, Ł.: Principle of heat pipes construction and operation. J. Chłodnictwo i Klimatyzacja nr **3** (2010). ISSN 1425-9796
2. Adrian, Ł.: Badania termowizyjne i przykłady ich zastosowań, rozdział w poradniku "Wentylacja, Klimatyzacja, Ogrzewanie" pod redakcją prof. dr hab. inż. T. R. Fodemskiego, III (2014). ISBN 83-88285-86-6
3. Payakaruk, T., Terdtoon, P., Ritthidech, S.: Correlations to predict heat transfer characteristics of an inclined closed two-phase thermosyphon at normal operating conditions. Appl. Therm. Eng. **20**, 781–790 (2000). LNCS Homepage, http://www.springer.com/lncs. Last accessed 21 Nov 2016
4. Park, J.E., Vakili-Farahani, F., Consolini, L., Thome J.R.: Experimental study on condensation heat transfer in vertical minichannels for new refrigerant R1234ze(E) versus R134a and R236fa. Exp. Therm. Fluid Sci. **35**, 442–454 (2011)
5. Smirnov, H.F. (Henry F.): Transport Phenomena in Capillary-Porous Structures and Heat Pipes. CRC Press, Boca Raton (2010r). ISBN 9781420062076

Geothermal Energy in Poland. Selected Aspects of Geothermal Resources Development

Anna Sowiżdżał

Abstract Geothermal energy is an ecological, renewable energy source. However, its effective utilization depends on many different factors, related to (i) hydro-geothermal conditions of the region, (ii) proper design of the investment and (iii) formal and legal framework. The characteristic features of geothermal investments are high investment expenditures resulted mostly from high drilling costs of geothermal wells. Hence, the critical element facilitating the utilization of geothermal energy is the financial support in the form of government grants or loans. Recently, geothermal resources in Poland are relatively underdeveloped as only 6 geothermal plants are in operation together with spa-and-wellness, and therapeutical centers. Geothermal potential confirmed by extended scientific studies is much higher, particularly in the Polish Lowlands where both the Lower Cretaceous and the Lower Jurassic aquifers reveal favourable hydrogeothermal conditions suitable for effective development of geothermal resources. The following paper presents the currently recognized geological conditions, which control the size of geothermal resources and macroeconomic determinants (financial support, energy prices), which control the operation of geothermal installations in Poland.

Keywords Geothermal energy · Poland · Geothermal resources
Financial support

A. Sowiżdżał (✉)
Department of Fossil Fuel, Faculty of Geology, Geophysics and
Environmental Protection, AGH University of Science and Technology,
Al. Mickiewicza 30, 30-059 Krakow, Poland
e-mail: ansow@agh.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_41

1 Introduction

The essential of geothermal resources exploitation is the development of groundwaters showing the highest possible reservoir and working temperatures, the highest discharge under artesian conditions and the lowest total dissolved solids (TDS). Obviously, such ideal parameters of geothermal reservoir not always exist in the nature. The hydrogeothermal conditions are the key factors controlling the effective development of geothermal resources. The principal factor governing the accumulation of groundwaters is the presence of reservoir rocks showing favourable properties. Groundwaters filling the pore spaces should have relevant parameters: temperature, discharge, TDS and chemical composition, which ensure wide range of their practical usage for heat generation, balneology, recreation, consumption, etc.

The important geological parameter influencing the profitability of geothermal installations is the depth to groundwater horizon. Theoretically, the deep horizons should have higher reservoir temperatures. However, such deeply buried rocks are subjected to diagenetic processes which deteriorate reservoir properties and, thus, limit the discharge from and the injection to the reservoir. Moreover, the development of deep reservoirs generates high investment expenditures due to the costs of deep drillings. Although hydrogeothermal conditions in particular regions do not change, the recognition levels of these conditions may improve, e.g., after completion of a new exploration well, which provides new geological data or when the new results of laboratory analyses emerge. In some cases, in the regions of complicated geological structure or in the areas of rather limited geological data (as some parts of the Carpathians), determination of hydrogeothermal parameters may bring about serious problems. On the contrary, in the regions of relatively simple geological settings (e.g. in the Polish Lowlands), the evaluation of hydrogeothermal parameters generates much less errors and, consequently, the geological risk of potential investors is much lower.

Unfortunately, the key factor—favourable hydrogeothermal conditions—is only the halfway to final success. The effective development of existing geothermal resources requires the presence of energy consumers and the proper design of geothermal installations. Any product is useless if the producer cannot find the buyer. In the case of geothermal energy, the investments will work properly only in the areas where the concentration of heat demand exists together with favourable heat distribution conditions to the customers. The installation will be cost-effective depending on: (i) the annual load factor related to the time of full capacity operation, (ii) the usable temperature drop and (iii) the distance between the geothermal wells and the heat consumers.

The importance of these factors results from the structure of capital expenditures and running costs of installations, which utilize the low-enthalpy geothermal waters. Geothermal installations reveal high capital expenditures due to high costs of drillings at very low running costs. Moreover, the prevailing part of costs carried during the construction of installation is independent on the amount of heat extracted from the produced geothermal water. In order to ensure low unit costs of heat extraction, it is important to achieve maximum possible annual load of installation, i.e., maximum utilization of potential thermal energy resources. In practice, two principles must be obeyed: (i) to minimize the temperature of spent water directed to the injection well and (ii) to maximize the annual load factor of installation. Both principles enable the operator to keep the annual heat extraction at highest possible and stable level, which increases the annual heat production and reduces the unit costs of thermal energy [1].

Another important factor is the changing economic macro-environment, which affects the competitiveness of geothermal energy sources as well as the availability and the cost of capital used for the investment. Here, the crucial role is played by pro-ecological policy of the state and the amount of financial resources allocated for scientific research and subsidies of geothermal investments. In various countries, governments variously subsidy the utilization of renewable energy sources including the geothermal installations, which directly influences the expansion of this particular branch of energy industry. Essential role is played also by the costs of energy generation from conventional sources including the current fuel prices.

Generally, all the controlling factors discussed above can be categorized into the three groups: (i) geological conditions of geothermal resources, (ii) local operational conditions of geothermal installations and (iii) macro-economic conditions including energy prices and financing sources of geothermal investments. Below, current conditions of geothermal energy utilization in Poland are presented, categorized into these three groups of controlling factors.

2 Geological Conditions of Geothermal Resources

The world geothermal resources are distributed very irregularly. Geothermal systems can be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case the systems will be characterized by low temperatures, usually no higher than 100 °C at economic depths; in the second case the temperatures could cover a wide range from low to very high [2]. Particularly favourable conditions for the formation of high-temperature geothermal systems, occur within the crustal plates, in rifts and in subduction zones. An example of such area is Iceland, where geothermal resources are closely associated with the country's volcanism and its location on the Mid-Atlantic Ridge [3]. Poland shares the zone of low-temperature resources, which can be utilized first of all for heat generation. Geothermal wells document reservoir temperatures below 100 °C. The highest temperature—97.5 °C—was noticed in Konin, within the Lower Jurassic aquifer, at 2660 m depth. This geothermal water shows TDS about 150 g/l and high discharge—about 150 m^3/h [4].

Geothermal resources in Poland are relatively well-recognized. Since the 1980s, the research projects have been initiated at the Department of Fossil Fuels, Faculty of Geology, Geophysics and Environment Protection of the AGH University of Science and Technology in Kraków. The R&D project financed by the Ministry of Science and Higher Education included the regional studies on geothermal waters in the Liassic aquifer of the Polish Lowlands as well as in the Tertiary and Mesozoic aquifers of the Carpathians. Simultaneously with the basic science research including the methodology of resources assessment, the development projects were run, which resulted in the construction of first Polish geothermal installation in the Podhale region. The following projects provided the analysis of opportunities for geothermal installations in almost 200 towns located in the Polish Lowlands. The possibilities of geothermal energy development in Poland were summarized in geothermal atlases of the Polish Lowlands, the Carpathians and the Carpathian Foredeep [1, 5–9] as well as the Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary system in Poland [10]. All these projects document the high potential for utilization of hydrogeothermal resources, first of all for heat generation but, in selected regions (Fig. 1), also for power generation using the binary installations [10, 11]. In last years, the research projects were run dealing with the evaluation of hot dry rocks (HDR) potential in Poland using the EGS technologies [12–15].

The results of these studies were summarized in Fig. 1, which presents the regions in Poland most amendable to the development of geothermal energy. The highest potential exists in the Polish Lowlands and in the Podhale region.

The Polish Lowlands is the largest geothermal region in Poland. Geothermal resources are hosted in Mesozoic strata among which the most promising are both the Lower Jurassic and the Lower Cretaceous formations. Significant resources of geothermal energy are accumulated also in the Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations, but their geothermal potential is much lower when heat generation is considered [16]. This opinion is supported by the parameters of operating thermal plants utilizing the Lower Jurassic (Pyrzyce, Stargard Szczeciński) or Lower Cretaceous (Uniejów, Mszczonów, Poddębice) aquifers.

The Podhale region is undoubtedly the “geothermal gem”. Here operates the largest and the oldest geothermal installation in Poland, completed in the 1990s. Geothermal water of temperature 80–86 °C is produced from three wells of total certified discharge 960 m^3/h. The aquifer comprises Middle Triassic limestones and dolomites [17].

In the remaining part of the Polish Carpathians, complicated geological structures result in low discharges of the wells and problematic renewability of geothermal resources, which provides high geological risk for geothermal plants localization, although some particular sites are still worthy to consider, e.g., Wiśniowa area [8].

The less complicated geological setting of the Carpathian Foredeep also shows geothermal potential related to Devonian and Carboniferous carbonate sequences in the western part, the Middle Jurassic sandstones in the eastern part as well as the Upper Jurassic carbonates, and the Cenomanian sandstones in the central part of the Carpathian Foredeep [7, 18]. Among these rocks, the highest potential discharges

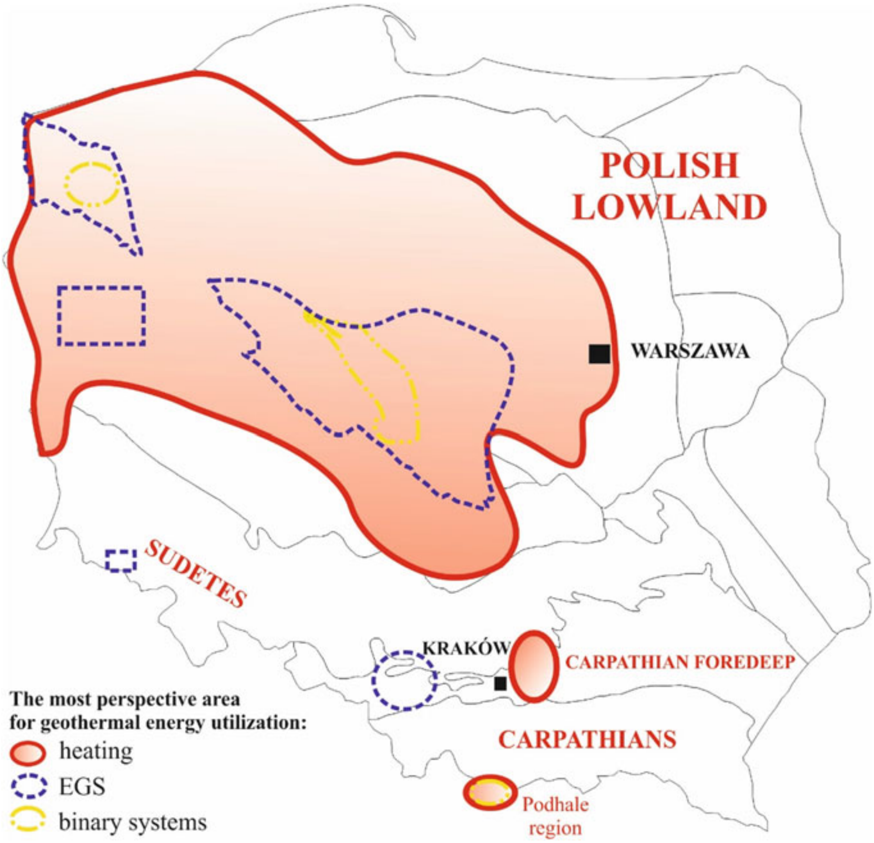


Fig. 1 The most prospective area for geothermal energy utilization in Poland (based on [1, 5–10, 13, 14, 18])

from the wells—over 200 m^3/h—were recorded in the Cenomanian aquifer. It is surprising because in almost all the rest of the Carpathian Foredeep, the estimated discharges from geothermal wells are at the level from several to some tens of m^3/h but never exceed 60 m^3/h. This is a serious problem when development of geothermal resources for heat generation is considered.

3 Local Operational Conditions of Geothermal Installations

The most important purpose of geothermal resources utilization is the heat generation. This is an effect of low-temperature geothermal waters prevailing in Poland. Moreover, geothermal plants should be localized in the areas where there is a demand for thermal energy. The important opportunities of geothermics in Poland are: (i) construction of entirely new systems in the areas where space heating installations did not exist, as yet and (ii) construction of geothermal systems supplementary for the existing heat distribution networks. In each case, local operational conditions of heat distribution networks must be thoroughly analyzed including not only the network parameters but also the competition with the other thermal energy sources present at the local market. The lack of heat distribution network in particular area should not be regarded as an argument against the geothermal investment but should become rather a circumstance of their construction, which will be reflected in the investment expenditures.

The specific character of geothermal energy utilization suggests that geothermal plants should be localized in the areas of high numbers of potential heat buyers. According to the Central Statistical Office of Poland [19], Polish administration system includes: 16 districts, 314 counties, 66 town granted the status of a county and 2478 communes. Among 919 towns, 303 have the status of municipal communes and 616 other are mixed, municipal-rural communes. Average population density is 123 persons/km^2. The highest density—over 3000 persons/km^2—was found in 10 administration units. Thus, there is a relatively high potential for construction of geothermal heat plants, particularly in towns or regions of high population density.

4 Macro-economic Conditions

4.1 Financial Support of Geothermal Investments

Recently, the financial support of geothermal investments in Poland is provided by the Central Fund for Water Management and Environment Protection [20].

The domestic sources are allocated for two programs:

1. Geology and Mining Industry, Part 1—Recognition of geological structure of Poland and management of mineral raw-materials, and groundwaters, related to the needs of domestic geology.
2. Improvement of air quality, Part 1—Utilization of geothermal resources for energy generation.

Within the first program, financial support can be granted for environmental studies related to exploration for and assessment of geothermal waters, and heat extraction from hot dry rocks. Potential beneficiaries may apply for full reimbursement of eligible costs if the investor is the local authority unit or up to 50% of eligible cost if the investor is the other entity. The program includes the drilling of exploration well.

Within the second program, support can be granted for construction of new geothermal heat or heat-and-power plant, modernization or expansion of existing geothermal installation, modernization or expansion of existing heat generation system by adding the geothermal installation and for drilling or reconstruction of a geothermal well (but not exploration well). Potential beneficiaries can be the business entities. The allocated funds amount 500 million PLN in the form of preferential or commercial credits, or equity investments. However, the beneficiary must document that generated thermal energy will be purchased by the consumers (including the connection of geothermal installation into the existing heat distribution network). The program does not apply to recreational and balneological centers. In March, 2017, the program has been updated—50 million PLN were allocated as non-repayable financing for investments in electric energy generation using the ORC technologies. The beneficiaries can be granted up to 50% of eligible costs under the conditions of the state aid.

4.2 Energy Prices

Every two years, the All-Poland Geothermal Congress is organized by the Polish Geothermal Society and other institutions involved in utilization of domestic geothermal energy resources. Tradition of the congress is the presentation of changes in prices of geothermal energy [21] (Fig. 2). Analysis of 2016 data indicates that the price of geothermal energy for end-users places between the prices of coal-sourced and gas-sourced energy. Hence, the geothermal heat is competitive in relation to conventional heat sources, particularly to heating oil, sometimes even to natural gas. Total unit price of thermal energy purchased by the net consumer fell

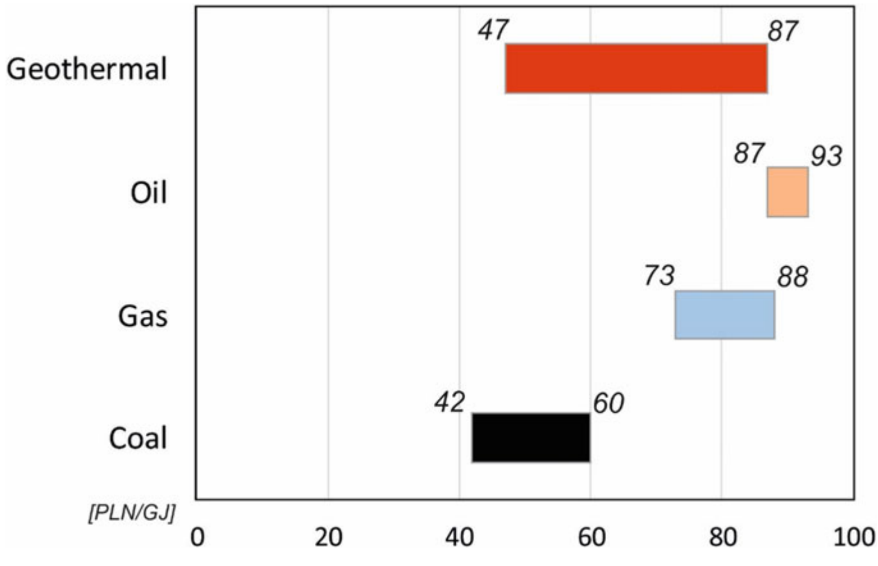


Fig. 2 Comparison of energy prices from different heat sources (min–max) (based on [21])

into the range of 42–93 PLN/GJ for analyzed energy sources (coal, natural gas, heating oil, geothermal water). The lowest thermal energy prices were offered by coal-fired thermal plants (42-about 60 PLN/GJ). Gas-sourced energy costed from about 73 to 88 PLN/GJ. The most expensive was the heating oil energy, which costed from about 87 to 93 PLN/GJ. The price of geothermal heat varied from 47 to 87 PLN/GJ depending on the parameters of geothermal water deposit.

4.3 Remaining Factors

An important limiting factor affecting the expansion of geothermal energy extraction is the geological risk emerging when the first geothermal well is under drilling. In some countries e.g., in France [22], the insurance fund exists for (short- and long-term) geological risk, which generates favourable environment for geothermal investments. Another barrier is raised by high drilling costs, which constitute an essential item of investment expenditures.

5 Summary

The economic effectiveness of geothermal investments is influenced by many factors. The most important issues are related to hydrogeothermal conditions prevailing in the regions, particularly to the discharge and the wellhead temperature of produced water. Only high discharge and high wellhead temperature combined with relatively low TDS may guarantee the successful life of geothermal project. In Poland, hydrogeothermal parameters are well-recognized for aquifers from the Polish Lowlands, the Carpathians and the Carpathian Foredeep. The hydrogeothermal aquifers of favourable thermal and petrophysical parameters have been localized and these parameters seem to ensure high discharges of geothermal wells. Apart from the Podhale region where development of geothermal waters dates back to 1990s, particularly promising are the Polish Lowlands where several potential localizations can be indicated of new geothermal plants. However, the successful development of such plants requires the presence of heat buyers, especially the residents of densely populated cities in which the local authorities are interested in development of geothermal energy in their region. The key factor facilitating this development is the system of financial support. In Poland, the financing of geothermal investments is available, which may result in construction of new geothermal plants and will rise rather low share of geothermal energy in total energy balance of the country. Increasing utilization of geothermal energy will bring ecological and social benefits in particular regions and in the whole country. Moreover, geothermal energy is local source of energy that can contribute to economic benefits. Iceland being a prime example. The oil crises in 1973 and 1979 caused Iceland to change its energy policy, reducing oil use and turning to domestic energy resources, hydropower and geothermal heat. This policy meant exploring for new geothermal resources, and building new heating utilities across the country. The economic benefits of the government's policy to increase the utilisation of geothermal energy can be seen when the total cost of hot water used for space heating is compared to the consumer cost of oil [23]. Comparison of energy prices from different heat sources in Poland it can be seen that in some cases geothermal energy can compete with oil and sometimes even with gas. Government policy is crucial to the further development of geothermal energy in Poland.

Acknowledgements The paper prepared under AGH-UST statutory research grant No. 11.11.140.031.

References

1. Górecki, W., et al. (ed.): Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. Ministry of Environment. ZSE AGH, Kraków (2006)
2. Bertani, R.: Geothermal energy. Sustain. Dev. Environ. Manage. 207–219 (2008)
3. Ragnarsson, A.: Utilization of geothermal energy in Iceland. In: International Geothermal Conference, Reykjavík (2003)
4. Geotermia Konin Homepage. http://www.geotermiakonin.pl. Last accessed 30 June 2017
5. Górecki, W., et al. (ed.): Atlas of geothermal resources of Paleozoic Formations in the Polish Lowlands. Ministry of Environment. ZSE AGH, Kraków (2006)
6. Górecki, W., et al. (ed.): Atlas of Geothermal Waters and Energy Resources in the Western Carpathians. AGH KSE, Kraków (2011)
7. Górecki, W., et al. (ed.): Geothermal Atlas of the Carpathian Foredeep. AGH KSE, Kraków (2012) (in Polish)
8. Górecki, W, et al. (ed.): Geothermal Atlas of the Eastern Carpathians. AGH KSE, Kraków (2013)
9. Górecki, W., Sowiżdżał, A., Hajto, M., Wachowicz-Pyzik, A.: Atlases of geothermal waters and energy resources in Poland. Environ. Earth Sci. **74**(12) (2015). ISSN 1866-6280
10. Bujakowski, W., Tomaszewska, B., et al. (eds.): Atlas of the Possible Use of Geothermal Waters for Combined Production of Electricity and Heat Using Binary System in Poland. MEERI PAS, Kraków (2014), p. 305
11. Pająk, L., Bujakowski, W.: Energia geotermalna w systemach binarnych. Przegląd Geologiczny **11**(2), 61, 699–705 (2013)
12. Bujakowski, W., Barbacki, A., Miecznik, M., Pająk, L., Skrzypczak, R., Sowiżdżał, A.: Modelling geothermal and operating parameters of EGS installations in the lower triassic sedimentary formations of the central Poland area. Renew. Energy **80**, 441–453 (2015)
13. Sowiżdżał, A., Papiernik, B., Machowski, G., Hajto, M.: Characterization of petrophysical parameters of the Lower Triassic deposits in prospective location for Enhanced Geothermal System (central Poland). Geol. Q. **57**(4), 729–744 (2013)
14. Sowiżdżał, A.: Possibilities of petrogeothermal energy resources utilization in central part of Poland. Appl. Ecol. Environ. Res. **14**(2), 555–574 (2016)
15. Sowiżdżał, A., Kaczmarczyk, M.: Analysis of thermal parameters of Triassic, Permian and Carboniferous sedimentary rocks in central Poland. Geol. J. **51**, 65–76 (2016)
16. Sowiżdżał, A., Hajto, M., Górecki, W.: The most prospective areas for geothermal energy utilization for heating and power generation in Poland. In: Proceedings European Geothermal Congress 2016, Strasbourg, France (2016)

17. Kępińska, B.: Przegląd stanu wykorzystania energii geotermalnej w Polsce w latach 2013–2015 Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój nr 1/2016 (2016)
18. Sowiżdżał, A.: Characterization of geothermal reservoirs parameters in Polish part of Carpathian Foredeep. Carpathian J. Earth Environ. Sci. **10**(2), 237–246 (2015)
19. Central Statistical Office: Powierzchnia i ludność w przekroju terytorialnym w 2016 r. Warszawa (2016)
20. Central Fund for Water Management and Environment Protection Homepage. http://www.nfosigw.dov.pls. Last accessed 30 June 2017
21. Pająk, L., Bujakowski, W.: Analiza zmian cen energii cieplnej pochodzącej z instalacji geotermalnych i wybranych źródeł konwencjonalnych na podstawie taryf rozliczeniowych w latach 2007–2016. Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój nr 1/2016 (2016)
22. Dumas, P., Angelino, L.: Financing geothermal energy. In: Proceedings of the World Geothermal Congress, 2015, Australia. Paper No. 04011 (2015)
23. http://www.nea.is/media/utgafa/GD_loka.pdf

Kinetics of Drying Silver Birch (*Betula pendula* Roth) as an Alternative Source of Energy

Szymon Głowacki, Weronika Tulej, Małgorzata Jaros, Mariusz Sojak, Andrzej Bryś and Rafał Kędziora

Abstract The aim of the work was to study the kinetics of drying silver birch shoots with three different diameters, and compare the results with the results obtained from mathematical modelling of the drying process. The work also discusses biomass as a renewable resource of energy, with special emphasis on wood as energy fuel. Also, drying process as well as modelling were described in greater detail. The aim of the work was realized based on the conducted laboratory experiments, for which shoots of silver birch with the diameter of 1, 2 and 3 cm were used. They were dried at the temperatures of 40, 50, 60, 70 and 80 °C. Based on the obtained results, the following were determined: water content of the samples and the difference between the real water content in the samples and the content obtained from the mathematical model by determining the relative error of the model. The work also contains graphical analysis of the obtained results.

Keywords Biomass · Wood · Water content · Drying kinetics

1 Introduction

Natural environment is being largely destroyed by industry, which is continuously developing and requires increasing amount of energy. The development of industry is related to using conventional sources of energy, i.e. coal, gas and oil. The main products of combustion of such fuels are nitrogen oxides, sulphur oxides and dust. They contribute to increasing air pollution, and contaminate water and soil. Destruction of natural environment may be slowed down using various methods, a more important one being limited use of conventional fuels, and increasing the use of renewable sources of energy. It is estimated that Poland's greatest resources of renewable energy is biomass, in particular, wood biomass. Use of wood as energy

S. Głowacki (✉) · W. Tulej · M. Jaros · M. Sojak · A. Bryś · R. Kędziora
Faculty of Production Engineering, Warsaw University of Life Sciences—SGGW, Warszawa, Poland
e-mail: glowackisz@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_42

fuel has numerous advantages, i.e. relatively high calorific value, low emission, and much lower sulphur content in combustion gases in comparison to combustion gases from coal combustion [1].

Water is the main component of live plant cells and it is moisture that has a significant impact on the calorific value of wood. Therefore, prior to the process of combustion, the wood requires drying. Pellets also require dried wood [2, 3]. The most common method of drying is convective drying, which uses liquid or gas as a drying agent, which collects water from the material being dried. Kinetics of drying involves changes of water content and temperature during the process of drying [4]. The process of drying is extremely complicated. Therefore, complex mathematical models are required to describe it, which models allow to determine conditions of drying of a given material, which makes the process less energy-consuming [5].

The use of biomass is advantageous in professional power industry, as it is characterized by stable quality, favourable price and close location from the power plant, as well as high degree of concentration [6].

Water and density, as well as, to a lesser extent, type and method of biomass production, have impact on its calorific value. The calorific value of wood of natural water of 50–60% is between 6 and 8 GJ/t, drying the material to water content of 10–20% increases its calorific value 14–16 GJ/t, and fully dried material the calorific value is as high as 19 GJ/t. Approximately, ash content in burned woodchips ranges between 0.5 and 3%, straw −4%, and coal—as much as 12%. It can easily be noticed that combustion of wood biomass is characterized by production of significantly smaller amount of ash and volatile dust. The content of sulphur compounds in wood does not exceed 0.05%, i.e. it is 16 times smaller than in coal (0.8%) [7].

Convection is a process used in drying to remove water from the material being dried. In this process, the agent, i.e. air or, less frequently, overheated vapour is used to supply heat and remove water from the material being heated [8]. Convective drying is a process, in which the exchange of mass and heat occurs simultaneously. During convective drying, water content and temperature change all the time [9, 10].

The conception of convective drying of agricultural products is the subject of numerous scientific works. Research on this subject and the development of technology made it possible to construct mathematical models to describe drying process. The models are based on the laws of mass and heat exchange [11, 12]. Thorough understanding of mechanisms responsible for transport of mass and heat in moist capillary-porous materials is indispensable for the appropriate design of such processes. The complexity of the drying process mainly depends on the changing mechanisms of heat and mass transport during heating, resulting from changing water content and the type of bond between water and the material [1]. Models of the process of drying are a rich source of information related to the phenomenon being studied. Sometimes, the model of the process may provide more information and explanations than the experiment itself [13, 14]. The development of computer science resulted in the development of computer programs, which allows scientists to compare simulations of the drying process with the results obtained from real experiments [15].

2 Scope and Aim of Work

The aim of the work is determination of the impact of the parameters on the course of the drying process of shoots of silver birch with diameters of 1, 2 and 3 cm, and verification of the mathematical model describing the process of drying.

The scope of work comprises performing the examinations of silver birch drying process in five different temperatures of the drying agent, i.e. 40, 50, 60, 70 and 80 °C and using the mathematical model to compare the results obtained from modelling and the results of the examinations.

3 Methodology

The silver birch drying process was examined in the drying laboratory of the Warsaw University of Life Sciences in Warsaw, Faculty of Production Engineering, Department of Fundamental Engineering.

The research involved using silver birch shoots from one location, collected at the same time. Silver birch typically reaches to 25 m, with the trunk of up to 0.6 m in diameter. The trunk is branchless to the height of approx. 15 m, cylindrical, may be deformed at the butt end. The bark is milk-white and ragged at the lower part of the trunk, in older trees. Young branches have resin warts.

Five shoots 3 cm in diameter each, five shoots 2 cm in diameter each, and 5 shoots 1 cm in diameter each were used. Each shoot used in the experiments was 25 cm long. Each shoot was cut into 5 cm pieces, and each piece was labelled with a letter of the alphabet from "a" to "e". The pieces with the same diameters were then used to make samples which were used in the drying experiments. In this method, five samples of shoots of the same diameter were obtained [16].

The obtained samples were dried in five temperatures of air: 40, 50, 60, 70 and 80 °C. Biomass was dried in convective drier UNB 400 manufactured by Memmert in natural convection. The computer, connected with the electronic laboratory scales WPX 650 manufactured by Radwag, recorded the weight of the sample being dried every 60 s [17]. When the mass of the material being examined remained stable, the dry substance content was determined, using the drying furnace, in which the samples were further fully dried in the temperature of 105 °C, according to the Polish Standard PN-77/D-04100.

4 Analysis of the Results of Experiments

Based on the sample mass loss M(τ) during drying (τ) and the dry substance content Ms water content in the sample u(τ), dry mass content was determined using the following equation:

$$u(\tau) = (M(\tau) - Ms)/Ms\ [\text{kg}\ \ H_2O/\text{kg}\ \ \text{d.s.}] \tag{1}$$

Each sample was labelled in the following way: two first digits denote drying temperature, and the third digit denotes the diameter of the sample, e.g. the symbol 801 means that the sample was dried at the temperature of 80 °C and it contained wood pieces 1 cm in diameter.

Dry substance content in each sample is presented in Table 1.

The results of research were presented in graphical form (Fig. 1).

Initial water content of the sample of 1 cm in diameter was 0.85 kg H_2O/kg d.s., whereas samples of 2 and 3 cm in diameter had similar initial water content of 0.75 kg H_2O/kg d.s. In the temperature of 70 °C for the sample with the diameter of 1 cm, the process of drying takes the least time. After 500 min from the beginning of the process of drying, the water content for 1 cm sample amounted to 0.1 kg H_2O/kg d.s., for 2 cm—0.2 kg H_2O/kg d.s., for 3 cm—0.25 kg H_2O/kg d.s. After

Table 1 Dry substance content in the samples

Sample number	801	802	803	701	702	703	601	602
Dry substance content [g]	11.580	44.810	93.860	11.239	44.426	92.949	11.292	45.816
Sample number	603	501	502	503	401	402	403	
Dry substance content [g]	90.183	11.209	45.316	93.562	11.620	45.151	95.561	

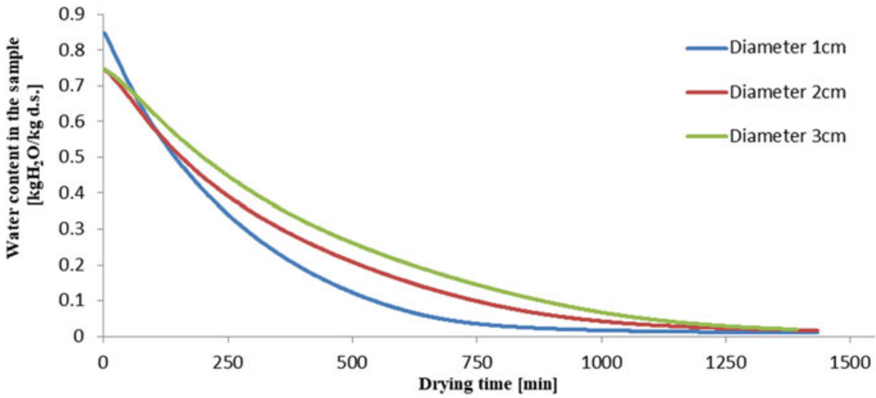


Fig. 1 Change in water content during drying of silver birch in the temperature of 70 °C

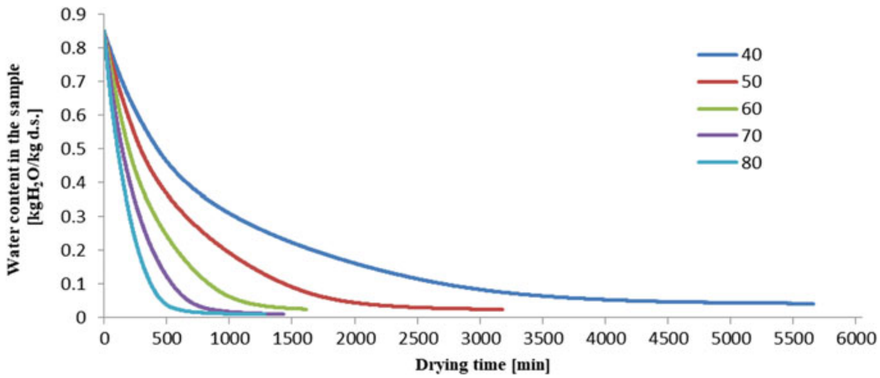


Fig. 2 Change of water content during drying of silver birch shoots with the diameter of 1 cm in different temperatures

1000 min, the process slows down considerably, and water content in the samples begins to stabilize. When the drying process is complete, water content in the samples was equal 0.010, 0.017 and 0.019 kg H_2O/kg d.s. for the samples with diameters 1, 2 and 3 cm, respectively.

Figure 2 presents drying curves for the samples with the diameter of 1 cm in different drying temperatures, namely, 40, 50, 60, 70 and 80 °C. The process in the temperature of 40 °C lasted the longest. Obviously, as the temperature increases, the drying time reduces. In the temperature of 80 °C, the drying process was complete after 500 min as further drying did not result in considerable changes in water content of the samples. Initial water content in each case was almost identical and was equal 0.85 kg H_2O/kg d.s. After the process was completed, the final water content in the sample was equal to 0.042 kg H_2O/kg d.s. for the sample dried at 40 °C, whereas it was 0.009 kg H_2O/kg d.s. for the sample dried at w 80 °C.

The following theoretical model [18] was used to describe the kinetics of water content while drying process takes place in the second period:

$$u(\tau) = u_r + (u_0 - u_r) * \exp^{-K\tau} \qquad (2)$$

where:

$u(\tau)$ water content in time t [kg H_2O/kg d.s.]
u_r equilibrium water content [kg H_2O/kg d.s.]
u_0 initial water content [kg H_2O/kg d.s.]
K drying coefficient [min^{-1}]
τ time [min].

Drying coefficient was defined using the above formula, which requires the initial water content, equilibrium water content and water content in time. Initial water content was determined based on the first measurement of the sample mass, and the equilibrium water content was assumed for a given sample as a minimum

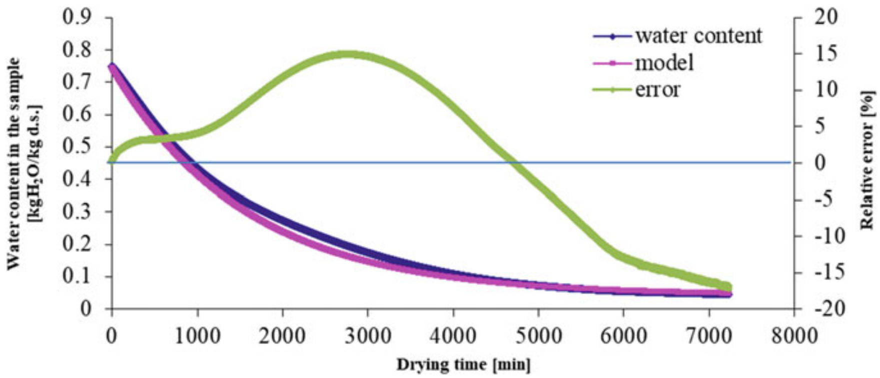


Fig. 3 Modelling of drying curve for the sample with the diameter of 3 cm, dried at the temperature of 40 °C

value obtained based on the research. Water content in time was calculated based on the recorded measurements of the sample mass.

Results of modelling were presented in graphical form, with the relative error being the difference between the results from the model and the results from the experiments involving drying silver birch (Fig. 3).

From the beginning of the process, the values from the model differ from the real values until 3000 min, when the relative error reached 15%; in minute 4750, both values were identical and the error was equal 0%. After that, the error increases until the measurements are completed. This is because it is only a simplified theoretical model and does not take into account many factors of the drying process [19]. However, it is accurate enough that many authors are used in modeling the drying process of various biological products in the second period.

The figure below shows the results of modelling (relative error, water content obtained from the model (2), water content obtained during drying and equilibrium water content) for each sample.

Figure 4 shows that the value of drying coefficient K is larger for samples dried at higher temperatures. Conversely equilibrium water content decrease while the drying temperature increases. Unfortunately the value of the relative error increases for higher drying temperatures, with the exception being sample 501, whose error is less than 1.7% from the error for sample 401.

Drying coefficient (K) increases while the drying temperature increases, because the drying process is much faster due to the intensified diffusion of water. Equilibrium water content decreases while the drying temperature increases, because this results in a higher energy supply to the dried samples, and consequently, increased separate particles of water from the samples undergo drying process (Fig. 5).

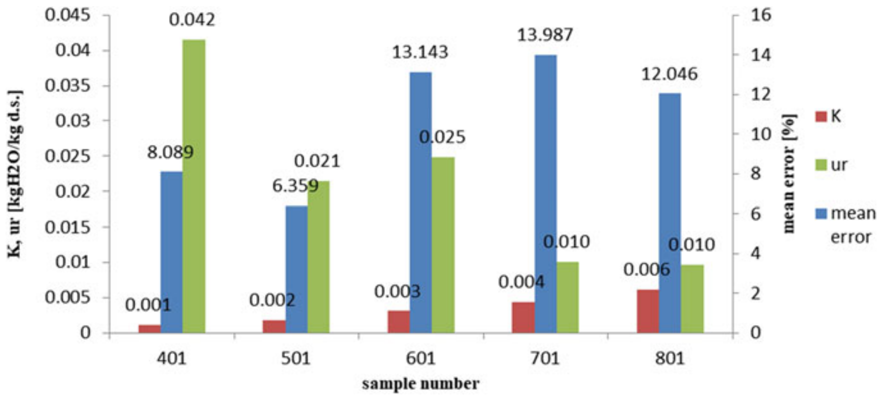


Fig. 4 The research results obtained from modelling and drying process for 1 cm samples (drying coefficient, equilibrium water content and relative error)

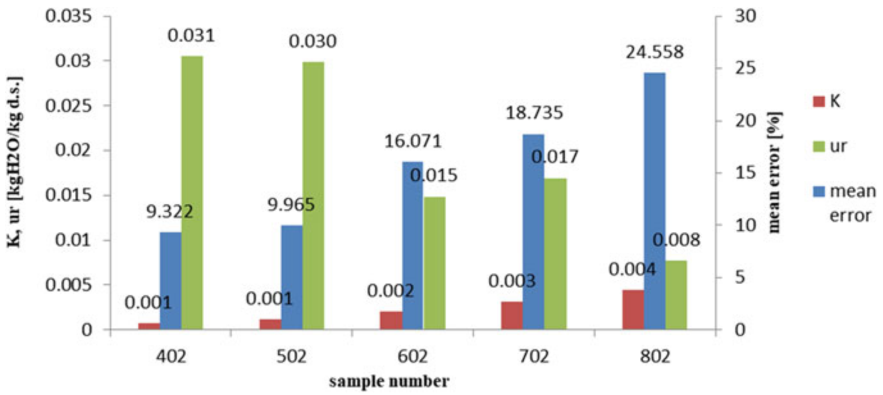


Fig. 5 The research results obtained from modelling and drying process for 2 cm samples

In case of 2 cm samples, the values of both mean error and drying coefficient are higher for higher drying temperatures. On the other hand, equilibrium water content is lower for samples dried at higher temperatures (Fig. 6).

Similarly to the previous cases, the higher the drying temperature of the sample, the higher the mean error and coefficient K, and the equilibrium water content is inversely proportional to the drying temperature.

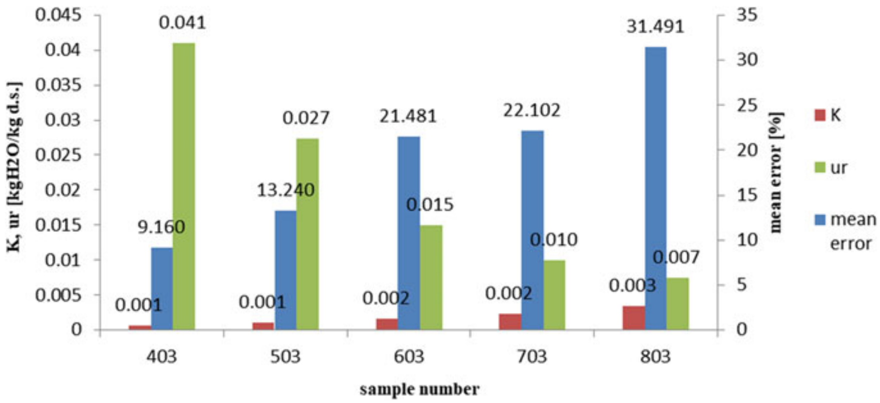


Fig. 6 The research results obtained from modelling and drying process for 3 cm samples

5 Summary

Use of renewable resources of energy for production of electrical power or heat does not result in environment degradation. The main method of environment protection is gradual introduction of energy-saving technologies in industry and increase of share of energy from renewable resources in power industry. Water content in the wood has the greatest influence on the calorific value. Therefore, it is extremely important that the wood be dried prior to combustion or other type of energetic use.

Based on the analysis of the research, the following conclusions were drawn:

- The duration of drying process depends, i.a. on the diameter of the material being dried. It was especially visible in the first stage of drying, when water loss for samples with the smallest diameter was significantly faster in comparison with 2 and 3 cm samples.
- The process of drying samples with the diameter of 1 cm dried at the temperature of 40 °C lasted 5660 min, whereas at 80 °C it took over 4 times shorter.
- Initial water content in the samples also depended on the diameter of shoots. For the diameter of 1 cm, initial water content amounted to 0.85 kg H_2O/kg d.s., and for diameters 2 and 3 cm, water content was similar, approx. 0.75 kg H_2O/kg d.s.
- The mathematical model of the drying process that was verified for each of the examined samples, and comparing it with the results obtained from drying shows that the greatest values of relative error were reached towards the end of the drying process when the water content is very low.
- The mathematical model used for the purpose of this work accurately reflects the course of the drying process, with the maximum mean error not exceeding 31.5%. The smallest mean error between the values from the model and the real values, equal 8.4%.

- The higher the temperature of drying the larger the error between the values from the model and the real values, except 1 cm sample dried at 50 °C.

References

1. Kowalski, S.J.: Uogólniony opis transportu masy i ciepła w procesach suszenia. Inż. Ap. Chem. **49**(4), 38–39 (2010)
2. Brys, A., Brys, J., Ostrowska-Ligeza, E., Kaleta, A., Gornicki, K., Glowacki, S., Koczon, P.: Wood biomass characterization by DSC or FT-IR spectroscopy. J. Therm. Anal. Calorim. **126**(1), 27–35 (2016). https://doi.org/10.1007/s10973-016-5713-2
3. Wróbel, M., Frączek, J., Francik, S., Ślipek, Z., Mudryk, K.: Influence of degree of fragmentation on chosen quality parameters of briquette made from biomass of cup plant *Silphium perfoliatum* L. In: Malinovska, W.L., Osadcuks, V., Malinovska, L., Osadcuks, V. (Red.), 12th International Scientific Conference on Engineering for Rural Development—Proceedings (T. 12, ss. 653–657). Latvia University of Agriculture Faculty of Engineering (2013)
4. Głowacki, Sz., Gendek, A.: Application of forced drying methods in preparation of forest chips for energy purposes. Annals of Warsaw University of Life Sciences—SGGW. Agriculture 58 (Agricultural and Forest Engineering), pp. 29–34 (2011)
5. Panyawong, S., Devahastin, S.: Determination of deformation of a food product undergoing different drying methods and conditions via evolution of a shape factor. J. Food Eng. **78**(1), 151–161 (2007)
6. Zawistowski, J.: Spalanie biomasy o małej podwyższonej wilgotności. Materiały konferencyjnych „Biomasa dla elektroenergetyki i ciepłownictwa – szanse i problemy". pp. 58–63. Wieś jutra. Warszawa (2007)
7. Hałuzo, M., Musiał, R.: Ocena zasobów i potencjalnych możliwości pozyskania surowców dla energetyki odnawialnej w województwie pomorskim. Biuro Planowania przestrzennego w Słupsku, Słupsk (2004)
8. Ciemniewska-Żytkiewicz, H., Bryś, J., Bryś, A., Reder, M., Sujka, K.: Wpływ procesu prażenia na zmianę zawartości wody oraz barwy orzechów laskowych. Postępy techniki przetwórstwa spożywczego 23/42/1, 83–84 (2013)
9. Falade, K.O., Abbo, E.S.: Air drying and rehydration characteristics of date palm (*Phoenix dactylifera* L.) fruits. J. Food Eng. **79**(2), 724–730 (2007)
10. Grzegory, P., Piotrowski, D.: Suszenie surowców roślinnych wybranymi sposobami. Postępy techniki przetwórstwa spożywczego **1**, 92–94 (2013)
11. Ciesielczyk, W., Kamińska, A., Skoneczna, J.: Badania procesu suszenia fluidalnego rozdrobnionej biomasy drzewnej. Inż. Ap. Chem. **50**(5), 26–27 (2011)
12. Jaros, M., Pabis, S.: Inżynieria systemów. Wydawnictwo SGGW, Warszawa (2007)
13. Kaleta, A., Górnicki, K.: Podstawy techniki cieplnej w inżynierii rolniczej. Wydawnictwo SGGW, Warszawa (2009)
14. Kaleta, A.: Thermal properties of plant materials. Wydawnictwo SGGW, Warszawa (2007)
15. Zawistowski, P., Arabas, J., Głowacki, S.: Modeling of wood biomass drying process with the use of neural nets. Warszawa (2010)
16. Bieńkowska, D.: Opis Patentowy PL 217485 B, No: 397087, Sposób suszenia biomasy drzewnej w suszarni taśmowej
17. Szalewicz, Ł., Uruski, Ł.: Aparatura procesowa i chemiczna. Suszarki - aparatura do suszenia. Akademia Górniczo-Hutnicza, Kraków (2010)

18. Pabis, S.: Teoria konwekcyjnego suszenia płodów rolnych. PWRiL, Warszawa (1982)
19. Sojak, M., Glowacki, Sz.: Analysis of giant pumpkin (*Cucurbita maxima*) drying kinetics in various technologies of convective drying. J. Food Eng. **99**(3), 323–329 (2010)

Analysis of Potential Related to Grass-Derived Biomass for Energetic Purposes

Andrzej Bryś, Joanna Bryś, Szymon Głowacki, Weronika Tulej, Paweł Zajkowski and Mariusz Sojak

Abstract According to the climate energy package of the EU, biomass is and will be the most important source of energy of all renewable resources of energy (RRE). Experts from the European Association of Biomass estimate that it will be caused by tree-fold increase in demand for this source of energy (Gradziuk in Gospodarcze znaczenie i możliwości wykorzystania słomy na cele energetyczne w Polsce. Wyd. Instytut Uprawy Nawożenia i Gleboznawstwa - Państwowy Instytut Badawczy w Puławach, 2015, [1]). In Poland, the wastelands cover 475,000 ha (Central Statistical Office of Poland. Statistical Yearbook of Agriculture, 2016, [2]), and could be used as a source of biomass, e.g. for biogas plants or for briquette production. Waste grass from green areas such as parks, gardens, garden plots, and biomass from roadsides (motorways and highways) should also be taken into account. The amount of waste changes annually as it depends on vegetation, weather, method of green areas and gardens nurturing. Green waste is mainly produced from spring till autumn, and the amount produced during these seasons is much higher than in winter (Jędrczak, Biologiczne przetwarzania odpadów. Wydawnictwo Naukowe PWN, Warszawa, 2007, [3]). Therefore, grass briquetting is desirable as briquetted grass may be used throughout the year. One of the most important stages of briquette production is drying raw material, i.e. grass.

Keywords Biomass · Grass · Drying · Biofuels · Briquettes

A. Bryś (✉) · S. Głowacki · W. Tulej · P. Zajkowski · M. Sojak
Katedra Podstaw Inżynierii, Wydział Inżynierii Produkcji, SGGW,
ul. Nowoursynowska 164, 02-787 Warsaw, Poland
e-mail: andrzej_brys@sggw.pl

S. Głowacki
e-mail: szymon_glowacki@sggw.pl

W. Tulej
e-mail: weronika_tulej@sggw.pl

J. Bryś
Wydział Nauk o Żywności, Katedra Chemii, SGGW,
ul. Nowoursynowska 159 C, 02-776 Warsaw, Poland
e-mail: joanna_brys@sggw.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_43

1 Introduction

19th and 20th centuries are the period of rapid development in almost all fields of industry, as well as economy and urban planning. Every year, spendings on new technologies are higher and contribute to the development of urban and rural areas. Together with industrial development and global population growth, the demand for energy is increasing. Until mid-19th century, almost all sources of energy were renewable. The industrial revolution changed this trend, and resulted in using more efficient solutions in order to cover the constantly growing energy consumption. Renewable resources of energy were replaced with fossil fuels. These fuels are convenient to use due to the large amount of energy obtained during combustion. However, they have an adverse effect on the environment. Moreover, fossil fuels resources are limited, and, according to the estimates, they will have run out by the end of this century [4]. Increasing demand for energy and increased emphasis on environment protection, as well as EU directives on the share of RRE (Renewable Resources of Energy) in the total amount of energy, lead to searching for new solutions related to renewable energy. Based on the EU climate energy package it may be assumed that biomass will be the most important RRE. It is forecast that its share will have an upward tendency [1]. According to the Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste. Biomass is the most varied source of renewable energy as it occurs in three states of aggregation: liquid (transportation biofuels), gaseous (biogas) and solid (e.g. briquettes). The emission factor of biomass is zero, which means that biomass uses as much CO_2 during its growth as it releases in the combustion process. Moreover, it releases much less CO, nitrogen and SO_2 [5]. Solid biofuels share in obtaining energy from renewable resources, according to the European Union carriers is the largest, and, in 2014, it amounted to 43.8% within the EU. In Poland, it was equal 76.6% [6]. Solid fuels include waste from industrial plants that process timber, biomass from energy plants, biomass from farms, forest biomass and biomass from urban areas and wastelands. In 2016, the total area of wastelands in Poland in 2016 reached 469.5 thousand hectares [2], which wastelands are a potential source of grass biomass. Also, biomass from housing and industrial districts as well as other built-up, urbanized, recreational and holiday areas, which comprised 678.1 thousand hectares in 2016 should also be taken into account. An important source of grass biomass in Poland may be communication areas, including motorways, highways, railways with the total area of 921.4 thousand hectares [2]. Due to the fact that grass grows most intensively in spring and summer, it should be briquetted and stored for use in the periods of increased demand for energy. Additionally, briquetted grass has smaller volume, which lowers storage and transportation costs. In order to use grass for energy purposes it should undergo drying process, which is one of the most energy-consuming stages of briquettes production.

2 Materials and Methods

Three types of grass were used for the experiments, i.e. lawn grass (mowed regularly), annual grass (mowed once a year) and perennial grass from urban areas and wasteland. The material for examinations was collected in Poland in the Mazovia Province in the second half of June, from all places simultaneously. Lawn grass contained such plants as common dandelion (*Taraxacum officinale*), English ryegrass (*Lolium L.*), rough bluegrass (*Poa trivialis L.*) and white clover (*Trifolium repens L.*), typical for city lawns. The length of grass was between 1 and 7 cm, with the following percentage share of different types of plants:

– English ryegrass (*Lolium L.*)—43%
– rough bluegrass (*Poa trivialis L.*)—41%
– common dandelion (*Taraxacum officinale*)—10%
– white clover (*Trifolium repens L.*)—6%

Two main types of annual grass were examined: rough bluegrass (*Poa trivialis L.*) and English ryegrass (*Lolium L.*), whose length ranged between 75 and 85 cm, and the percentage share in the total mass was similar. Perennial grass samples were collected from wastelands, and they mainly contained 95–105 cm long couch grass (*Elymus repens*). The types of grass are presented in Fig. 1.

Water content (u) in all types of grass was determined using the gravimetric method. Temperatures of biomass drying were selected based on the literature [7], and included low-temperature free air drying and high-temperature drying [8]. The drying process was conducted in natural conditions (in ambient temperature), and in the chamber convection drier at the temperatures of 60 and 80 °C, without the drying agent flow. The readings from the precision scales, accurate to 0.001 g, were recorded automatically every minute. For drying in natural conditions, the measurements were taken every two hours from hour 07:00 in the morning to 21:00 in the evening. In the dried grasses, gross calorific value (heat of combustion) was determined by burning the substance being examined in constant volume conditions, in the pressure bomb calorimeter, in oxygen atmosphere. Ash content was also determined in the material being examined, by combusting the material in the muffle furnace. All research experiments were performed thrice. Readings of air temperature and moisture were obtained from the weather station located at Warsaw University of Life Sciences in the Ursynów District of Warsaw.

Fig. 1 Types of grass used for drying

3 Results

Initial water content (u) in the examined sample differed and was equal 1.86 kg H_2O/kg d.s. for regularly mowed grass; 3.67 kg H_2O/kg d.s. for annual grass, and 2.90 kg H_2O/kg d.s. for perennial grass. Grass mowed once a year had the highest water content, which is caused by the fact that it did not contain old dry elements of the plant, while lawn grass had the smallest amount of water which may be explained by the fact that young grass shoots dry-up quickly during periods of drought. Figure 2 shows the drying curve for grass dried in natural conditions. It may be observed that the drying time of all types of grass depends on the initial water content. For the grass mowed regularly, the drying time was the shortest, and after day 4, it reached the value, which allowed for briquette production. Both annual and perennial grass, despite long time of drying (7 days) was not dry enough to start the process of briquetting as the optimum moisture of biomass for briquetting is 8–12%. It may also be concluded that both drying temperature and air moisture both had an impact on the content of water in the grass. During the night, when air moisture increased and temperature decreased, water content in the grass being dried increased (Fig. 2).

For grass dried at the temperature of 60 °C, the drying time shortened considerably to 4 h for lawn grass and perennial grass, and it reduced to 9 h for annual grass, which is presented in Fig. 3. For grass dried at 80 °C, the drying time also

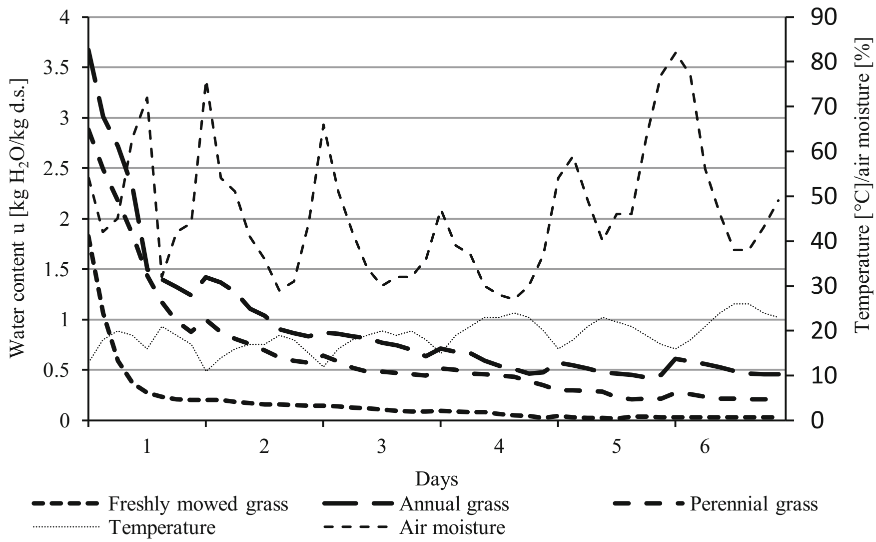


Fig. 2 The course of changes of water content (u) during drying in natural conditions, together with curves of temperature and air moisture changes (additional, secondary axis on the right)

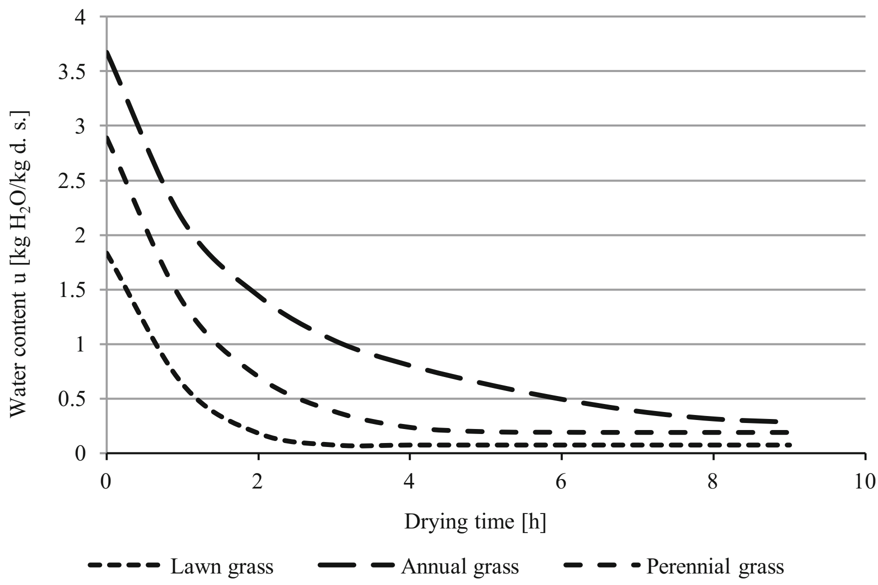


Fig. 3 Course of changes in the water content (u) during drying in chamber drier at the temperature of 60 °C

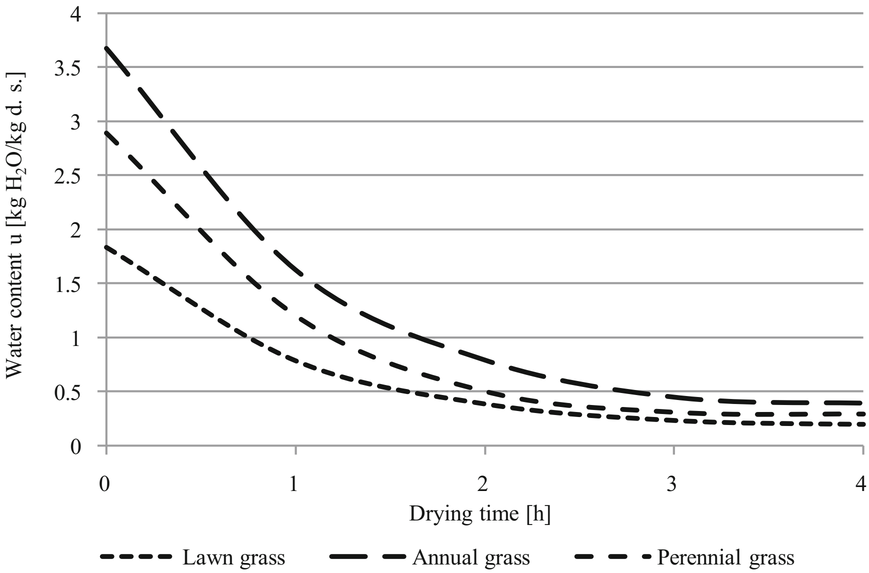


Fig. 4 Course of changes in water content (u) during drying in chamber drier at the temperature of 80 °C

Table 1 Gross calorific value and ash content in the examined grasses

Grass type	Gross calorific value (kJ/g)	Ash content (%)
Lawn grass	18.5	8.26
Annual grass	18.7	3.25
Perennial grass	19.4	2.25

shortened in comparison to drying at the temperature of 60 °C and was equal 3.5 h for all the samples being examined (Fig. 4).

Based on the analysis of gross calorific values obtained for the combusted grasses it may be concluded that perennial grass has the highest gross calorific value and the lowest ash content. Lawn grass has the highest ash content and the lowest gross calorific value (Table 1). Increased ash content in the sample may be attributed to contamination resulting from mowing the grass with fuel lawn mower. It may also by concluded based on the obtained results that perennial grass is the most desirable source of biomass to be used for briquetting as it has the highest gross calorific value and the lowest ash content. Although the initial water content is high, it is not the highest of all the examined samples.

4 Conclusions

Poland has a lot of wasteland, which may be used for grass biomass production. Additionally, quite a lot of biomass may be obtained from housing and industrial districts, and other built-up and urbanized, recreational areas and holiday areas. Due to the rising number of motorways, highways and railways, the amount of biomass, which may potentially be obtained from such areas, increases. Lawn grass has the highest ash content, which indicates its contamination with sand and soil during mowing. It is undesirable in the process of briquetting as it causes quicker wear-off of the elements of press machinery. The duration of lawn grass drying was the shortest in all temperatures. In natural conditions, the drying time of grass is long, and for perennial and annual grass it is impossible to dry the grass to the desired moisture content in 7 days. Perennial grass has the best qualities as regards its use for energy purpose as it has the highest gross calorific value and low ash content.

References

1. Gradziuk, P.: Gospodarcze znaczenie i możliwości wykorzystania słomy na cele energetyczne w Polsce. Wyd. Instytut Uprawy Nawożenia i Gleboznawstwa - Państwowy Instytut Badawczy w Puławach (2015)
2. Central Statistical Office of Poland. Statistical Yearbook of Agriculture (2016)
3. Jędrczak, A.: Biologiczne przetwarzania odpadów. Wydawnictwo Naukowe PWN, Warszawa (2007)
4. Kisiel, R., Wasiuta, A.: Stan i rozwój energetyki wiatrowej w unii europejskiej. J. Agribus. Rural Dev. **1**(11), 141–154 (2009)
5. Szlachta, J.: Aspekty wykorzystania biomasy na cele energetyczne cz.1, Ekonauta, PCEPPiU, Wrocław 25–26 (2003)
6. Central Statistical Office of Poland. Energy from renewable sources in 2015 (2016)
7. Kobayashi, Y., Yokoo, K.: Practical use of solar-dehumidification dry kiln. In: 5th International IUFRO Wood Drying Conference, Quebec City, Kanada (1996)
8. Loo, S., Koppejan, J.: The Handbook of Biomass Combustion and Co-firing. Earthscan, London (2008)

Energy Characteristics of Compacted Biofuel with Stabilized Fraction of Municipal Waste

Beata Brzychczyk, Tomasz Hebda and Jan Giełżecki

Abstract An analysis of the energy characteristics of compact biomass formed from biomass of giant miscanthus and the stabilized fraction of municipal sewage sludge, depending on the percentage of stabilization. Five types of compacted fuel with a content of 5–25% stabilization at three moisture contents of 12, 15 and 18% were subjected to the evaluation of energy properties. Standards for solid biofuels were used. The created biofuel was subjected to a combustion process to determine a preliminary analysis of the kinetics of the process. Based on the research, it has been shown that biocompatible fuel can be generated with a maximum additive of a stabilized fraction of municipal waste up to 10%. The proposed additive does not significantly affect the reduction in the calorific value of compact fuel. In addition it allows the recovery of energy contained in waste and it is an alternative to their disposal. The moisture content of the test mix should not exceed 15%.

Keywords Biofuel · Stabilizate · Combustion · Energy properties
Miscanthus × *giganteus*

1 Introduction

Solid biofuels are fuels made from combustible biomass. According to EU Directive 2009/28/EC, biomass means any biodegradable matter including industrial and municipal waste fractions and industrial residues from forestry and agriculture.

Consequently an attempt was made to establish a biomass-based on solid biomass of the giant miscanthus biomass with the addition of waste that was a stabilized fraction of the municipal sewage sludge. The premise for trying to model the solid biofuel was the calorific value of the stored waste at about 6 kJ g^{-1} and the

B. Brzychczyk (✉) · T. Hebda · J. Giełżecki
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka Nr 116, 30-149 Krakow, Poland
e-mail: Beata.Brzychczyk@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_44

reduction of the construction of new landfills. The use of stabilizer in the form of an additive in compact biofuel in which the basic ingredient would be a biomass from energy crops could be a solution to the above problem [1].

In Poland a waste management is carried out in accordance with the following hierarchy: waste prevention (ZPO), reuse preparation, recycling, other recovery and disposal processes. On the other hand, the main targets of waste management are among others: the reduction of biodegradable municipal landfills, ZPO and reduction of the amount of waste deposited (KPGO 2022). According to the Ordinance of the Minister of Economy of 16.07.2015, some waste fractions may be stored at the landfill other than hazardous and inert waste. Their calorific value can not be greater than 6 kJ g^{-1} [2–4].

As a consequence, the minimization of stockpiles is minimized including depositing stabilization. It is built into the MBP installation, in its biological part. The stream of mixed municipal waste is divided into overrun and subsectional fraction directed to biological stabilization [5].

The final product of the process is a stabilizer with parameters meeting the Regulation of the Minister of the Environment of 11 September 2012 which is then the most often deposited on the landfill. The calorific value of stored waste prompts the search for other, economically justifiable solutions aimed at the energetic use of combustible components contained in biologically treated municipal waste. In addition, existing technological lines for the production of biofuels compacted from energy crops can easily be expanded by adding a stabilizer to the raw material [6–9].

The compact biofuel is produced by agglomeration of the raw material. The shredded plant material under the influence of external and internal forces is formed into a specific shape to produce a specific final product [10–12]. The determination of energy parameters of solid fuels such as combustion heat and calorific value, ash content, volatile matter content, humidity content, C, H, N, O and S elemental composition, Cl content, heavy metal content, softening, melting and flowing ash, kinetics of combustion, others, allow to design the process of thermal processing together with the selection of suitable technology [11–14].

Parameters were evaluated to meet fuel standards for non-wood pellets. It was determined whether the given mixture in the set humidity meets the standard and its fuel class. On this basis the range in which the maximum stabilizate content of the mixture is found so that it meets the standard. Preliminary analyzes of changes in combustion kinetics were performed. The scope of the study included the determination of: analytical moisture, C, H, S and N content, volatiles, ash content, calorific value, ignition temperature, ash melting temperature and combustion kinetics.

1.1 Materials and Methods

Collection and preparation of samples. Five blends were prepared for the study to form a compact biofuel based on giant miscanthus and a stabilized fraction of municipal waste (stabilizate). Raw material was the biomass of giant miscanthus from the cultivation of the Faculty of Production Engineering and Energetics of the University of Agriculture in Cracow. The calorific value of the miscanthus is between 14 and 17 MJ kg^{-1} while the fresh straw humidity is 15–30% [11, 15, 16].

Stabilization was obtained from MIKI Mieczysław Jakubowski, Cracow. The collected material complies with the required standards. The biomass of the miscanthus after harvest was cut into about 30 cm pieces then with the stabilizer it was dried at 378 K for 24 h. The material thus prepared was crushed in a 6 mm knife mill. At the next stage mixtures of giant mackerel with stabilizate were prepared in the following proportions: 95:5, 90:10, 85:15, 80:20 and 75:25. The resulting blends were further comminuted in a 4 mm mesh knife mill. With complete mixes of 12, 15 and 18% total humidity pellets with a diameter of 12 mm were formed. The agglomeration process took place on the endurance machine at a preset pressure of 166.66 MPa.

Analytical moisture content, calorific value, C, H, S and N content, volatiles and ash content were determined for all five mixtures with a moisture content of 12% and then converted to dry conditions. Mixtures of 15 and 18% were converted to working states. Test specimens were collected according to EN 14778—2011. The material was milled in a LMW vibratory mill to a fineness of less than 0.1 mm so that it could be analyzed in accordance with the standards for solid biofuels. The finished material has been labeled.

The determination of the ignition temperature, ash melting temperature and the combustion kinetic study were carried out for compacted biofuels with a moisture content of 12%.

The determination of analytical moisture. The analytical humidity was determined according to PN-EN 14774-3-2010 by the dryer method. The test sample weighing 1 g $\pm$ 0.1 g was air dried at 378 K $\pm$ 275 K in an ELKON oven for 60 min then the sample was weighed and re-dried for 30 min. The procedure was repeated to obtain a constant weight. Then the material was placed in the desiccator to reach ambient temperature and then weighed. All conversion to dry conditions and work conditions have been made in accordance with PN-EN 15296-2011.

The determination of carbon, hydrogen, sulfur and nitrogen content. The determination of carbon and hydrogen content was carried out in accordance with PN-EN 16948-2015 and sulfur according to PN-EN 15289-2011, using a CHS 580 analyzer to sample 100 mg of total incineration in a furnace at 1623 K. The nitrogen content was determined according to PN-EN 16948-2015 using nitrogen and protein analyzer "DUMATHERM" ELTRAN-580. A sample of 40 mg was incinerated in a reactor according to the Dumas method -rapid burning of samples in an atmosphere of pure oxygen. The results of all analyzes were retrieved from the operating program installed on the computer connected to the analyzer. Output values are given for samples in the analytical state. Values of executed marks were averaged.

The determination of the content of volatiles. The design of the volatiles was done in accordance with PN-EN 15148-2010. The test specimen weighing 1 g ± 0.1 g was placed in a standardized vessel which was covered with a sealed lid and then roasted without air at 1173 K ± 283 K for 7 min ± 5 s. FCF 22P muffle furnace. After this time the sample was removed, quenched for a period of 5–10 min and then placed in a desiccator to stabilize against ambient temperature and re-weighed.

The determination of ash content. The ash content determination was carried out in accordance with PN-EN 14775-2010. A sample of 1 g ± 0.1 g was placed in a vessel which was placed in a cooled muffle furnace FCF 22P by heating in the first stage of the furnace to 523 K for 30 min and heating for 60 min. In the second stage the temperature was raised to 823 K ± 283 K for 30 min maintaining it for 120 min. After this time the sample was removed and quenched for 5–10 min. Once the ambient temperature has been reached the sample is weighed.

The determination of calorific value and heat of combustion. The calculation of calorific value was carried out in accordance with the standard PN-EN 14918-2010. Analyzed sample of 1 g ± 0.1 g was incinerated in IKA C 5000 control calorie in a pure oxygen atmosphere. After the correction of the nitrogen and sulfur content of the fuel the combustion heat value was read. The calorific value in the dry state was calculated according to the standard PN-EN 14918-2010.

The determination of inflammation temperature. The ignition temperature was carried out in an inductive horizontal tube furnace. Single pellet biofuel grain was used for the combustion process. Basler acA4600-10uc scan camera records the image by recording the drying, degassing and ignition of the gaseous combustible components at a rate of one frame per second. To simultaneously measure and record the temperature with a thermocouple placed in the vicinity of the sample pellet. The image was then analyzed for flame and temperature. The parameter was set for a blend with a moisture content of 12% for all stabilization shares.

The determination of melting point of ash. The ash melting point determination was made in accordance with PN-ISO 540 2001.

Samples to determine the melting point were previously incinerated in accordance with PN-EN 14775-2010 by placing the material in a ceramic crucible and then heating step by step in a muffle furnace type FCF 22P. In the first stage it was kept within 30 min to 823 K for 60 min. In the second stage the oven temperature was raised to 823 K ± 283 K for 30 min and maintained for 120 min. The finished ash was cooled down using a mortar and then sieved through a 1 mm sieve. Pastilles were formed to determine the ash melting temperature of the material by hand presses. Investigation of the melting point of the ash was carried out in a high temperature tube furnace. The ash-shaped sample was placed inside the graphite tube of the induction furnace heating the sample at a rate of 303 K min^{-1} to 1173 K above this temperature at 283 K min^{-1}. The process was recorded using a Basler acA4600-10uc scan camera. A visual assessment of the sample changes was made by superimposing the images onto the measuring grid. On this basis the melting point of the ash was determined [16].

The study of combustion kinetics. The combustion kinetic study was performed using a vertical RST 20 × 200/100 M/spec tube furnace. A compact biofuel sample was placed in a basket inside the tube furnace suspended to the balance. The temperature was measured using a thermocouple installed inside the furnace. Weight losses and temperature were recorded using the software included as part of the furnace's measuring and measuring equipment. The study program assumed that the furnace was heated to 873 K. The program of heating process was carried out at a temperature increase of 20 K min^{-1}. The whole process was computerized. Continuous recording of changes in mass parameters measured to within 1 mg and temperature measured to within 273.25 K, was continuously recorded. Thanks to the increase in temperature it was possible to determine the stages of the combustion processes and to deduce the key temperature range in which the greatest mass loss occurred.

1.2 Result and Discussion

Energy properties. Table 1 summarizes the average results of the energy properties of the biofuels tested. Because of the lack of standards for solid biomass from biomass with the addition of waste, the assessment of model blends has been made to comply with PN-EN 14961-6-2012. The above standard specifies solid fuels produced from mixtures of materials differentiating them into Class A and B.

According to the standard the maximum moisture content for solid grade A biofuels is below 12% while for class B below 15%. Each of the prepared and tested mixtures in a working condition with a moisture content of 12% was eligible for Class A, whereas biofuels with a content of 15% moisture were classified as Class B. The standards did not meet the 18% moisture content of the biofuel in the

Table 1 Energy properties of compacted biofuels in dry state

No.	Parameter	Unit	Biofuel compacted with stabilized fraction of municipal sewage sludge				
			5%	10%	15%	20%	25%
1.	Calorific value	kJ g^{-1}	17.13	16.98	16.72	16.17	15.58
2.	Ash content	%	6.97	9.75	11.37	15.21	20.03
3.	Content of volatiles	%	74.42	73.12	71.23	68.24	66.36
4.	Content C	%	46.84	45.82	45.17	44.14	43.07
5.	Content N H	%	5.60	5.35	5.09	4.77	4.59
6.	Content S	%	0.10	0.12	0.12	0.17	0.23
7.	Content N	%	0.34	0.33	0.30	0.29	0.28
8.	Melting point of ash	K	1510	1467	1424	1371	1330

working state, but a study with evaluation of their suitability and use for other parameters was carried out for them.

The ash content in dry matter for Class A fuels is up to 5%, for Class B up to 10%. None of the mixtures formed did not meet the requirements of the highest class, Class A. The requirements for the lower class only reached 5 and 10% stabilizers, 6.97 and 9.75%, respectively of the ash content, mixtures above 15% did not meet requirements of this parameter.

Fuel value in class A of solid biofuels is defined in this standard at a level higher than 14.1 kJ g^{-1}. Class B is assumed to be equal to or higher than 13.2 kJ g^{-1}. Mixes of 5, 10 and 15% stabilizer at a moisture content of 12% meet class A for compact biofuels. In contrast biofuels made from a mixture of 20 and 25% of the stabilizer at 12% humidity attain class B. For higher humidity class A, due to the calorific value, only the blend with 5% stabilizer with a moisture content of 15%. The standard requirements do not apply to mixtures with 20% stabilizer content and with 18% moisture content and 25% stabilizer content and with 15 and 18% humidity in the working state.

The nitrogen content of the dry mass of biofuels according to class A should be below 1.5%, for class B below 2%. Each of the tested blended biofuel blends meets the required values for Class A. Normally the sulfur content of dry matter for grades A and B should be less than or equal to 0.2%. Among the tested blends only 25% of the stabilizer achieved bioavailability above the norm. All other fuels meet the standard in this regard.

The energy characteristics of compacted biofuels with a stabilized fraction of municipal sewage sludge verified on a pellet standard PN-EN 14961-6-2012 were met only by fuel with 5 and 10% stabilizer, and 12 and 15%. Formed biofuels are assigned class B for biofuels produced from mixed composition. Ash content in dry matter proved to be the most important parameter influencing the class definition of biochemical compounds tested.

The results of the study of changes in calorific value of compacted biofuels made from mixtures based on percentage of stabilization at different fuel moisture values are shown in Fig. 1. The highest calorific value was found in biofuel with 5% stabilizer and 12% moisture content (14.78 kJ g^{-1}), whereas the smallest showed a mixture with 25% stabilization and 18% moisture content (12.33 kJ g^{-1}). Increasing the stabilization additive in fuel lowers its calorific value.

The content of volatiles. The highest content of volatiles (see Fig. 2) showed a mixture of 5% stabilizer and 12% moisture content (65.5%) and the lowest content of volatile mixtures with 25% content of stabilizer with 18% moisture content (54.41%).

Ash content. The highest ash content (see Fig. 3) at 17.63% showed a 25% content of stabilizer with a moisture content of 12%. The smallest value at 5.72% was obtained for a 5% stabilizer mix at 18% humidity.

The temperature of inflammation. The highest temperature of 597 K was reached for the compact biofuel formed from 25% stabilizer. The lowest temperature (571 K) was reached for the 5% stabilizer blend. Increasing the proportion of

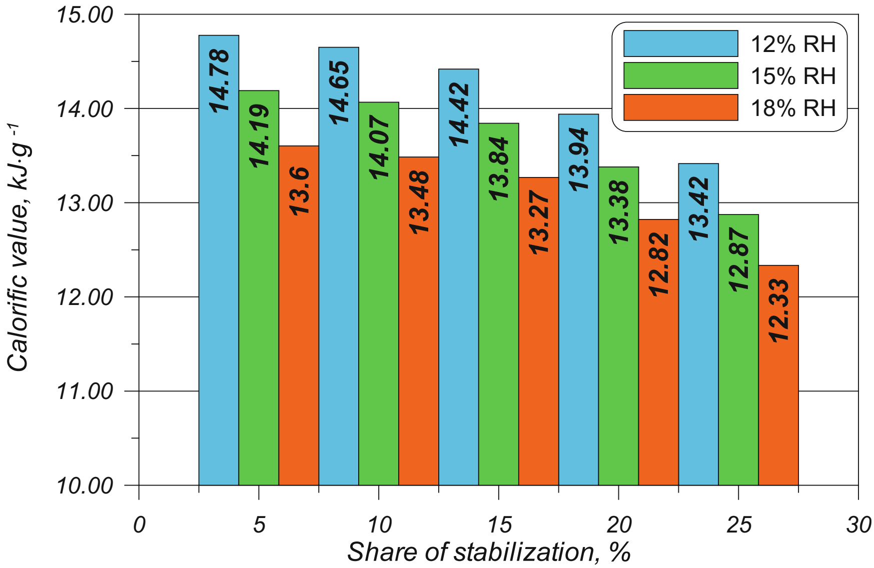


Fig. 1 Calorific value depending on the proportion of stabilized municipal waste sludge fraction for different moisture content in fuel, an analytical state

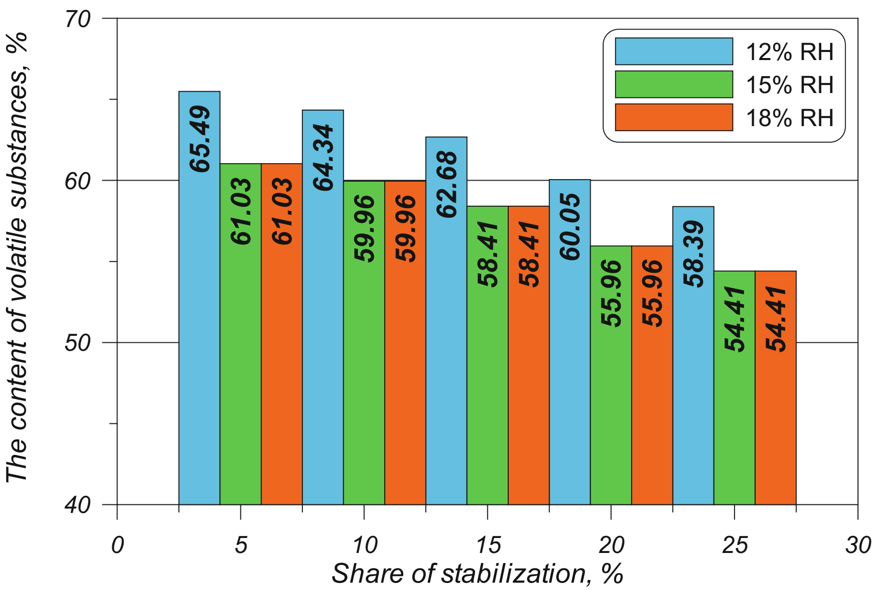


Fig. 2 The content of volatiles depending on the proportion of stabilized fraction of municipal sewage sludge for different moisture content in fuel, an analytical state

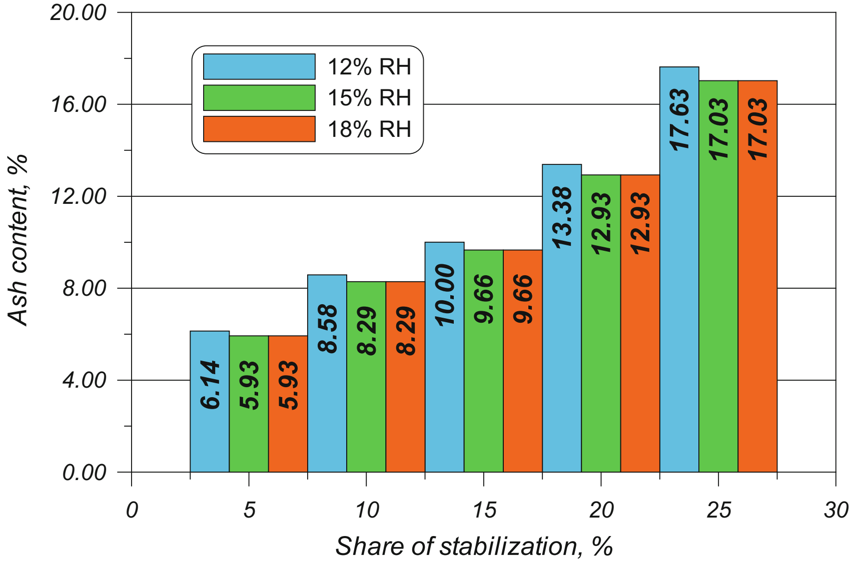


Fig. 3 Ash content depending on percentage of stabilization for different biofuel humidity, an analytical state

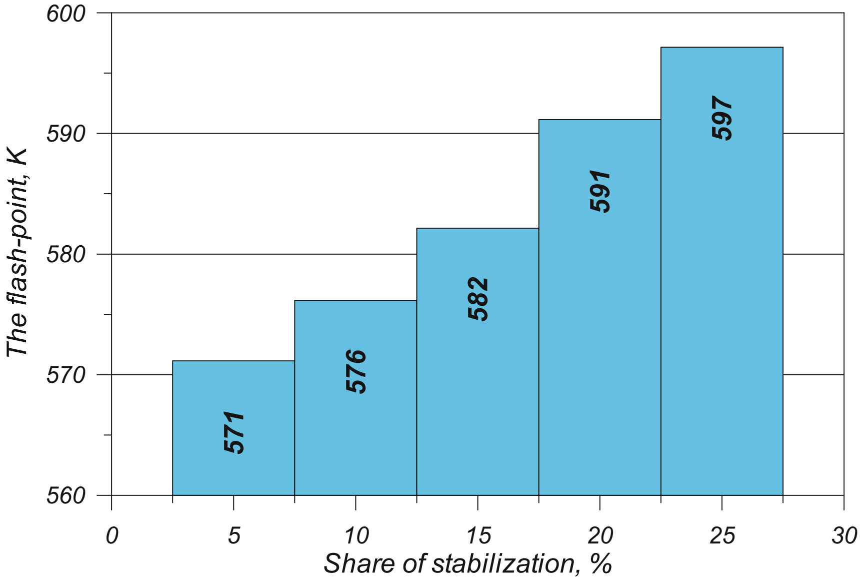


Fig. 4 The temperature of compacted fuel ignition for different stocks of stabilized fraction of municipal waste sludge, for 12% of moisture content

stabilization results in an increase in the temperature of the inflammation while reducing the volatiles (see Fig. 4).

The melting point of ash. The highest temperature (1510 K) was obtained for the ashes generated from the combustion of biofuel with 5% stabilizer and 12% moisture content (see Fig. 5). The lowest temperature (1330 K) was determined for a sample formed from a mixture of 25% stabilizer and 12% moisture content. The difference between the melting temperatures was due to the addition of a fraction of the stabilized waste.

The kinetics of combustion. The average results of the combustion kinetics study for the five types of compact biofuels and the moisture content of 12% are shown in Fig. 6. Each process consisted of 5 stages: heating and drying, thermal decomposition, post-combustion. The graph shows the relationship between mass loss and temperature increase for a given biofuel. For each biofuel, there is a similar pattern of heating and drying stages during which the fuel has lost a specified 12% moisture content. The next stage was thermal decomposition characterized by slight weight loss. Its duration depended on the degree of stabilization. The shortest time was observed for 5% stabilized biofuel and the longest for 25%. Subsequently, the combustion phase of the thermal decomposition product was started with the largest and fastest mass loss in the samples tested. At the earliest, this stage was started for 5% stabilization fuel.

For fuel with 25% stabilizate content, the stage of incineration of thermal decomposition products occurred at the latest. For the fuel formed from mixtures

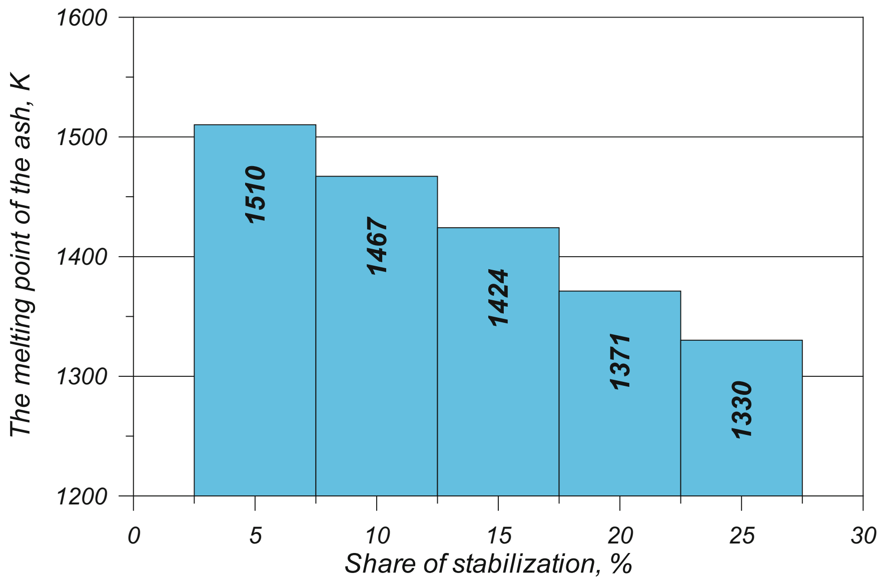


Fig. 5 The melting temperature of ash produced from compact fuel for the different shares of the stabilized fraction of municipal waste sludge and 12% of humidity content

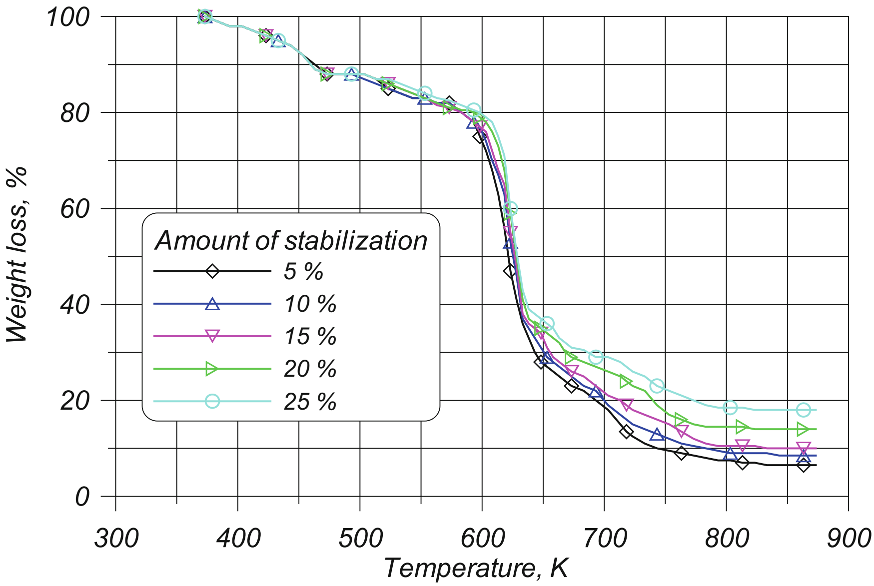


Fig. 6 Kinetics of the combustion of compact fuel with stabilization from 5 to 25%, [own studies]

with a 5% stabilization ratio this step was observed between 583 and 648 K then 52% weight loss was observed. For biofuels with 25% stabilization the combustion temperature range was between 603 and 663 K and 49% weight loss. The mass losses and temperature range of the remaining mixtures were between the values of these extreme fuels. The next stage was post-combustion residue after thermal decomposition and combustion of coke residues lasting until a constant mass of samples equal to the value of the ash content. The largest weight loss, about 16.5%, was for the 5% blend, the smallest for the 25% blend where a decrease of about 12% was observed.

The most liquid combustion process showed a biofuel compacted with a 5% share of a stabilized fraction of municipal waste. This result is due to the highest chemical uniformity of the fuel. For this biofuel also had the largest loss of mass amounting to about 94% of which 12% was humidity and 82% were substances that were burned. With the increase in the proportion of stabilization the flux of the combustion process decreases, the temperature of the start of the combustion step of the thermal decomposition products increases and, in the first place, the loss of mass increases which results in less heat generation. This is most evident for biofuels with a 25% stabilization. In this case, the total fall was 82%, after which the humidity content of the fuel was only 70%. The difference between extreme fuels is as much as 12%. Blends of 10 and 15% of stabilization exhibit similar process fluidity and slightly higher starting temperatures of the combustion stage to a 5% blend.

2 Conclusions

The energy characteristics of compacted biofuels made from biomass mixtures with the addition of stabilized fraction of municipal waste with content between 5 and 15% of stabilization were not significantly different.

Both calorific value and combustion kinetics for three mixtures of 5, 10, 15% stabilization were similar.

The maximum moisture content of the modeled fuel was set at 15%.

Increasing the stabilization content from 5 to 25% increases the ash content by as much as 13% in the fuel produced.

As the proportion of stabilization increases, the melting point of the ash decreases with increasing sulfur content.

The value of the stabilized fraction of municipal sewage sludge at the level of 10–15% can be considered as optimal for the development of fuels while attempting to manage the waste.

This range was determined taking into account the ash content in the dry matter which for the content of 10% of the fractions in the mixture was 9.75% and for the 15% of the stabilization amount 11.37%. Permissible content of ash for 5% molded fuels for Class A and 10% for Class B Based on the research, it has been found that stabilizers can be used to form mixtures for the production of compact biofuels. It does not significantly affect the reduction in calorific value. In addition it allows the recovery of energy contained in waste and is an alternative to waste management.

Acknowlegements This Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Walendziewski, J., Kułażyński, M., Surma, A.: Identify the potential of waste and their types to produce solid alternative fuels. The science and technology network “Energia”. Wrocław (2007)
2. Bień, J., Gandor, M.: Combustion kinetics of sewage sludge under oxygen-enriched atmosphere. Eng. Prot. Environ. **14**(3), 233–244. Polish Academy of Sciences Committee on Environment Engineering (2011)
3. Kordylewski, W., Bulewicz, E., Dyjkon, A., Hardy, T., Słupek, S., Miller, R., Wanik, A.: Combustion and Fuels. In: Kordylewski, W. (ed.) Publishing House of Wroclaw University of Technology. Wrocław (2005) (in Polish)
4. National waste management plan 2022 z dnia 1 lipca 2016r. [online]. http://www.monitorpolski.gov.pl/MP/2016/784. Access 07 Jan 2017
5. Siemiątkowski, G., Nolepa, A., Binner, E., Paciorkowski, M., Glanz, R., Poluszyńska, J., Gąsior, D.: Mechanical-biological processing of biodegradable fraction of municipal waste. Guide to selected technologies and methods of testing and evaluation of waste generated in these processes. In Editor Siemiątkowski G.: Publisher Silesian Institute Sp. z o.o. Opole (2012). ISBN 978-83-7511-151-4 (in Polish)

6. Jędrczak, A., Szpadta, R.: Guidance on the Requirements for Composting, Fermentation and Mechanical-Biological Waste Processing. Ministry of the Environment Department of Waste Management, Warszawa (2008) (in Polish)
7. Lewandowski, W. M.: Proekologiczne odnawialne źródła energii. WNT. Warszawa (2007)
8. Ściążko, M., Zuwała, J., Pronobis, M.: Co-combustion of Biomass and Alternative Fuels in Power Industry. Silesian University of Technology. Zabrze, Publisher Institute for Chemical Processing of Coal (2007). (in Polish)
9. Skalmowski, K., Wolska, K., Pieniak, U., Ruszczyńska, I.: Study of Technological Properties of Municipal Waste. Publishing House of Warsaw University of Technology, Warszawa (2004). (in Polish)
10. Frączek, J., Cieślikowski, B., Ślipek, Z.: Evaluation of biofuels quality solid compact part 1: quality requirements. Buses-Technol. Oper. Transp. Syst. **10**(12), 161–169 (2011). ISSN 1509-5878 (in Polish)
11. Król, D.J.: Biomass and Fuel Molded from Waste in Low-Carbon Combustion Technologies. Silesian University of Technology, Gliwice (2013). (in Polish). ISBN 978-83-7880-010-1
12. Wandrasz, J.W., Wandrasz, A.J.: Fueled biofuels and fuel from waste in thermal processesh. Seidel - Przywecki Sp. zoo Warszawa (2006). ISBN 978-83-919449-7-2
13. PN-EN ISO Solid biofuels—Determination of calorific value
14. Maga, J., Nozdrovisky, L., Pepich, S., Marhavy, L., Hajdu, S.: Komplexny model vyuzaitia biomasy na energeticke ucely. Slovenska pol'nohospodarska univerzita v Nitre, Nitra (2008)
15. Niedziółka, I., Bogucka-Kocka, A., Kocki, J., Piekarski, W., Szczot, E., Sarec, O., Orkiszewska, D.: Technology of Production of Biomass Briquettes. Society of Scientific Publishers "Libropolis". Lublin (2014) (in Polish)
16. Nęcka, K., Lis, S., Dródź, T., Nawara, P., Wrona, P., Oziembłowski, M.: Characterization of a prototype laboratory for the ash test of tube ash. Electrotech. Overview 1(12), 109–112 (2016). https://doi.org/10.15199/48.2016.01.26 (in Polish)

Influence of Internal Deposits on Diesel Engine Injectors on the Parameters of the High Pressure Common Rail System (HPCR)

Bogusław Cieślikowski and Janusz Jakóbiec

Abstract The complexity of the deposits formation process on the components of compression ignition engine, including high-pressure injection Common Rail systems, is gaining global significance. Knowledge related to the mechanisms of their formation and chemical composition is still insufficient and requires further studies. The studies allowed, hypothetically, assuming several mechanisms of their formation, but each of these require further research in order to be verified and finally confirmed. This is due to high complexity of the factors and conditions that may affect the initiation of the deposit formation, of which the most important are: fuel and additive composition and type of contaminants from fuel production and transport. Deposits' physical nature may vary, as these may be soaps, salts of metals or ashless materials like imide or amide forms of organic polymers. This article contains the results of the research on the assessment of HP Common Rail injector and EGR components contamination and their technical condition, after 120 thousand km operational run, with the use of diesel and biofuel B10.

Keywords Engine · Fuel injection · Injector · Fuel

B. Cieślikowski (✉)
Department of Mechanical
Engineering and Agrophysics, Faculty of Production Engineering and Energetic,
Agricultural University of Cracow, ul. Balicka 116B, 30-149 Kraków, Poland
e-mail: cibogdan@poczta.onct.pl

J. Jakóbiec
Department of Fuels Technology, Faculty of Energy and Fuels,
AGH University of Science and Technology Krakow, al.a.Mickiewicza 30,
30-059 Kraków, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_45

1 Introduction

The operating conditions of compression-ignition engines and the design of modern High Pressure Common Rail fuel injection (*HPCR*) systems, high temperature, high pressure, small diameter of fuel injector openings impose the use of fuels with high thermal and oxidation resistance, reduced content of solid impurities,, microbiological contamination resistance and, above all, efficient detergent-dispersant additives preventing the formation of IDJD (*Internal Diesel Injector Deposits*) and coking of injector tips. The introduction FAME into the biodiesel fuel oil causes the presence of sediment to intensify. Dependence of sediment formation in EGR system (*Exhaust Gas Recirculation*) and HPCR system was demonstrated [2].

The significant impact on the process is:

– physicochemical properties of fuel;
– component composition;
– thermo-oxidative resistance.

The complexity of sediment formation on the components of the compression ignition engine in this high-pressure Common Rail injection system is becoming increasingly global. Knowledge of sedimentation mechanisms and their chemical composition is still insufficient, and therefore these processes require further investigation. In order to ensure the cleanliness and efficiency of HPCR systems, diesel should meet not only the requirements of EN 590: 2013-12 but also the guidelines of injection molders presented in the 2012 Common Fuel Directive for Fuel Requirements for Diesel Injection System—Diesel Fuel Injection Equipment Manufacturers—Common Position Statement 2012 and World Fuel Charter for Diesel Category 4—fifth edition of September 2013.

2 Emission of Particulate Matter (PM)

Following factors play crucial role for optimisation of combustion process in compression-ignition engines [10]:

– Fuel qualities (viscosity, density, fractional composition, cetane number, lubricity),
– Engine structural parameters (shape of combustion chamber, inlet system, compression ratio),
– Type and parameters of fuel injection (injection pressure, injection interval, stream range, vertical angle).

The phenomena that occur at the initial stage of combustion (ignition deceleration) determine its course, effectiveness, and emission of fuel toxic ingredients. Chemical ignition deceleration, which is one of major factors of the process, is conditioned mainly on fuel properties, such as fractional composition, heat of evaporation, continuous diffusion, pressure of saturated vapour, etc. These elements are crucial for the course of diffusion and heat exchange between air and fuel, forming fuel blend, and the value of self-ignition temperature. Considering optimal course of combustion, the duration of the initial stage (ignition deceleration) should be as short as possible and shortened along with the increase of engine rotational speed. The longer ignition deceleration causes the more fuel accumulation in combustion chamber and the more sudden combustion process (explosion stage) as well as the higher peak value of combustion pressure. The best self-ignition values, characterised by the least value of self-ignition deceleration, are attributed to diesel oils—normal chain, saturated hydrocarbons (paraffins). Fuel spraying is one of the most important factors related to combustion in compression-ignition engines. It is determined by the structural parameters of combustion chamber, the features of injection system and the parameters of injection [5].

Considering optimisation of combustion, sprayed fuel should be featured by possibly identical dimensions of all drops. The higher spray level (smaller diameter of drops) and spray homogeneity cause enhancement of vaporisation and combustion of fuel. The researches for new solutions related to injectors in Common Rail high-pressure injection system contributed to implementation of piezoelectric injectors. Injector tap diameter (from 0.123 to 0.117 mm) and length (to 0.85 mm) as well as increase in fuel injection dosage in the entire range of engine operation have been changed. Improved fuel spraying, increase in the range of stream and decrease in potential fuel coking on the surface of sprayer have been obtain [4, 6]. Propagation of flame in conventional compression-ignition engine with direct injection during kinetic combustion, at 5.5° crankshaft rotation upon fuel injection (right hand side) at the moment of forming heterogeneous diffusion flame with visible section of “separation”.

The type and physicochemical properties of fuel (viscosity, density, fractional composition, cetane number, lubricity) and operational conditions of compression-ignition engine have material effect on the mechanism of deposit formation. The results of numerous researches indicate the complexity of the process of deposit formation PM which may be diverse in respect of salts of metals’ content in diesel oil, containing FAME or polymer ashless materials [1].

Necessity to limit deposit formation on Common Rail high-pressure fuel injection components has become an indicator for some researches [7, 8]. Diesel oils that have been commercially distributed may include various acidic components (non-saturated fatty acids) used as lubricating additives. That may support deposit formation due to the presence of acidic impurities and metal ions. As per corrosion inhibitors that have been applied in the form of $NaNO_2$ in refinery pipelines (fuel flow), >0.1 mg/kg content, may react with fatty acids forming sodium soaps of fatty acids [9, 11].

The dependence of sediment formation in the EGR system (Exhaust Gas Recirculation) resulting from incorrect injector operation has been demonstrated which leads to error codes in the OBD II system. As an example was used the monitoring systems of vehicles with an engine DURATORQ TDCi. Analyzing the processes of heat and mass transfer over a distance of the engine intake system, called attention to a number of simplifications in the formal description, leading to establish a temporary tolerance range of recirculation. Functional analysis system and knowledge of diagnostic procedures, using selected recording car operating parameters, is the appropriate focus in the damage location process [3]. The aim of this study was to determine the influence of diesel oil Ekodiesel Ultra with biocomponents B10 used as a modern fuel to power diesel engines on the formation of deposits in the HPCR and EGR. Analysis was performed in a certified laboratory by means of energy dispersive X-ray fluorescence and infrared spectroscopy methods. The subject of the study was the deposits formation in elements HPCR and EGR resulting from the use of diesel oil with biocomponents. The inference focused on the analysis of the content of unoxidised organic ingredients precipitated in the elements.

3 Evaluation of the Technical Condition of HPCR and EGR Components

In case of compression-ignition engines with fuel direct injection, its features determine quantity and duration of piezoelectric sprayer coking that is conditioned by fuel composition, fatty acid residue, package of additives and various solid impurities.

The range of studies included:

- Generic analysis of deposits including chemical composition;
- Technical condition assessment of piezoelectric injector HPCR (frictional centre) and EGR;
- Technical condition assessment of sprayer socket and taps (scanning microscope).

Technical condition of piezoelectric injectors in Common Rail compression-ignition engine including the type of deposits have been assessed through operational testing of vehicles powered by Ekodiesel Ultra and B10 biofuel as a mixture of 10% (V/V) FAME (Fatty Acid Methyl Esters) and 90% (V/V) ON —upon 120 thousand kilometre run.

Vehicle check-up procedures with OBDII diagnostics, for identification of reasons in case of periodical engine inefficiency, were carried out. Examples of selected operational parameters are shown in Table 1 that is related to correct *Smooth Running Control—SRC* including records for DPF regeneration state.

For the purpose of this analysis, microscopic assessment for opening alterations, as a result of deposit formation and cavitation damages, was applied. Deposit formation within opening zone of fuel outlet on sprayer (see Fig. 1). Microscopic testing that demonstrates deposit formation in injector inlet of the sprayer supplied with B10 biofuel (see Fig. 2).

Table 1 Examples of engine selected operational parameters in the course of OBD II diagnostics

Control parameter	Measured value	Standardised value
Rotational speed	830 rev/min	Range of revolutions: up to 1500 rev/min
Dosage correction	98% 106%	Allowable value 20%
Cylinder injectors 1, 2, 3, 4	114% 95%	
Differential pressure for DPF Atmospheric pressure	176 hPa 990 hPa	230 hPa 600–1080 hPa
Mass air flow rate	290 mg/cycle	300 mg/cycle
Reload pressure	92 kPa	Basic value 100 kPa
Injection dosage	6.7 mg/cycle	6.8 mg/cycle

Fig. 1 View on contaminated piezoelectric injector sprayer shown from the side of outlets upon 120 thousand kilometre operational run

4 Visualisation Testing on Fuel Injection with Piezoelectric Injectors

Visualisation testings on fuel injection were carried out with Siemens piezoelectric injectors featured by 0 and 120 thousand kilometre operational run with the application of test stand for testing pump and injectors in Common Rail injection system that has been supplemented with high-pressure pump outlay module and volumetric efficiency (see Fig. 3).

Assessment of the run of fuel injection in Common Rail system was carried out with application of Autotechnika tester that enabled simulation of injector or injector unit control, adjustment of injector opening time and frequency of switching on, including injector open impulse counting. The tester enabled injector opening time control within 200–2000 ms and each 10 ms step, injector opening frequency within 1–50 Hz and each 1 Hz step, at the number of counted impulses within 1–10,000 and each 1 step.

Geometry of fuel injection was recorded with High Speed Star 5 La Vision camera that was equipped with monochromatic CMOS converter (1024 × 1024 definition at 3000 frames per second)—(see Fig. 4).

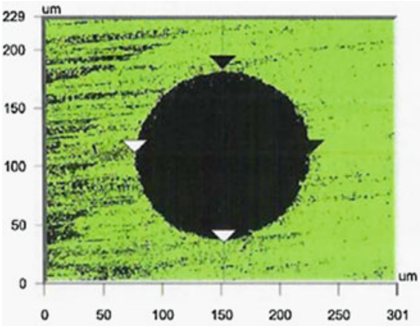
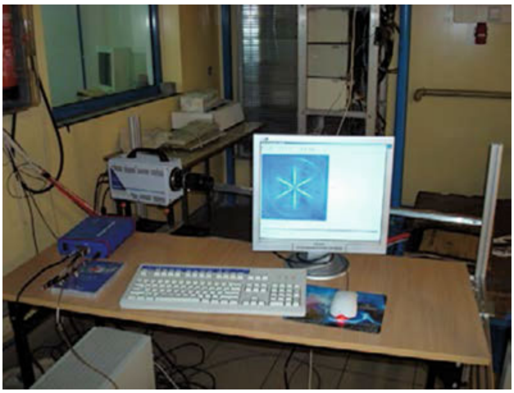


Fig. 2 Technical condition of a tap on injector sprayer that is supplied with B10 biofuel upon 120 thousand kilometre operational run recorded by camera

Fig. 3 Test stand for high-pressure pump and injectors in Common Rail fuel injection system

Fig. 4 View on test stand including High Speed Star5 camera



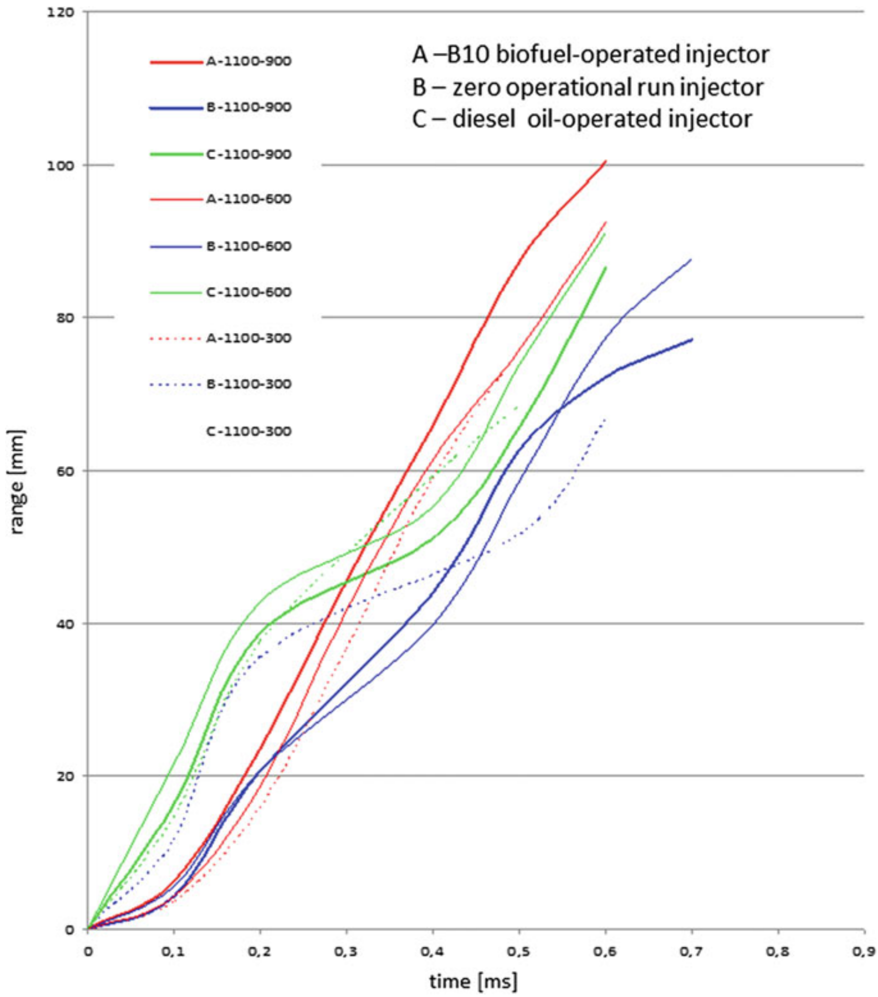


Fig. 5 Fuel stream range versus injection time at 110 MPa pressure on injectors, in the course of operational run (120 thousand kilometre), supplied with diesel oil and B10 biofuel as well as for zero operational run supplied with B10 biofuel

The scope of testing included assessment of fuel stream range versus injection time at nominal pressure for injectors supplied (120 thousand kilometre) with diesel oil and B10 biofuel as well as at zero operational run injector supplied with B10 (see Fig. 5).

5 Diagnosis of the Engine Using a Scan Tool

The area of the unification of the diagnostic principles has been significantly extended by compliance of the controllers with the software according to the OBD II system meeting both the SAEJ1830 and ISO9141-2 standards. The coexistence of the diagnostic controllers was initiated when the ISO15031-3 standard was introduced allowing communication through the CAN standard (Controller Area Network) [7]. The skill of making multi-symptom diagnostic conclusions and the knowledge of technical solutions used in the functional system of a vehicle are a basis for the formulation of correct diagnostic decisions [2]. An important step in the development of OBD was the notation and definitions of the trouble codes (SAE J2012). The pulling of the error codes from the controller is possible with a scan tool. Diagnostic scan tools (SAE J1978) and the description of the individual scan tool operating modes (SAE J1979) are also subject to standardization.

Upon detecting the diagnostic interface connection of the TEXA Navigator TXT scanner (see Fig. 6), the vehicle error codes stored in the ECU were analyzed.

Codes saved:

P0402 Exhaust gas recirculation flow,
P0476 Exhaust pressure control valve.

Analysis of parameters taken from the ECU and given by the manufacturer showed deviations from the required values.

Written error codes P0100 to P0104 may provide additional information in evaluating the performance of the EGR (abnormal recirculation). Written error codes from P0110 to P0114 are assigned to the inlet air temperature sensor. Typically problematic in identifying a fault is the effect of simultaneously storing error codes in the P0235 to P0242 turbocharger pressure circuit supplied with the error code of the recirculated exhaust gas temperature sensor from group P0544 to P0549. The problem of identifying the fault is the effect of simultaneously storing the error codes in the DPF pressure sensor group P0470 to P0474 supplied with the P0475 to P0479 exhaust valve recirculation error code.

The parameter in this group of measurement blocks is the current mass flow signal defined by the MAF sensor. An important parameter is the percent value of the PWM fill factor that confirms the setting of the stepper motor EGR valve. In the

Fig. 6 TEXA Navigator TXT scan tool

Fig. 7 The deposits on the inner surface of the EGR channel in the DURATORQ TDCi engine

analyzed system, when the valve was closed, the value of the fill factor deviated from the permissible level, above 70%, and when the valve was open, the value was also within 38%. As the mass air flow rate was blocked, they also changed in the range of 460–520 mg/cycle when the EGR valve was closed. When the EGR valve was opened the air was also within 120 mg/cycle. The mass air stream must also vary and not fall between 180 and 340 mg/cycle. An important fact to note is the course of mass flow changes, the value of which should change gradually from the moment the EGR valve is set. The prolonged expected time of change in mass air flow may indicate excessive contamination of the EGR valve actuators leading to delays in its positioning (see Fig. 7).

The analyzes indicate that the process of deteriorating performance of high pressure Common Rail fuel injection systems by the emerging deposits with the characteristics of the spray tip has a significant effect on the EGR system. In this case, replacing the EGR valve with a new one will not improve engine performance, since the error codes will be repeated again. Diagnosis of the motor with error code analysis requires an understanding of the principles of motor system co-operation to indicate the cause of engine malfunction rather than replacing the components directly indicated by the fault code number.

Recorded damage to precision pairs of injectors operating on B10 biofuel must be attributed to the presence of unsaturated fatty acids and metal ions resulting from the presence of the FAME biocomponent. The chemical composition of the fuel, and especially the biofuel additives, largely determines the tendency for sediments to form around the nozzle outlets. The presence of linoleic and linolenic acid leads to the process of oxidation and polishing of the biofuel.

6 Conclusions

1. Limitation of deposit formation on operational elements of piezoelectric injectors in Common Rail high-pressure fuel injection system supplied with mercantile diesel oil and B10 biofuel requires application of more efficient detergent-dispergate additive and, at the same time, guarantee demanded operational properties.

2. The range of fuel flow according to the injection time results in significant discrepancies in the operation of piezoelectric injectors in the HP Common Rail diesel system and B10 biofuels result from the different physicochemical properties of these products and the increased formation of B10 biofuel deposits.
3. Controlling the fuel injection process (diesel, B10) is a valuable source of information and diagnostic tests with analysis of stored fault codes to identify the cause of the engine failure unequivocally.
4. Studies indicate that the process of deteriorating the performance of high pressure Common Rail injection systems by the emerging spray tip characteristics has a significant impact on the EGR system.

References

1. Chapman, L.: Diesel soap—formation and related problems. In: National Tanks Conference. Boston, 21 Sept 2010 (2010)
2. Caprotti, R., Breakspear A: et al.: Detergency requirements of future diesel injection system, SAE Paper 2005-01-3901 (2005)
3. Cieślikowski, B.: Spectral analysis of deposits from a catalytic converter of diesel engine. Combust. Engines **3**(146), 1–6 (2011)
4. Hiroyasu, H., Arai, M.: Structures of fuel sprays in diesel engines. SAE Paper 900475 (1990). https://doi.org/10.4271/900475
5. Mazanek, A., Jakóbiec, J.: Ocena jakości paliw silnikowych w badaniach eksploatacyjnych. *Nafta–Gaz* **1**, 75–92 (2009)
6. Merker, G.P., Schwarz, Ch., Teichmann, R.: Combustion Engines Development: Mixture Formation, Combustion, Emissions and Simulation. Springer, Berlin (2012)
7. Novel-Cattin, F., Rincon, F., Trohel, O.: Evaluation method for diesel particulate trap regeneration addititives: application to fire additives. SAE Paper 2000-01-1914 (2000). https://doi.org/10.4271/2000-01-1914
8. Quigley, R., Barbour, R., Fahey, E., Arters, D., Wetzel, W., Ray, J.: A study of the internal diesel injector deposit phenomenon. In: TAE, Fuels 7th Annual Colloquium, January 2009 (2009)
9. Pehan, S., Jerman, M., et al.: Biodiesel influence tribology characteristics of a diesel engine. Fuel **88**(6), 961–1152 (2009)
10. Stanik, W., Jakóbiec, J., Wądrzyk, M.: Design factors effecting the formation of the air-fuel mixture and the process of combustion in compression ignition engines. Combust. Engines. ISSN 0138-0346-2013 R nr 3dod. CD s. 40–50
11. Stępień, Z.: Przyczyny i skutki tworzenia wewnętrznych osadów we wtryskiwaczach silnikowych układów wysokociśnieniowego wtrysku paliwa. Nafta-Gaz **3**, 256–262 (2013)

An Analysis of Municipal Waste Management in a Selected Urban Municipality on the Basis of Selectively Collection

Grzegorz Przydatek, Danuta Kamińska and Kinga Kostrzewa

Abstract The qualitative and quantitative analysis of waste from groups 15, 17, and 20 covering 10 types of the waste collected in the years 2014–2015 in the city with a population of more than 50,000 people, showed a significant increase of their mass by 415.55 Mg, despite a slight increase in the number of inhabitants. Seasonal variation in the amount of waste collected, with particular regard to the spring season, occurred during the analysed period. The highest (48%) share of waste collection was classified in group 15, and when broken down into predominant types the highest (34%) was glass packaging waste. Likewise, the highest achieved values for the daily collection rate of 0.038 kg per capita^{-1}, and the annual collection rate of 13.9 kg per capita^{-1} were related to glass packaging waste and showed a general increase. A low, 6% share of bulk waste was characterised by a significant value of standard deviation. The statistical analysis of the study results confirmed a high positive correlation showing the increase of waste most often classified to group 17. This increase of waste in the analysed area of the city has confirmed the gradual effectiveness of the implemented system solutions in the waste management.

Keywords Waste management · Municipal waste · Segregation

1 Introduction

The Municipal Solid Waste (MSW) Management System poses a serious challenge for both developed and developing countries due to the environmental risks associated with waste and public health [1]. Municipal waste is any waste produced mainly in households, and amounts to more than two thirds of their waste stream [2]. The main sources of MSW are human households and infrastructure (industrial,

G. Przydatek (✉) · D. Kamińska · K. Kostrzewa
Technical Institute State University of Applied Sciences in Nowy Sącz,
Zamenhofa 1a Street, 33-300 Nowy Sącz, Poland
e-mail: gprzydatek@pwsz-ns.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_46

educational, trading, etc.). The current changes in waste management under the act of 13th September 1996 on the maintenance of cleanliness and order in municipalities [3], appointed municipalities as the owners of their waste. Such a solution should help to increase the amount of waste recovered according to the hierarchy of proceedings while reducing the waste going to the landfill site. The need to reduce the amount of waste produced and to increase the levels of their recovery requires selective collection to be carried out in municipalities, which should include the transfer of basic fractions such as paper, metal, glass, and plastics, composite packaging, and biodegradable waste [4]. The main responsibility for implementing and evaluating this policy is usually ascribed to local authorities [5]. An important verification factor of the effectiveness of the implemented changes is the amount of waste generated daily and its annual accumulation, with particular attention being paid to municipalities with a population exceeding 50,000 people. A very important aspect in waste management is monitoring, as unreasonable resource management may contribute to excessive waste [6, 7].

2 Purpose of the Study and Research Methodology

This paper is based on a qualitative and quantitative analysis of municipal waste collected selectively throughout a month in a city with a population of over 50,000 people. The data on the basis of a questionnaire was provided by the City of Nowy Sącz and concerned waste classified to the following groups; 15—packaging waste; sorbents, wiping cloths, filter materials, and protective clothing not included in other groups, 17—waste from construction, repair, and demolition works of buildings and road infrastructure, and 20—municipal waste including selective fractions, taking into account 10 types [8].

The average number of data for particular types of waste in the analysed period was 21. The work identified the per capita daily and annual accumulation rates, taking into account the number of registered citizens. The results of the study were statistically analysed using Statistica 12 software (StatSoft Polska, StatSoft, Inc. USA) to determine arithmetic mean, standard deviation, minimum and maximum. In addition, for the identified groups of waste, the relationship between the variables tested was determined on the basis of Spearman's rank correlation coefficient. The research results obtained are presented in tabular, graphical and descriptive form.

The aim of the study was qualitative and quantitative analysis of selectively collected waste in the area of Nowy Sącz in the years 2014–2015 in the context of evaluating of the waste management.

3 Characteristics of Waste Management

The city of Nowy Sącz is the third largest in Lesser Poland Voivodeship located in its southern part, in terms of waste reception has been divided into 37 areas. Selective collection of municipal waste in this area was carried out by three waste disposal companies with the following frequencies:

- paper, metal, plastics, glass—at least once a month,
- biodegradable waste—at least twice a month,
- bulk waste—twice a year by leaving waste for reception on specific dates,
- construction and demolition waste classified as municipal—transfer after an individual application.

Selectively collected waste such as paper, metal, plastics, glass, as well as biodegradable waste are collected in coloured plastic bags with a capacity of 120 dm^3.

4 Result Analysis

The number of residents in the years 2014–2015 has slightly increased by 50 people (Table 1). In 2014, the largest amount of waste was collected selectively in October at a level of 358.47 Mg, while in February the amount was the lowest of 109.32 Mg. This year, an increase of 0.23 Mg has been seen. In the next year, the highest result of 465.69 Mg was reached in April, and the lowest was recorded at 151.99 Mg in March. In total, in the years 2014–2015, there was an increase in the amount of selectively collected waste by 415.55 Mg (Fig. 1).

Waste subject to analysis was classified into 3 groups and 10 types [8];

- 150101—Paper and cardboard packaging, 150107—Glass packaging,
- 170101—Concrete waste and concrete rubble from demolition and repair works,
- 170107—Mixed concrete waste, brick rubble, ceramic waste and equipment waste other than those mentioned in 17 01 06, 170904—Mixed waste from construction, repair, and demolition works other than those mentioned in 17 09 01, 17 09 02 and 17 09 03,
- 200139—Plastics, 200307—Bulk waste, 200101—Paper and cardboard,
- 200102—Glass, 200201—Biodegradable waste.

The lowest percentage had waste classified as group 17 (23%), while the highest (48%) was classified as group 15. The highest percentage of waste according to the

Table 1 Number of inhabitants of the city of Nowy Sącz in years 2014–2015

Year	Number of inhabitants
2014	83,853
2015	83,903

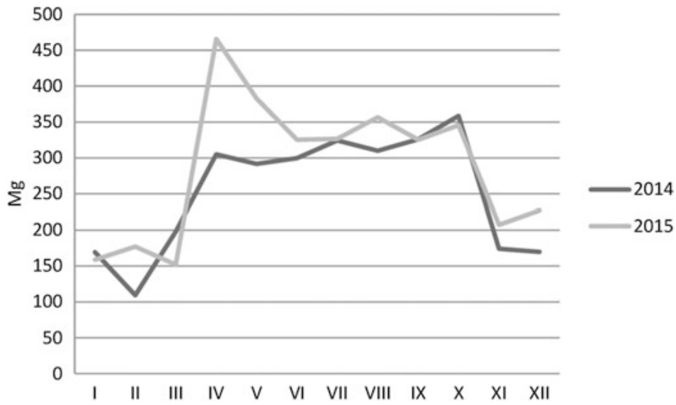


Fig. 1 The amount of selectively collected municipal waste in particular months

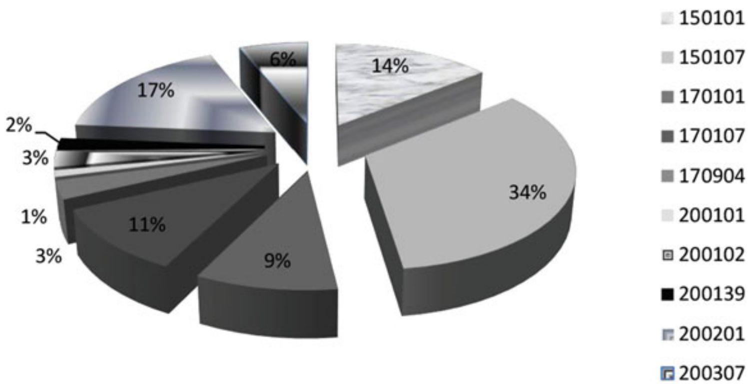


Fig. 2 Average fraction of selectively collected waste by type from 2014 to 2015

type was on waste code 150107 (34%) and the smallest waste code was 200101 (1%). The highest percentage of waste from group 17 was code 170107 (11%), and in group 20 of code 200201 (17%) (Fig. 2).

In the years 2014–2015 the highest average amount 151.77 Mg of selectively collected waste by month was related to the waste of code 200307 (in April), and the smallest amount one was 1.38 Mg of code 150107 (in May) (Fig. 3).

The daily rate of waste accumulation per capita in the analysed period ranged from 0.001 kg (code 200101) to 0.038 kg (code 150107), with 0.01 on average (Fig. 4). The highest value was reported in 2015, while the lowest value was observed twice in two separate years. The daily amount of packaging waste per capita ranged from 0.048 to 0.056 kg, and showed an increase of 0.008 kg, and in the case of construction waste, the ratio was within the range of 0.022 to 0.024 kg, and showed a slight increase of 0.002 kg.

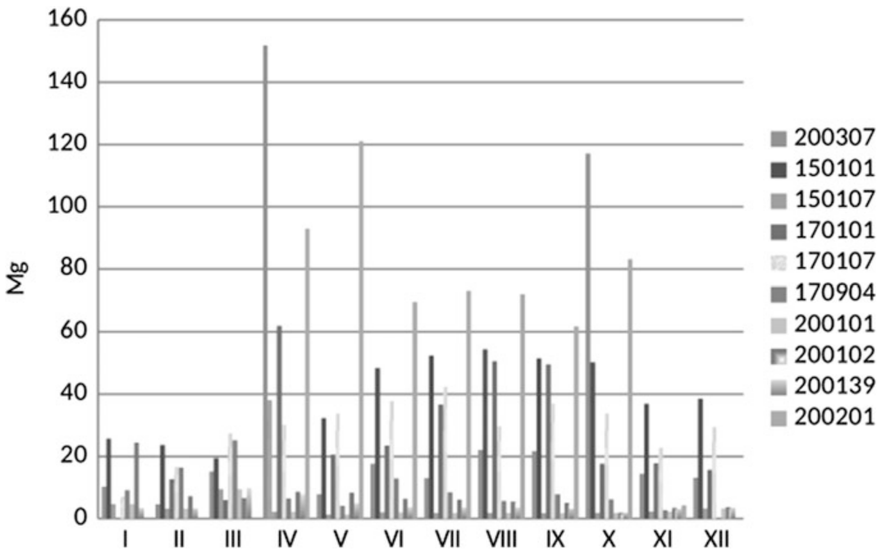


Fig. 3 Average amount of selectively collected municipal waste by type in each month

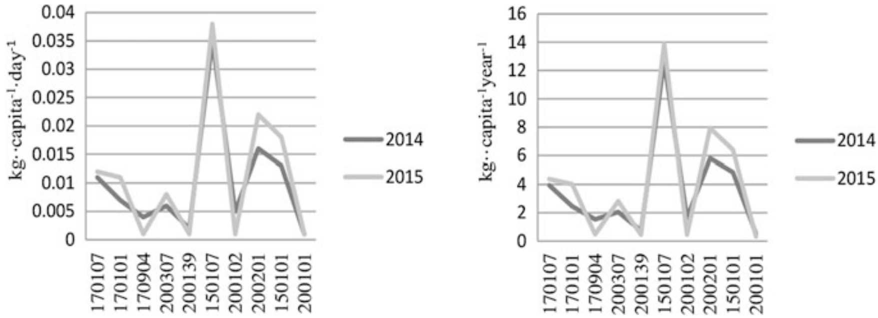


Fig. 4 Value of accumulation rate of selectively collected waste in Nowy Sącz per capita **a** per day **b** per year

The analysis of the annual mass accumulation rate per capita confirmed similarly the highest value of 13.9 kg (code 150107) and the lowest value of 0.32 kg (code 200101) with an average of 3.87 (Fig. 4). The volume of packaging waste per capita ranged from 17.47 to 20.30 kg per year^{-1}, and showed an increase of 2.83 kg. Furthermore, the amount of construction waste per capita in particular years ranged from 7.95 to 8.88 kg, which confirmed an increase of 0.93 kg.

In general the smallest amount of collected waste reported was for code 200101 (0.53), and the largest for code 150107 (111.29). The average amount of waste collected in group 15 varied from 3.05 (code 200101) to 92.59 Mg (code 150107) with a standard deviation from 13.57 (code 150107) to 15.86 (code 150101).

Table 2 Range, average values, and standard deviation by waste types

Waste type	Range	Average	Standard deviation
[Mg]			
150101	3.28–60.24	39.30	±15.86
150107	49.37–111.29	92.59	±13.57
170107	1.80–46.54	29.11	±11.48
170101	5.94–78.66	28.63	±19.41
170904	2.70–25.20	7.58	±6.50
200307	1.26–90.89	17.03	±24.50
200139	1.97–16.58	4.44	±3.45
200102	1.98–44.76	7.37	±8.79
200201	4.29–147.98	76.80	±34.05
200101	0.53–17.19	3.05	±3.30

Table 3 The correlation between variables of waste types

		Correlation		
Waste type	170107	170904	200102	150101
170904	−0.559740	–	–	–
200139	–	0.551361	0.861306	−0.536048
150107	0.507826	–	–	–
150101	0.566957	–	–	–

In group 17, the average value was from 7.58 (code 170904) to 29.11 Mg (code 170107) and the standard deviation within 6.5 (code 170904)—19.41 (code 170101). In group 20 the average was within the range of 3.05 (code 200201)—76.8 Mg (code 200201), while the standard deviation from 3.3 (code 200101)—34.05 (code 200201) (Table 2).

Based on the statistical analysis of the results of the study, a positive correlation was found between the waste codes 170107–150107 (r = 0.507826, $p < 0.05$), 170107–150101 (r = 0.566957, $p < 0.05$), 170904–200139 and (r = 0.551361, $p < 0.05$), 200102–200139 (r = 0.861306, $p < 0.05$). The negative correlation was found between waste codes 170107–170904 (r = −0.559740, $p < 0.05$) and 150101–200139 (r = −0.536048, $p < 0.05$) (Table 3).

5 Discussion

With the increase in the number of residents, the amount of waste collected selectively has also risen. A similar trend of population growth has been demonstrated by Taiwo [9].

The largest amount of waste was observed in April and the lowest in February, which confirmed seasonal variability [10]. The amount and morphological composition of waste is usually influenced by the level of income, the size of households, and their age structure [11]. The highest average amount of selectively collected waste occurred in May and included biodegradable waste. Similarly Zana et al. [12], observed in May the largest amount of municipal waste in comparison to the remaining months. The demonstrated increase in the amount of selectively collected waste by 415.55 Mg confirmed the improvement behind the implementation of systemic assumptions in waste management. Mandyl et al. [13] have shown that waste management efficiency can be the result of process optimisation, which affects the efficiency of the processes, and hence the amount of waste collected.

The most significant components of the morphological composition of selectively collected waste were: glass waste (34%), biodegradable waste (17%), and paper and cardboard packaging waste (14%). Salau et al. [14] have also showed a significant share of biodegradable waste and paper and cardboard waste. Other researchers [15] have confirmed in their studies a slightly lower share of glass waste and paper and cardboard waste. A considerable share of 11% among the waste classified to group 17 was mixed concrete and debris waste, which included concrete, reinforcement, bricks, and blocks [16]. A similar percentage of this type of waste was attained by Ioana et al. [17]. The amount of packaging waste per capita in the analysed years increased by 0.008 kg per day^{-1}. Some researchers [18] in Asian countries considered the increase in waste per capita in the range 0.3–1.0 kg per day^{-1} as significant. The rate of mass accumulation of selectively collected waste on the analysed area per year per capita increased by 2.83 kg. The largest amount of collected packaging waste per capita was 20.30 kg per year^{-1}. This result was similar to the one of 28 kg per year^{-1} per capita reported by Dahlén et al. [19]. Getahun et al. [20] connected the upsurge in this rate to the increase of members in families. The increase in the amount of waste from group 17 was also found on the basis of the analysed rates, which increased respectively per capita by 0.002 kg per day^{-1} and 0.93 kg per year^{-1}. Overall, over the analysed years, you can see an increase in the rates, with the exception of waste with codes 170904, 200139, 200101 and 200102. At the same time the highest values of the analyzed rates of waste accumulation both in the daily and annual terms occurred in the second studied year. In the case of MSW per capita in Nowy Sącz, the increase over a two-year period amounted to 74 kg [21], and confirmed the dominance of the waste collected non-selectively.

The smallest amount of waste—paper and cardboard (0.53 Mg), and the largest glass packaging (111.29 Mg), showed a significant difference between the quantities of selectively collected waste. Likewise the smallest dispersion confirmed value of paper and paperboard results (the lowest standard deviation of 3.30), while the largest was the dispersion of biodegradable waste (the highest standard deviation of 34.05). One of the highest values of the standard deviation was 24.50, which confirmed a low concentration of average results for bulk waste with a low, 6%. The lower percentage of these waste in Hong Kong in municipal waste streams was presented by Chung et al. [22]. In general, in the area of the examined municipality, there has been an increase in the amount of collected bulk waste, which corresponds to a worldwide trend [23]. Another lower value of deviation (13.57) showed a greater concentration around the average with over 30% of glass packaging waste. Based on a statistical analysis of the results of the study, there was a high positive correlation between the seven types of waste, with a significant percentage of group 17. This confirms the existence of a statistically significant correlation between the amount of waste collected in groups 15 and 17, related to the increase in their quantity. Domingo and Luo [24] also confirmed such a spike which included waste from group 17.

6 Conclusions

On the basis of the qualitative and quantitative analysis of waste generated in the city in 2014–2015, the following conclusions can be drawn:

- With a slight increase in the number of residents, the amount of selectively collected waste increased by 415.55 Mg.
- The most often selectively collected waste belonged to 10 types from groups 15, 17, and 20.
- The largest amount of waste collected selectively was reached in the spring and the smallest amount was reached in the winter, which showed seasonal variability.
- The increase in mass of selectively collected waste included five types of waste, while the decline encompassed the four ones.
- The highest general percentage of waste outstood in group 15 (48%), and in terms of types, the same was true for glass packaging waste (34%).
- The highest rates of waste accumulation per capita differ both in the daily volume of 0.038 kg, as well as in the annual one (13.9 kg), and were achieved with a significant share of glass packaging waste.
- Glass packaging waste from group 15 distinguishes the highest arithmetic mean and the standard deviation of the highest value is characterized by biodegradable waste from group 20.
- Significant value of standard deviation for bulk waste pertained at a low 6% share.
- A high positive correlation was observed between the variables with a significant participation of waste from group 17 and the negative correlation was found only in two cases.
- The increase in the amount of selectively collected waste in the city confirms the gradual effectiveness of the implementation of systemic assumptions in waste management.

Acknowledgements The authors of the paper would like to thank the City of Nowy Sącz for sending on the necessary materials and the State University of Applied Sciences in Nowy Sącz for financial support which enabled the study to be conducted.

References

1. Hannan, M.A, Abdulla Al Mamun, M., Hussain, A. Basri, H., Begum, R.A.: A review on technologies and their usage in solid waste monitoring and management systems: issues and challenges. Waste Manag. **43**, 509–523 (2015)
2. OECD. Sector case studies: household energy and water consumption and waste generation: trends, environmental impacts and policy responses. (ENV/EPOC/WPNEP(2001)15/FINAL). Organisation for Economic Cooperation and Development Environment Directorate 1999–2001 Programme on Sustainable Development. Paris, France, 7–56 (2001)
3. Act of 13th September 1996 on the maintenance of cleanliness and order in municipalities (Journal of Laws of 2016, Item 250 with later amendments) (in Polish)
4. Przydatek, G.: A comparative analysis of municipal waste management systems. Pol. J. Environ. Stud. **25**(5), 2107–2112 (2016)
5. Callan, S.J., Thomas, J.M.: The impact of state and local policies on the recycling effort. East. Econ. J. **23**(4), 411–423 (1997)
6. Johansson, O.M.: The effect of dynamic scheduling and routing in a solid waste management system. Waste Manag. **26**(8), 875–885 (2006)
7. Faccio, M., Persona, A., Zanin, G.: Waste collection multi objective model with real time traceability data. Waste Manag **31**(12), 2391–2405 (2011)
8. Ordinance of the Minister of the Environment of 9th December 2014 on the waste catalogue (Journal of Laws of 2014, Item 1923) (in Polish)
9. Taiwo, A.A.: Waste management towards sustainable development in Nigeria: a case study of Lagos state. Int. NGO J. **4**, 173–179 (2009)
10. Tałałaj, I.A., Walery, M.: The effect of gender and age structure on municipal waste generation in Poland. Waste Manag. **40**, 3–8 (2015)
11. Al-Momani, H.: Solid waste management: sampling, analysis and assessment of household waste in the city of Amman. Int. J. Environ. Health Res. **4**, 208–222 (1994)
12. Zana, C.D., Fernandes, F., Gasparino, J.C.: Solid construction waste management in large civil construction companies through use of specific software—case study. Acta Scientiarum Technol. **39**(2), 169–176 (2017)
13. Mandl, U., Direx, A., Iskovitz, F. The effectiveness and efficiency of public spending economic paper. 301. Economic Commission Brussels; Directorate General Economic and Monetary Affairs, ISBN 978-92-79-08226-9, 1–34 (2008)
14. Salau, O., Osho, G.S., Salau, M.: Urban sustainability and the economic impact of implementing a structured waste management system: a comparative analysis of municipal waste management. Practices Developing Countries. Int. J. Reg. Dev. **4**(1), 1–13 (2017)
15. Amber, D.M., Kuller, N., Gukop, N.: Municipal solid waste generation. Characteristics and energy potential of solid waste. Asian J. Eng. Sci. Technol. **2**(2), 84–88 (2012)
16. Hung, F.C., Kamaludin, N.S.: Professionals views on material wastage level and causes of construction waste generation in Malaysia. Malays. Constr. Res. J. **21**(1), 33–54 (2017)
17. Ioana, A., Istrate, F.E., Buzatu, M., Petrescu, M.I., Semenescu, A., Sohaciu, M.: Analysis of collecting and recycling of somewaste categories in Romania U.P.B. Sci. Bull., Series B, **78** (2), 203–212 (2016)
18. Glawe, U., Visvanathan, C., Alamgir, M. Solid waste management in least developed Asian countries—a comparative analysis, 1–29 (2014), www.researchegate.net. Accessed 12 June 2017

19. Dahlén, L., Vukicevic, S., Meijer, J.E., Lagerkvist, A.: Comparison of different collection systems for sorted household waste in Sweden. Waste Manag. **27**, 1298–1305 (2007)
20. Getahun, T., Megistie, E., Haddis, A., Wasie, F., Alemayehu, E., Dadi, D., Van Gerven, T., Van der Bruggen, B.: Municipal solid waste generation in growing urban areas in Africa: current practices and relation to socioeconomic factors in Jimma., Ethiopia, Environmental Monitoring. Assessment **184**(10), 6337–6345 (2011)
21. CSO http://www.bdl.stat.gov.pl. Last accessed 17 June 2017
22. Chung, S.S., Winifred Lau, K.Y., Zhang, C.: Measuring bulky waste arisings in Hong Kong. Waste Manag. **30**(5), 737–743 (2010)
23. Alexander, C., Curran, A., Smaje, C., Williams, I.: Evaluation of bulky waste and reuse schemes in England. Waste Res. Manag., 141–149 (2009)
24. Domingo, N., Luo, H.: Canterbury earthquake construction and demolition waste management: issues and improvement suggestions. Int. J. Disaster Risk Reduction **22**, 130–138 (2017)

Determination of Methyl Mirystate Content in Biofuels Using NIR Spectroscopy

Damian Marcinkowski, Mirosław Czechlowski, Weronika Gracz, Krystian Butlewski and Wojciech Golimowski

Abstract Liquid biofuels of the second generation can be considered fuels produced from non-edible raw materials, i.e. fried oils and animal fats. At the same time, recognizing biofuels of such origin as fully valued requires that their physicochemical properties be similar to traditional diesel. Due to the limited supply of non-edible fats and dispersed sources of their production, the production of biofuels on an industrial scale is economically unjustified. The good thing is local production. For this reason, cheap, easy to use biofuel quality assessment methods for small production sites should be developed. The objective of this study is to construct calibration models with the least squares regression (PLS) method adopted for the prediction of the content of methyl myristate (concentration from 0 to 5%) in rapeseed oil methyl ester (RME) on the basis of the obtained absorption spectra within near infrared range. The mean-squared error of the predictor that equals to 0.05% will be used to apply the developed calibration models to assess the quality of biofuels according to the standard PN-EN 14214.

Keywords Rapeseed oil · Biofuel · NIR spectroscopy · Calibration model
Animal fats

1 Introduction

Due to diminishing reservoirs of crude oil and a dramatic increase in the society's energy needs over the last few years, the growing importance of liquid fuels have been observed [1–3]. The application of traditional non-renewable energy sources, i.e. crude oil, natural gas or hard coal, degrades the environment and emits the excessive amount of carbon dioxide and other greenhouse gases into the

D. Marcinkowski (✉) · W. Gracz · K. Butlewski · W. Golimowski
Institute of Technology and Life Sciences, Biskupińska 67, 60-463 Poznań, Poland
e-mail: d.marcinkowski@itp.edu.pl

M. Czechlowski
Poznań University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_47

atmosphere [4]. The guidelines of the European Union on renewable energy sources suggest the necessity of increasing a share of biocomponents in the fuel industry and of limiting a share of biocomponents made from food raw materials [5]. The second-generation of liquid biofuels may be produced from waste products of different origins, i.e. used frying oils or animal fats [6]. Biodiesel refers to both pure fatty acid methyl esters (FAME) or fatty acid ethyl esters (FAEE) and mixtures of fuel and diesel fuel in order to obtain fuel that improves conditions of the engine operation [7]. The biodiesel quality control is a significant issue as the characteristics of biodiesel determine the performance and reliability of the diesel engine [6]. The European quality standard EN 14214 provides for thresholds of 25 biofuel quality parameters that need to be observed by users of motor vehicles. Since various research methods need to be applied, their analysis is time consuming and expensive [8]. Therefore, there are constantly sought newer analytic methods to shorten the analysis time and to reduce costs of standard analyses while keeping a correct result. This issue is significantly essential for biofuel producers as a product's physicochemical features are strictly affected by a kind and quality of the raw material applied [9, 10].

At present, the commonly applied diagnostic methods apply high-performance liquid chromatography (HPLC) or gas chromatography (GC). Freedman [11] was a pioneer of the method for monitoring the transesterification reaction with the use of the thin layer chromatography technique. Schale devised methods for analysing biodiesel deriving from various kinds of oils with the application of the gas chromatography technique coupled with the mass spectrometry (GC-MS) [12]. Monteiro [13] determined the content of α-linoleic acid by using the gas chromatograph fitted with a flame ionization detector (FID-GC) [14]. He also described the application of the fluid chromatograph fitted with a light dispersion detector by evaporation (HPLC–ELSD) to determine the content of water and α-linoleic acid.

The alternative for chromatographic methods is analyses based on the near-infrared spectroscopy (NIR). The near-infrared spectroscopy may monitor the composition of diesel fuel mixed with biofuels [15, 16] and of individual methyl esters of fatty acids in biodiesel, as well as it may be used to mark water contained in biofuel [17, 18]. By using near-infrared spectra Veras applied the SIMCA (Soft Independent Modelling of Class Analogies) classification to classify 108 samples of biofuels into groups of raw materials used to produce them. Felizardo [19] developed calibration models that enable determining the content of water and methanol in biofuel according to the near infrared spectra. His idea was based on the fact that in the spectrum the hydroxyl group in water has a wide band at 5200 cm^{-1}, whereas methanol causes a broad peak at 4885–4480 cm^{-1} [19]. Knoethe [20] determined that soya bean oil and biodiesel could be distinguished at 4430–4425 cm^{-1} and at 6005 cm^{-1} in the NIR spectra.

The objective of this study is to construct calibration models with the least squares regression (PLS) method adopted for the prediction of the content of methyl myristate (concentration from 0 to 5%) in rapeseed oil methyl ester (RME) on the basis of the obtained absorption spectra within near infrared range. The mean-squared error of the predictor that equals to 0.05% will be used to apply the

Table 1 The physicochemical parameters of rapeseed oils used in the experiment

Parameters	Units	Rapeseed oil
Acid value	mgKOH g^{-1}	–
Density (15 °C)	kg m^3	918
Kinematic viscosity (40 °C)	mm^2 s	35.6
Flash-point	°C	236
Calorific value	kJ kg^{-1}	38,763

Table 2 Profile of fatty acid by gas chromatography

Fatty acids [%]		Rapeseed oil
Saturated fatty acids	16:0	4.3
	18:0	1.6
Monosaturated fatty acids	18:1	61.8
Polyunsaturated fatty acids	18:2	21.4
	18:3	8.6

developed calibration models to assess the quality of biofuels according to the standard PN-EN 14214.

2 Experimental

2.1 Materials

Unrefined rapeseed oil was used as supplied from Bastik (Poland) without further purification. Potassium hydroxide ($\geq$90%), methyl myristate and methanol were purchased from Aldrich. Reagents were used in the esterification reaction without prior purification. The physicochemical parameters of rapeseed oil were shown in Table 1 and profile of fatty acid was shown in Table 2.

2.2 Methods

2.2.1 Rapeseed Oil Methyl Esters (RME) Preparation

The reactor was charged the amount of rapeseed oil to obtain a desired oil/methanol ratio (1:6), then placed in constant-temperature bath with its equipment and heated (35 °C). The catalyst (1.7% w/w of potassium hydroxide, KOH; by weight of rapeseed oil) was completely dissolved in the methanol under stirring, and then the solution was added to the reactor. The time of the reaction began as soon as the potassium hydroxide/methanol solution was added and continued for 1 h. After the reaction, mixture was transferred to separatory funnel, allowing the glycerol to separate by sedimentation for 24 h. Glycerol layer was removed and the excess of methanol was removed by evaporation at 80 °C. A methyl ester was washed twice with a phosphoric acid water solution (3% v/v) and brine until a clear phase (methyl ester) was obtained.

2.2.2 NIR Spectroscopy

The near infrared absorbance spectra were obtained by transmission method with tec5 AgroSpec spectrophotometer equipped with two probes. The probe RP-7 generates the light beam penetrating the tested sample. Probe A40 was located 50 mm below the sample and collecting light passing through the sample. For recording spectra tec5 MultiSpec Pro 3.6 software were used. Absorbance spectra were recorded in the wavelength range 400–2170 nm in the interpolated resolution of 2 nm. For each sample spectra collection was repeated 20 times and averaged.

Individual samples of the mixture were obtained by dosing methyl myristate into the initial volume of methyl esters of 1 dm^3. At the first phase 0.5 cm^3 of methyl myristate was added to obtain samples with a concentration from 0.05 to 1.00% (v/v). When the concentration was above 1% 2 cm^2 of methyl myristate was each time added into the solution until the concentration of 5% (v/v) was obtained. After each dose of methyl myristate, the sample was intensively stirred for 5 min and then the volume of 50 cm^3 was collected from it and placed into a measuring cuvette, and for this sample the absorption spectrum was recorded. The content of the measuring cuvette was again put into the base mixture and another dose of methyl myristate was added. Consequently, 40 absorption spectra of the mixture of biodiesel/methyl myristate with a concentration from 0.05 to 5.0% (v/v) were recorded. In addition, absorption spectra of diesel and methyl myristate themselves were obtained.

Methyl myristate and the samples for spectrophotometric analyses were measured in compliance with the standard EN ISO 8655. The calibration models were developed with the PLS (Partial Least Squares Regression) method by using the Camo Unscrambler X programme, version 10.1. The data for the model construction based on the obtained spectra. Independent variables were quantities of methyl myristate implemented into the analysed sample. The models were validated by using the cross validation available in the PLS method algorithm. The models were developed on the basis of the NIPALS algorithm. When making the calibration models the following wavelength ranges were applied:

- 400–2170 nm—the full range of the recorded spectra,
- 750–950 nm—the first range of the great diversity of the electromagnetic radiation absorption by biodiesel and methyl myristate,
- 1150–1250 nm—the second range of the great of the electromagnetic radiation absorption by biodiesel and methyl myristate,
- 1740–1850 nm—the range of the largest diversity of the electromagnetic radiation absorption by biodiesel and methyl myristate.

3 Results and Discussion

3.1 NIR Spectroscopy Spectra Analysis

By analysing the absorption spectra of pure methyl myristate (Fig. 1) made within the range of 400–2170 nm, it can be said that both substances absorb electromagnetic radiation that has similar wavelengths. For the radiation ranged from 400 to 1100 nm the absorption value equals to zero. The following absorption spectra for pure methyl myristate show bands with peaks at the following wavelengths: 1198, 1397, 1421, 1689, 1752, 1932 and 2130 nm.

Figure 2 shows the absorption spectra of pure biodiesel, methyl myristate and their mixtures, in which the concentration of methyl myristate in biodiesel was gradually increased (0–5%). An increase in the concentration of methyl myristate leads to a significant increase in the absorption value. The enlarged figure shows the area of absorption spectra ranged from 1150 to 1250 nm that proves the precision of the analyses, i.e. those bands do not overlap each other and keep similar distances from each other within the entire length of the graph.

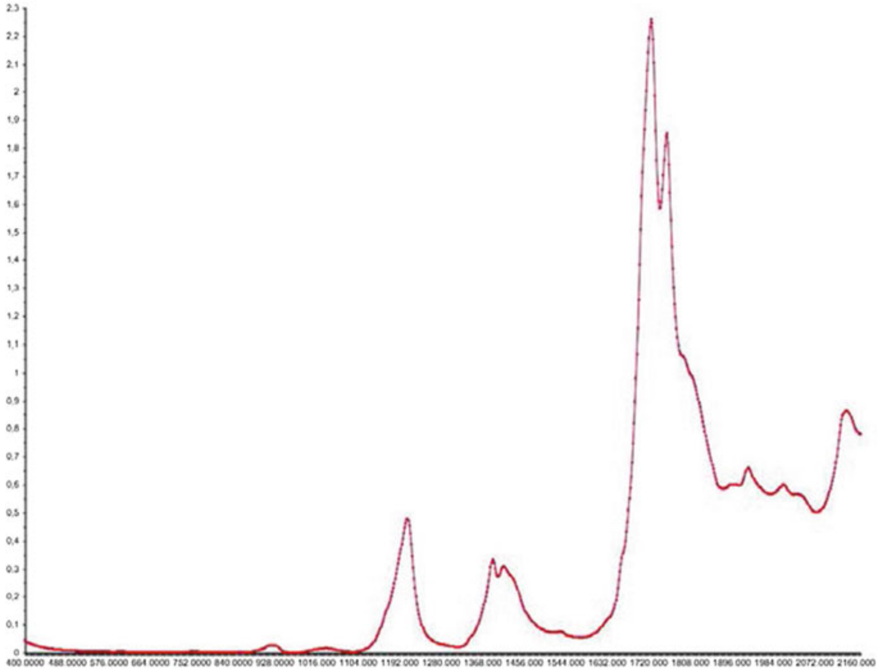


Fig. 1 Absorption spectrum of methyl myristate

3.2 Calibration Models

The analysis of the results set forth in Table 3 indicates that the calibration model made for the wavelength ranged from 1150 to 1250 is the most precise and its coefficient of determination (R^2C) is 0.996. The coefficient of determination for the cross validation of this model equals to 0.994. A mean-squared error of 0.123 excludes the application of this model in any further research when the concentration of methyl myristate is below 1%.

The precision of the calibration model based on the absorption spectra within the range from 1740 to 1850 nm is similar to the model made within the range from 1150 to 1250 nm, but its mean-squared error is 0.235, hence this model cannot be used in any further research.

The worst fitting is characteristic for the calibration model based on the absorption spectra ranged from 750 to 950 nm (R^2C = 0.913 and R^2V = 0.704). This model has high mean-squared errors of 0.455 for calibration and of 0.835 for predictor, hence this model is excluded from any further research.

Further research applied the calibration model developed within the wavelength range from 1150 to 1250 nm. The explanation for the variation model is set forth in Fig. 3.

Figure 3 shows a variance model of spectral data in the range of 1150–1250 nm. Based on this it is stated that the best fit of the model is for the 4-factor equation.

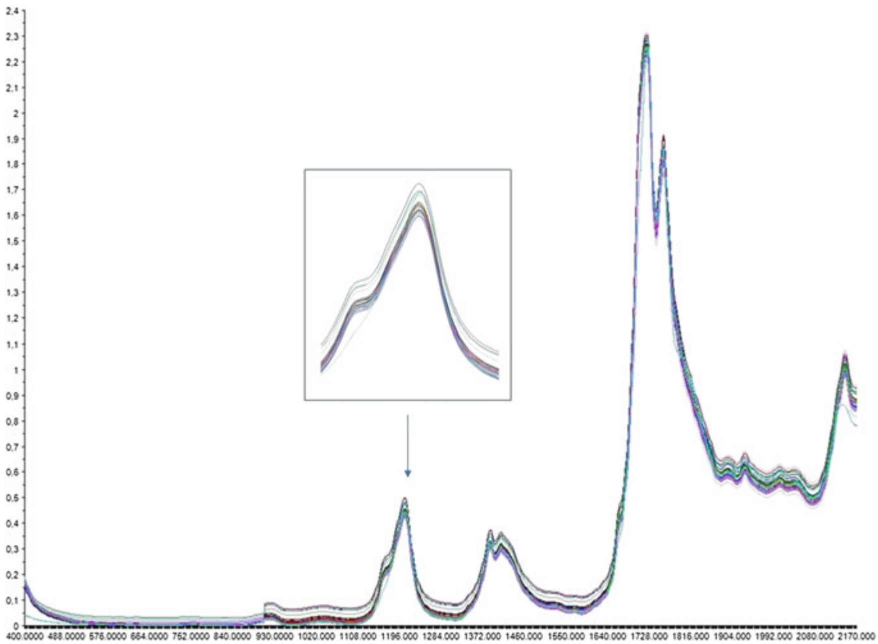


Fig. 2 Absorption spectra of ROME and methyl myristate (0–5%)

Table 3 Results of adjusting calibration models for the registered spectral data (R^2C—a coefficient of determination obtained for the calibration model; R^2V—a coefficient of determination obtained for model cross validation results; RMSEC—a mean squared error for the calibration model; RMSEV—a mean squared error for model cross validation results)

Wavelength [nm]	R^2C	R^2V	RMSEC	RMSEV
400–2170	0.992	0.973	0.138	0.263
750–950	0.913	0.704	0.455	0.847
1150–1250	0.996	0.994	0.091	0.123
1740–1850	0.989	0.977	0.161	0.235

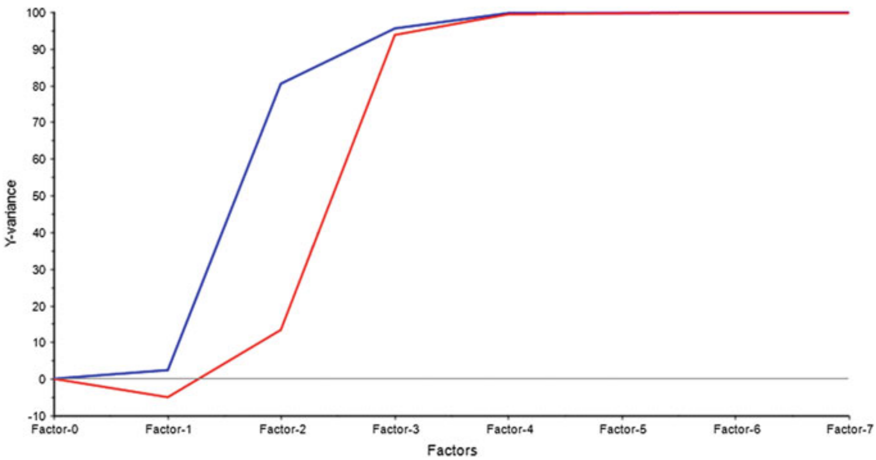


Fig. 3 Model of spectral data variation in the wavelength range 1150–1250 nm

Figure 4 shows an error in adjusting the model to the data. The prediction results have a coefficient of determination of 0.996, whereas the mean-squared error of the predictor equals to 0.09. The graph included in Fig. 4 shows a linear dependency between the prediction results and the reference data, i.e. the known concentration of methyl myristate in the identified samples. The line of the regression equation runs at an angle of almost 45°, which proves the unit value of the coefficient of the regression line inclination.

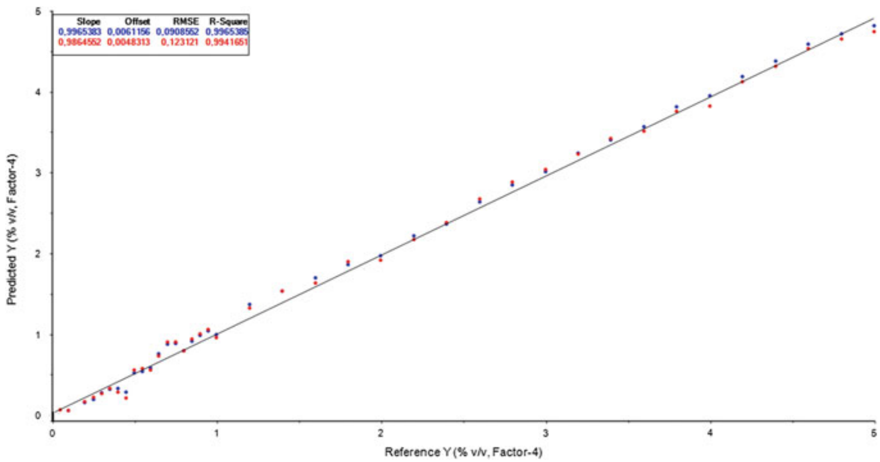


Fig. 4 Comparison of prediction results for the 1150–1250 nm spectrum range (Blue Circle: calibration set, Red circle: validation set)

4 Conclusion

The obtained results prove that the near-infrared spectroscopy may be applied to control the quality of the produced biofuels. The mathematical analysis of the spectra within the wavelength range from 1150 to 1250 nm enabled developing the calibration model that may be used to determine the content of myristic acid (range from 1 to 5%) in the second-generation of biofuels. The mean-squared error of the predictor that equals to 0.06% enables applying the calibration model according to the standard PN-EN 14214.

References

1. Abbaszaadeh, B., Ghobadian, M.R., Omidkhah, G.: Najafi. Energ. Convers. Manage. **63**, 138 (2012)
2. Shi, X., Yu, Y., He, H., Shuai, S., Wang, J., Li, R.: Fuel **84**, 1543 (2005)
3. Fazal, M.A., Haseeb, A.S.M.A., Masjuki, H.H.: Renew. Sustain. Energy Rev. **15**, 1314 (2011)
4. Atabani, A.E., Silitonga, A.S., Badruddin, I.A., Mahlia, T., Masjuki, H., Mekhilef, S.: Renew. Sustain. Energy Rev. **16**, 2070 (2012)
5. Tiwari, A.K., Kumar, A., Raheman, H.: Biomass Bioenerg. **31**, 569 (2007)
6. Golimowski, W., Berger, W.A., Pasyniuk, P., Rzeźnik, W., Czechlowski, M., Koniuszy, A.: Fuel **197**, 482 (2017)
7. Juan, J.C., Kartika, D.A., Wu, T.Y., Hin, T.-Y.Y.: Bioresour. Technol. **102**, 452 (2011)
8. Monteiroa, M.R., Ambrozin, A.R.P., Santos, M.S., Boffo, E.F., Pereira-Filho, E.R., Lião, L. M.: Talanta **78**, 660 (2009)
9. Liu, X., Piao, X., Wang, Y., Zhu, S., He, H.: Fuel **87**, 1076 (2008)

10. Sarin, R., Sharma, M., Sinharay, S., Malhotra, R.: Fuel **86**, 1365 (2007)
11. Freedman, B., Pryde, E.H., Kwolek, W.F.: J. Am. Oil Chem. Soc. **61**, 1215 (1984)
12. Schale, S.P., Le, T.M., Pierce, K.M.: Talanta **94**(94), 320–327 (2012)
13. Monteiro, M., Ambrozin, A., Liao, L., Ferreira, A.: Talanta **77**, 593 (2008)
14. Knothe, G.: J. Am. Oil Chem. Soc. **83**, 823 (2006)
15. Komorizono de Oliveira, I., de Carvalho Rocha, W.F., Poppi, R.J., Anal. Chim. Acta **642**, 217 (2009)
16. Alves, J.C.L., Poppi, R.J.: Talanta **104**, 155 (2013)
17. Bampi, M., Scheer, A.P., de Castilhos, F.: Fuel **113**, 546 (2013)
18. Veras, G., Gomes, A.A., Silva, A.C., Brito, A.L.B., Almeida, P.B.A., Medeiros, E.P.: Talanta **83**, 565 (2010)
19. Felizardo, P., Baptista, P., Uva, M., Menezes, J.C., Correia, J.N.: J. Near Infrared Spectrosc. **15**, 97 (2007)
20. Knothe, G.: J. Am. Oil Chem. Soc. **77**(5), 489 (2000)

Development of Small Agricultural Biogas Plants in Poland. The Evaluation of Technical and Economic Conditions

Edyta Wrzesińska-Jędrusiak and Łukasz Aleszczyk

Abstract This article covers the scope of preparatory work for the study of two designed biogas plants consisting of fermentation chambers. On the Polish market there are no original solutions for biogas installation dedicated to the small farms that take into account their specific characteristics. The concept of modular biogas installation has been developed in the Institute of Technology and Life Sciences, a solution in the form of two types of biogas installation for processing liquid substrates such as pig and bovine manure. The first variant, a mono-substrate reactor tank includes a filling that increases the surface area of microorganisms. The second variant was conducted under the Biostrateg 2 project "Developing innovative technologies complex utilization of waste generated during the fattening pigs" and uses a reactor, with a pump for lifting liquid which is patent protected. In order to estimate the energy efficiency of these two variants, the theoretical balance of energy needed to efficiently carry out the fermentation was calculated.

Keywords Biogas plant · Innovative technologies · Energy efficiency

1 Introduction

An agricultural biogas plant is a set of devices used to carry out methane fermentation of organic substrates produced on a farm as well as enable them to be used after the fermentation process. According to the Amendment to the Energy Law, which entered into force on 11 March 2010, agricultural biogas is defined as gaseous fuel obtained by methane fermentation of agricultural raw materials, by-products of agriculture, liquid or solid animal excrements, products Byproducts

E. Wrzesińska-Jędrusiak (✉) · Ł. Aleszczyk
Department of Renewable Energy, Institute of Technology and Life Sciences in Falenty Poznań Branch, Poznań, Poland
e-mail: e.jedrusiak@itp.edu.pl

Ł. Aleszczyk
e-mail: l.aleszczyk@itp.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_48

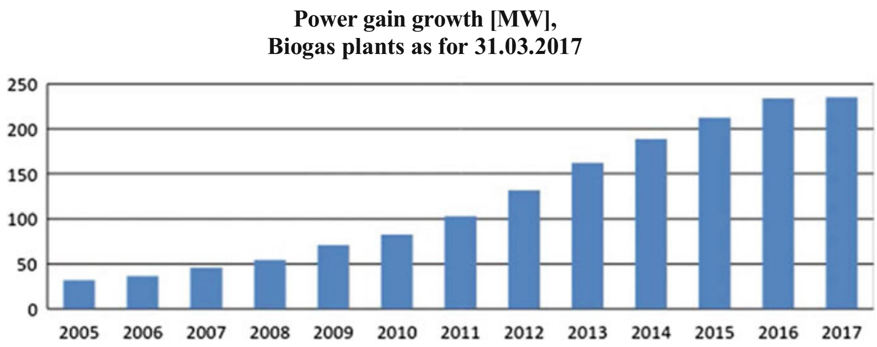


Fig. 1 Biogas plants in Poland 2005–2017, [own elaboration based on data from the Energy Regulatory Office of 31 March 2017]

or residues from the processing of products of agricultural origin or forest biomass, excluding gas derived from raw materials from sewage treatment plants and landfills.

In 2013 in July was adopted so-called "Energy Tripack", the main part of the tripack refers to the regulation of the gas market, it is also a support system for micro and small installations of RES (with a total installed capacity of up to 200 kW or a total installed capacity of no more than 600 kW). An important legislative instrument resulting from the provisions of this law is support for micro-installations (up to 40 kW of installed electrical power). Over the past 10 years, biogas has gained in importance, including agricultural biogas. Since 2005 the total installed energy in polish biogas plants increased 7 times till 2017 (Fig. 1).

In September 2014 in Poland, there were 55 agricultural biogas plants. For comparison, in 2011 there were only 22, and at the end of 2012–29 [1]. At present, according to published data of the Energy Regulatory Office of 1 January 2017 in Poland, there are 95 agricultural biogas plants with a total power of 103 MW and 206 biogas plants in other technologies with a total capacity of 130 MW. According to the National Action Plan on Renewable Energy, at the beginning of this year, nearly 280 MW of biogas plants should be used in all technologies, and by the end of this year 380 MW. The long-term perspective of the biogas sector assumes the achievement of 980 MWe installed by 2020 in biogas plants (also agricultural).

The changes in Poland's energy policy reflect the main assumptions of the European Union's energy policy, including: increasing the use of renewable energy sources (RES), reducing carbon emissions and increasing energy efficiency by 2020 (commonly known as 3 $\times$ 20), as well as full decarbonization of the energy sector up to 2050 [2–4].

According to the information of the President of the Energy Regulatory Office No. 44/2016 dated September 21, 2016 on the use of the term "installed electric power" (…). Under the concept of installed power supply, renewable energy sources shall be understood as the rated power of a power generating device (i.e. generator, photovoltaic or fuel cell) specified by the manufacturer, expressed in watts [W]. According to the Energy Regulatory Office, the installed power of a renewable energy source is not, for example, the power of a wind turbine, an internal combustion engine, a water turbine, and the power of inverters (in the case of installations using solar energy). The power installed in an installation of a renewable energy source is also not achievable power, maximum achievable power, net power, net achievable power, usable power, potent power raw power and the power of the unit (e.g. Wind turbine or hydropower or generator).

2 Efficiency of Biogas Plants

It is assumed that the biogas plant consumes about 9% of electricity produced for its own use and about 30% of its heat energy. Based on such assumptions, the annual energy and economic balance of any biogas plant can be calculated. In this work, six different biogas plants have been considered with a fermenter batch of 60 m^3 using an adhesive bed and without. The biogas plants are shown in Table 1. Moreover, the analyzed biogas plants differ in their HRT. The calculation assumes the following assumptions:

- a biogas yield of 1 t slurry of 20–35 m^3
- the working time of the cogeneration unit during the year is 8200 h
- electricity of 40%.

Table 2 shows the annual energy yield expressed in MWh.

The Ordinance of the Minister of Energy of 17 October 2016 on the reference price of electricity from renewable energy sources in 2016 and the periods of 2016 winners of the generators that won the auctions gives the maximum price in PLN that can be obtained for 1 MWh can be sold Electricity generators from renewable energy sources by auctions. Table 3 shows the electricity reference prices for biogas plants. Based on the above data, annual profits for the analyzed biogas variants were calculated. Table 4 shows the annual profit in PLN. Based on the results obtained, the net profit/gross profit/loss calculations for the analyzed biogas variants were calculated in PLN/DJP.

Economic balance of the analyzed biogas plants are presented in Figs. 2 and 3.

3 Biogas Plants for Smaller Farms

At present, there are many companies involved in the design, construction and operation of large biogas plants in the Polish agricultural biogas market. They offer ready-made projects and equipment for building objects ranging from 250 kW to several megawatts of electrical power [5]. Many large agricultural and biogas plants

Table 1 Performance of analyzed biogas plants

Parameters of biogas plants				Minimum performance				Maximum performance			
Vcz (m^3)	HRT	DJP	Yield of pig slurry (t/year)	Fermentation m^3 with 1t	Methane yield in biogas (%)	Biogas yield (m^3/year)	The resulting kW energy	Fermentation m^3 with 1t	Methane yield (%)	Methane yield in biogas (%)	The resulting kW energy
Without adhesive bed											
60	8	68	1379	20	55	34,000	7.5	35	55	59,660	14
	10	87.6	2191	20	55	43,820	9.6	35	55	76,685	18.5
	12	45.5	1160	20	55	22,750	6	35	55	39,818	11.5
With adhesive bed											
60	8	107	2684.5	20	55	53,690	11.4	35	55	93,357.5	15
	10	84	2100	20	55	42,000	10	35	55	73,500	20
	12	71.5	1788.5	20	55	35,770	7.8	35	55	62,597.5	11.8

Source Calculations of LBTBR ITP o/Poznań

Table 2 Annual net and gross energy yield in analyzed biogas plants

No.	Annual minimum gross energy yield (MWh)	Annual maximum gross energy yield (MWh)	Annual minimum net energy yield (MWh)	Annual maximum net energy yield (MWh)
1	61.5	114.8	56	104.5
2	49.2	94.3	44.8	85.8
3	78.7	151.7	71.6	138.0
4	82.0	164.0	74.6	149.2
5	93.5	123.0	85.1	111.9
6	63.9	96.8	58.2	88.1

Source Own calculations

Table 3 Reference for biogas installations acc.

No.	Biogas type	Reference price (zł/MWh)
1	Total installed electric power of no more than 1 MW using only agricultural biogas to Electricity generation	550
2	Total installed electric power of more than 1 MW, using only agricultural biogas to Electricity generation	550
3	Utilizing only biogas obtained from landfills for the generation of electricity	305
4	Utilizing only biogas extracted from sewage treatment plants for electricity generation	335
5	Utilizing solely for the production of electricity other than those specified in points 3 and 4 for biogas	340

Source Regulation of the Minister of Energy of 17 October 2016 Pos. 1765

Table 4 Annual revenue from biogas plants

No.	Annual minimum net income of PLN	Annual maximum net revenue
1	25,184.3	47,010.6
2	20,147.4	38,615.9
3	32,235.8	62,121.2
4	33,579.0	67,158.0
5	38,280.1	50,368.5
6	26,191.6	39,623.2

Source Own calculations

operating in Poland and abroad enable continuous improvement of existing technologies, methods of operation and equipment for their equipment. There is little knowledge about the construction of installations for smaller farms with area from 20 to 100 ha [6].

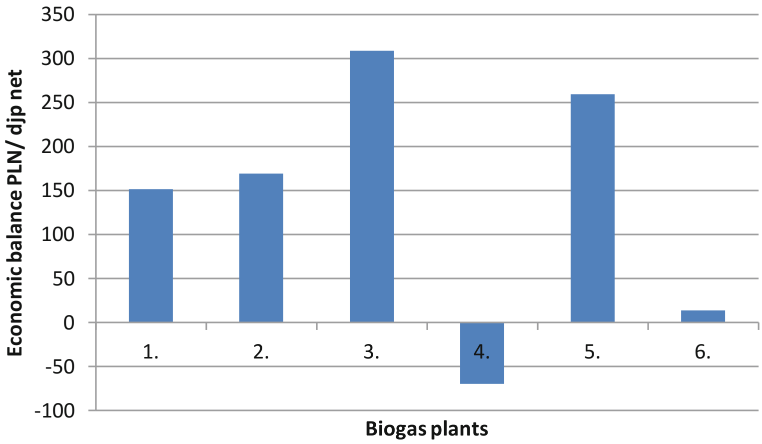


Fig. 2 Economic balance of biogas plants

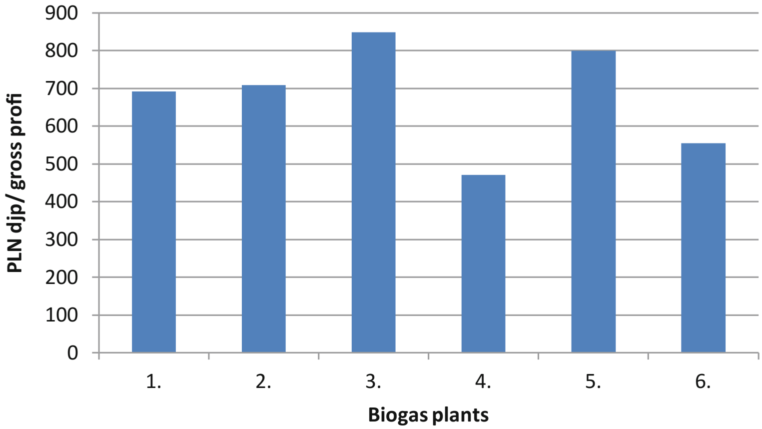


Fig. 3 Annual profit from the biogas plant

Taking into account biogas plants from the point of view of substrates for biogas production, the three groups are divided into three main groups. The first one consists of biogas plants using slurry (basic organic waste for the production of agricultural biogas). The second group is biogas based on other residues of agri-food production. And to the third group includes biogas plants, whose functioning depends on the cultivation of targeted crops, especially corn for silage [1].

Such installations in Poland are few and are mainly pilot plants. Also in other European countries, agricultural biogas plants are dominated by large installations with a capacity of more than 0.5 MWe [7].

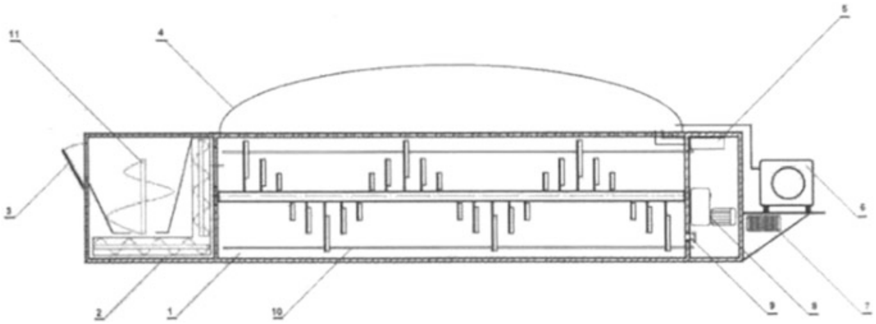


Fig. 4 Section of a single container biogas plant unit: 1—fermentation chamber, 2—dosing—reception tank, 3—lowered hatch, 4—biogas tank, 5—desulfurizing bacteria tank with oxygen applicator, 6—cogeneration unit, 7—heat exchanger, 8—paddle drive, 9—fermentation residue blow-down, 10—heating pipes, 11—mixing chamber (Kołodziejczyk, Myczko)

Because of the lack of original constructions taking into account the specifics of Polish farms, prepared for installation as repetitive installations, the Poznań branch of the Institute of Technology and Life Sciences has developed two concepts of micro biogas plants [7].

The first concept of the micro-biogas plant was developed with the company Mega sp. z.o.o. Bełżyce. It included the project and construction of a biomass processing container (Fig. 4.) for small farms. This one-chamber micro-biogas plant generates power from 2.43 to 16.76 kW, depending on the substrate at the farmer's disposal and the capacity of the biogas tank adjusted to the efficiency of the installation. The biogas plant was designed for the production of electricity and heat in the biogas combustion process, with the possibility of thermal treatment of the feedstock. The biogas plant can be used in various technological configurations as

- single micro installation,
- the main fermentation unit cooperating with post-fermenting tanks twice the capacity of the fermentation chamber.
- additional stage of hydrolysis for a larger biogas plant with a retention period depending on the type of feedstock from 4 to 10 days and associated with a tank of 250 m^3 [7].

The uniqueness of the solution introduced is the development of a modular biogas production system that is easy to transport and install on the farm [7].

For example, a container biogas plant operating in a one-stage wet fermentation system of up to 6 kW and a 30 m^3 fermentation chamber capacity assuming as a slurry substrate (d. m. 8%) and HRT 12 yields a biogas yield of 29,100 m^3/year, and an energy yield of 61,110 kWh. The power of the system is 4 kW (at 30% efficiency).

An installation concept for the disposal of livestock produced by livestock in a mono-substrate reactor that does not require the addition of other organic materials has been developed. The advantage of the proposed solution is the low demand for energy and green energy.

The installation consists of the following units:

– process tank—fermenter,
– biomass fermenter feeding system,
– post-fermentation drainage system,
– gas path layout,
– fermenter heating system,
– ONEC heating system,
– adsorber bed desorption system,
– automatic installation control system,
– Additional installation equipment.

The tank is equipped with a fermenter and its equipment enables the fermentation, control, and regulation (…). Inside the tank, there is a hybrid pump developed in ITP in Poznan for the circulation of fermented mass in the tank and auxiliary mixing of the contents of the biogas fermenter. It is mounted centrally to the axis of the system [7].

Literature

1. Chodakowska-Miszczuk Justyna Biogazownie rolnicze w rozwoju małoskalowych instalacji odnawialnych źródeł energii w Polsce, Roczniki naukowo ekonomiczne rolnictwa i rozwoju obszarów wiejskich II 102, z 1, 2015, s. 97–105
2. Dyrektywa Parlamentu Europejskiego i Rady 2009/28/WE w sprawie promowania i stosowania energii ze źródeł odnawialnych z dnia 23 kwietnia 2009 r. L. 140/16
3. Klose, F., Kofluk, M., Lehrke, S., Rubner, H.: Toward a distributed—power world. Renewables and smart girds will reshape the energy sector, The Boston Consulting Group, June 2010. Available from: http://www.bcg.com/documents/file51254.pdf [cit. 18.08.2014] (2010)
4. Ruester, S., Schwenen, S., Finger, M., Glachant, J.-M.: A post-2020 EUenergy technology policy: revisiting the Strategic Energy Technology Plan, EUI working paper RSCAS, vol. 39, European University Institute, Robert Schuman Centre for Advanced Studies, Florence School of Regulation, San Domenico di Fiesole (2013)
5. Myczko, A., Konieczny, R.: Istota biogazowni oraz procesy technologiczne i obiekty w biogazowniach. Budownictwo na obszarach wiejskich. Nauka, praktyka, perspektywy. Wyd. Politechniki Lubelskiej, Lublin (2013)

6. Hada, Ł., Myczko, R.: Prototyp kontenerowej mikrobiogazowni rolniczej. Problemy intensyfikacji produkcji zwierzęcej z uwzględnieniem ochrony środowiska i produkcji energii alternatywnej. Wyd. Instytutu Technologicznego Przyrodniczego, Falenty (2012)
7. Myczko, A., Kołodziejczyk, T., Sawiński, R., Myczko, R., Aleszczyk, L., Łaska-Zieja, B., Wałowski, G., Wrzesińska-Jędrusiak, E.: Koncepcje małych biogazowni do przerobu rolniczych pozostałości poprodukcyjnych. Aktualne problemy inżynierii biosystemów 2017, Wyd. Uniwersytetu Przyrodniczego w Poznaniu 2017s, 251–266 (2017)
8. Informacja Prezesa Urzędu Regulacji Energetyki nr 44/2016 w sprawie stosowania pojęcia mocy zainstalowanej elektrycznej. Warszawa, 21 września 2016 r.

Design and Development of a Didactic Mobile Installation with Solid Fuel Boilers and a Heat Pump

Grzegorz Pełka, Wojciech Luboń, Jarosław Kotyza, Daniel Malik and Paweł Jastrzębski

Abstract The emission of dust and pollutants from coal-fired boilers is the main source of air pollution in the Malopolska Region. This is due to the low awareness of inhabitants, particularly in suburban and rural areas, of the need for outdated heating systems and non-energy efficient houses to use considerable amounts of energy. The authorities of the region undertake activities aimed at educating and raising the awareness of the inhabitants. The AGH University of Science and Technology is a natural partner in these activities, especially in the field of education and popularization of energy efficient solutions. One of them is a mobile educational installation designed by AGH in cooperation with the boiler and heat pump producer Galmet. The construction of the installation was supported by a grant from the National Fund for Environmental Protection and Water Management. The leader of the project is the Foundation for the Support of Ecological Initiatives. The main aim of the designed installation is for didactic/ educational purposes in the field of air quality and pollution reduction connected with the utilization of coal fired boilers with various efficiency classes, according the PN-EN 303-5:2012 standard. The whole installation is in a 4-wheel trailer adapted to conduct the measurements and present the results. The installation consists of two solid fuel boilers (a boiler with an automatic fuel feeder and a boiler

G. Pełka (✉) · W. Luboń · J. Kotyza · D. Malik
Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: gpelka@geol.agh.edu.pl

W. Luboń
e-mail: lubon@agh.edu.pl

J. Kotyza
e-mail: kotyza@agh.edu.pl

D. Malik
e-mail: dmalik@geol.agh.edu.pl

P. Jastrzębski
Faculty of Management, AGH University of Science and Technology, ul. Gramatyka 10, 30-067 Kraków, Poland
e-mail: pjastrze@agh.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_49

with a manual fuel loading), heat pump, heat buffer, radiator and connection fittings (valves, pipes, circulation pumps, etc.). This allows the comparison of working conditions and pollutant emissions from each boiler. The system measures the level of pollution, analyzes exhaust gas and presents the results via a visualization system which allows mobile research to be conducted. This paper presents the methods of our research and focuses on the issue of low emissions and their impact on our environment and the inhabitants of Małopolska.

Keywords Coal-fired boilers · Mobile didactic rig · Low emission
Heat pumps

1 Introduction

According to the Central Statistical Office, solid fuels were used in 48.7% of households in Poland, with a total 14,276,000 households. In the countryside, 76.4% of the single-family houses use coal and 23.5% use it in the city [1]. Poland is currently the leader in the European market for solid fuel boilers, especially coal boilers, with a 47% market share in Europe [2]. On the other hand, persistently high levels of dust particles that are a major risk to public health are produced as a result. In Poland, the daily limit values for the airborne particles (PM10) have been persistently exceeded. The PM10 pollution in Poland is predominantly caused by low-stack emissions (emissions from sources with a height lower than 40 m) from household heating [3].

In Poland there are four notified testing laboratories, which conduct testing and the certification of solid fuel boilers according to EN 303-5:2012 standard. There are also laboratories in the universities and other scientific institutions which conduct R&D work into the construction of boilers or testing of boilers and measurements of their emissions [4–9]. Some companies offer didactic equipment on the subject of pellet boilers and heating installations. There has been, however, a lack of mobile didactic equipment with solid fuel boilers on the market to conduct lectures in the country in the field of low-stack emission reduction, the methodology of coal burning and promoting the new generation solid fuel boilers of the fifth class with an ecodesign certificate. This was the motivation to apply for a grant for the design and development of the mobile laboratory. The project was supported by the National Fund for Environmental Protection and Water Management. The Laboratory of Renewable Energy Sources and Energy Saving in Miękinia was a partner in a project called Mobilne Laboratorium "POLoNEs" (Przyczyny-Ograniczenie-Likwidacja Niskiej Emisji)—Mobile Laboratory "PoLoNEs" (causes—reduction—elimination of low stack emissions). The leader of the project is the Foundation for the Support of Ecological Initiatives from Kraków.

2 Polish Local and Central Legislation in the Case of Low-Stack Emissions

At the end of September 2016, a proposal for the regulation of the requirements for solid fuel boilers of not more than 500 kW was prepared by the Ministry of Development [10]. Following consultation, the modernized draft regulation on solid fuel boilers was presented on 17 January 2017. The project concerns boilers with power capacity below 500 kW. This regulation, similar to the Commission Regulation (EC) No 2015/1189 [11], does not only apply to boilers for domestic hot water supply, but also to steam or hot air generating boilers, cogeneration of solid fuel boilers and non-wood biomass boilers. The boiler emission limit values are defined as for class 5 according to PN-EN 303-5:2012 [12]. The project prohibits the construction of emergency grate boilers. The planned introduction of this regulation according to the draft is scheduled for 1 October 2017.

The Amendment of the Environmental Protection Law [13] of 10 September 2015 (The "anti-smog law") give the opportunity for a voivodeship to introduce restrictions or prohibitions on the operation of installations where fuels are burned to prevent adverse effects on human health or the environment. The resolution defines the limits of the scope of the ban on or the limitation of fuel combustion, and may specify types of authorized fuels and prohibited fuels. The resolution may include information on the duration of the restriction and the entities to which these restrictions apply.

On January 15, 2016, the Sejmik of the Małopolskie Voivodeship passed Resolution No. XVIII/243/16 on the introduction of restrictions on the operation of fuel combustion installations in the area of the Municipality of Kraków [14]. In this resolution, it was possible to use fuels such as natural gas (including liquefied natural gas), propane-butane, agricultural biogas or an other flammable gas and light heating oil. The restrictions relate to the combustion of fuels other than those mentioned above, in particular in boilers, fireplaces and ovens. The resolution comes into force on September 1, 2019. As a result, intensive activities, in the form of promotional campaigns and co-financing, are being carried out in the municipality of Kraków, aimed at replacing solid fuel boilers with other approved heat sources. By the year 2015, almost twenty four thousand fireplaces (boilers, stoves, fireplaces) for solid fuels were operating in Kraków [15]. In 2016, thanks to the Low Emission Reduction Program, 4,200 coal fired boilers were closed [16].

On January 23, 2017, the Małopolskie Voivodeship Sejmik adopted a resolution on the introduction of restrictions and prohibitions in the area of the Małopolskie Voivodship [17], concerning the operation of fuel combustion installations, which will apply throughout the whole voivodship (excluding the municipality of Kraków). Kraków also has a 2016 resolution which prohibits the use of the following fuels:

- coal-mule,
- containing biomass with a relative humidity of more than 20%.

The resolution authorizes the operation of solid fuel installations if they provide minimum seasonal energy efficiency and pollutant emission standards for seasonal heating as defined in Commission Regulation (EU) 2015/1189 of 28 April 2015 (implementing the Ecodesign Directive) and allow only automatic fuel delivery, except for gasification solid fuel systems. The regulation is valid from 1 July 2017. The resolution lays down the phasing out of non-compliant class 5 according to PN-EN 303-5: 2012.

Particularly high pollution caused by low emission occurs in Małopolska. One of the reasons for this is the low awareness of the population about the causes of low emissions. Education in this area is one of the fundamental directions of action taken by regional authorities to reduce and eliminate low emissions.

The AGH University of Science and Technology as one of the leading technical universities in the region and cooperates with local governments to improve the ecological awareness of inhabitants. Both central and local activities have confirmed the need for the "Polones" project and the construction of a mobile laboratory.

3 Project Goal and Assumptions of the Project

The purpose of the project was to build a mobile installation for pollutant emissions testing in installations using different heat sources, for example a device that does not meet emission standards, an Ecodesign boiler and a device using renewable energy sources, such as a heat pump. It is also important for educational activities to be carried out using a mobile installation. Presentation for local communities of an example of an system comparing different types of equipment will help to make them more aware the effects of poor quality fuel and/or the use of non-standard boilers.

Assumptions of the project:

- Designing the mobile didactic laboratory,
- Construction of the Laboratory,
- Commissioning and first tests,
- Conducting didactic activity.

4 Construction of the Didactic Components

The whole installation is fixed on a 4-wheel trolley (Fig. 1). The installation consists of 4 circulating loops (Fig. 2). The first and the second are loops from solid fuel boilers protected by an open system fed tank, located at the highest point of the heating installation. The automatic boiler Galmet Galaxia is 15 kW power capacity and uses a rotating retort furnace. The boiler is classified in the fifth or highest class

Fig. 1 The “PoLoNEs” mobile installation

according to standard EN 303-5:2012. The boiler passes the ecodesign directive [1] requirements. The second boiler is manual feeding with a 12 kW capacity and an over fire furnace. Both boilers work in pumping systems with independent pumps and are connected to the buffer tank through coil heat exchangers (two coils heat exchanger serially connected). The third loop is a Galmet Airmax air to water heat pump with a heating capacity of 6 kW (in the conditions A7/W35). This is a closed system equipped with an expansion vessel and safety valve. The loop is connected to the third coil heat exchanger in the buffer. The fourth loop is the cooling loop, connected to two hot water air heaters in a series (Fig. 1). The buffer tank is a 3 coils tank with a 300 l capacity. Each loop (besides the cooling loop) is equipped with heat meters and energy counters. The data from the energy measurement system is collected in the server. Each boiler has an independent chimney and each installation is filled with antifreeze.

5 Research and Didactic Activity

The research program developed for mobile installations is based on the analysis emitted by the combustion process for low-emission pollutants. The studies refer to the use of different quality fuels both in a device meeting the applicable emission standards and one that does not meet these standards. The different conditions under which the combustion process was carried out, such as using a fan, were also analyzed.

The scenarios of the lectures and shows are based on following a number of steps:

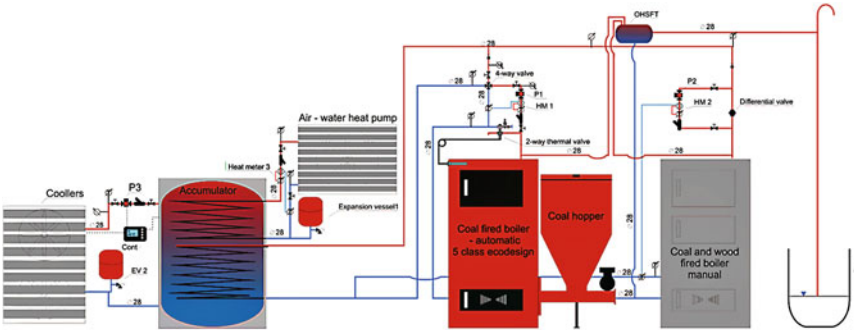


Fig. 2 Schematic diagram of the “PoLoNEs” Mobile Laboratory

- Stoking in the boilers and visual comparison of smoke at different stages of burning.
- Stoking in the boilers and utilizing the equipment for air quality measurements (air dust meter and air quality meter). Measurements conducted in the stream of flue gases at various distances from the trolley.
- Using a fine particle analyzer and flue gas analyzer. Monitoring in chimneys the emissions during different stages of firing.
- Presentation of the workings of air-water heat pumps including COP measurements.

6 First Measurements

For didactic purposes, measurements of particulate matter and carbon monoxide in flue gases was conducted. The measurements were made for an automatic feeding boiler, which works at 100 and 30% heating capacity—Table 1.

Table 1 Particular matter and carbon monoxide emission for two boilers and different conditions

Parameters	Coal boiler with retort burner, ecodesign, coal 28 MJ/kg		Manual feeding boiler with fan—dry beech wood	Manual feeding boiler without fan—dry beech wood
	Power capacity 100%	Power capacity 30%	Power capacity 100%	Power capacity 100%
Particular matter average reduced by uncertainty of measurements [g/m^3]	0.0292	0.0225	0.152	0.0715
Carbon monoxide average reduced by uncertainty of measurements [g/m^3]	0.488	0.498	9.84	4.874

When burning coal with a lower calorific value of 28 MJ/kg and 100% power capacity, particulate matter emissions were 29 mg/m^3 and at 30% power capacity 22.5 mg/m^3. The emission of carbon monoxide at 100% power capacity was 488 mg/m^3 and for 30% was 498 mg/m^3. The results in the system passes Ecodesign requirements.

For a manual feeding boiler, air dried beech wood was used. The first measurements were made using a fan to supply the air for burning. Particulate matter emission was 152 mg/m^3 and carbon monoxide emission were at 12.3 g. In the second case, when the fan was shut off and air was delivered through the air flap, natural draft particulate matter emissions were lower, equal to 71.5 mg/m^3 and CO emissions of 6 g/m^3.

In spite of the launch of the research program, the first analyzes clearly indicate a lower emission of carbon monoxide and particulate matter using a boiler meeting the emission standards. Since the studies were conducted in field conditions (with the participation of the residents of the locality) and not in laboratory conditions, the presentation of the comparison of emissions from the installed devices immediately after the test have additional educational value. Participants in the survey (as observers) may also become acquainted with the emissions generated by their devices or those which are very similar).

7 Summary

The designed and developed mobile didactic installation will be used to conduct ecological education throughout Poland. The equipment can also be used for testing various fuels in the context of their influence on low-stack emissions.

The mobility of the device allows research to be conducted directly at the place of residence of the people concerned (local communities, villages, small towns) where access to knowledge and information on low emissions and related hazards is limited. Field studies, the ability to immediately show results of research, research on equipment used by residents, improve the credibility of the results and contribute to improving the ecological awareness of the region's inhabitants.

Acknowledgements The paper was prepared under AGH-UST statutory research grant No. 11.11.140.031. Authors thank for Foundation for the Support of Ecological Initiatives for lending installation.

References

1. GUS—Central Statistical Office: Zużycie energii w gospodarstwach domowych w 2012 r. (2012)
2. Kubica, K.: Instalacje spalania małej mocy na paliwa stałe-węgiel, biomasę. Platforma Producentów Urządzeń Grzewczych na Paliwa stałe. Polska Izba Ekologii, Katowice (2013)

3. http://europa.eu/rapid/press-release_IP-15-6225_en.htm. Last accessed 20 May 2017
4. Kuczaj, A.: Emisja związków organicznych przy spalaniu biomasy. Civil Environ. Eng. **1** (2012)
5. Juszczak, M.: Pollutant concentrations from a heat station fuelled with a wood pellet and coffee husk pellet mixture. Arch. Waste Manag. Environ. Protect. **15**(3), 17–24 (2013)
6. Juszczak, M.: Concentration of carbon monoxide and nitrogen oxides (NO, NO_x) from a 25 kW boiler supplied periodically and continuously with wood pellets. Arch. Waste Manag. Environ. Protect. **15**(3), 17–24 (2013)
7. Matuszek, K., Hrycko, P., Stelmach, S., Sobolewski, A.: Carbonaceous smokeless fuel and modern small-scale boilers limiting the residential emission. Part 1. General aspects. Przemysł Chem. **95**(2) (2016). doi:https://doi.org/10.15199/62.2016.2.8
8. Matuszek, K., Hrycko, P., Stelmach, S., Sobolewski, A.: Carbonaceous smokeless fuel and modern small-scale boilers limiting the residential emission. Part 1. Experimental tests of new carbonaceous smokeless fuel. Przemysł Chem. **95**(2) (2016). doi:https://doi.org/10.15199/62.2016.2.9
9. Janicki, M.: The concentration of elementary pollution in exhaust gases during combustion of pellets, made of virginia and wood, in low-power boiler. Arch. Waste Manag. Environ. Protect. **16**(4), 103–112 (2014)
10. Projekt rozporządzenia Ministra Rozwoju w sprawie wymagań dla kotłów na paliwa stałe, https://legislacja.rcl.gov.pl/docs//526/12290459/12381988/dokument277446.pdf. Last accessed 2017/06/01
11. Commission Regulation (EU): Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel boilers (2015)
12. EN 303-5:2012 Heating boilers. Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW. Terminology, requirements, testing and marking
13. Ustawa z dnia 10 września 2015 r. o zmianie ustawy—Prawo ochrony środowiska Dz.U. 2015 poz. 1593
14. Uchwała Nr XVIII/243/16 Sejmiku Województwa Małopolskiego z dnia 15 stycznia 2016 r. w sprawie wprowadzenia na obszarze Gminy Miejskiej Kraków ograniczeń w zakresie eksploatacji instalacji, w których następuje spalanie paliw
15. www.bip.krakow.pl/zalaczniki/dokumenty/n/147200. Last accessed 2017/06/01
16. http://energetyka.wnp.pl/w-krakowie-zlikwidowane-w-2016-roku-4-2-tys-piecow-i-kotlow-weglowych,289830_1_0_0.html. Last accessed 2017/06/01
17. Uchwała Nr XXXII/452/17 Sejmiku Województwa Małopolskiego z dnia 23 stycznia 2017 r. w sprawie wprowadzenia na obszarze województwa małopolskiego ograniczeń i zakazów w zakresie eksploatacji instalacji, w których następuje spalanie paliw

Design and Development of a Didactic and Research Stand for Exploitation Tests Under Defined Conditions

Wojciech Luboń, Grzegorz Pełka, Jarosław Kotyza and Daniel Malik

Abstract To develop the laboratory of renewable energy sources in Miękinia, a new stand with a heat pump was created. The main aim of this stand is to increase the range of research in the Laboratory. This stand consists of:

- a heat pump module,
- a module to simulate the parameters of the heat source and heat sink,
- a module to display and register data and a remote control.

This creates opportunities for research about the efficiency of heat pumps in reference to present standard PN EN 14511 and previous standard PN EN 255. The data allows us to define the impact of the methodology described in the standards on the coefficient of performance. This stand is able to calculate the coefficient of performance according to set parameters of work, like temperature of heat source, temperature of heat sink or difference between inlet temperature and outlet temperature on the heat sink side. There is also research about the effect of the superheating of refrigerant on the efficiency of heat pumps. All of the research with this stand is intended to examine the efficiency of heat pumps. This stand was also made for didactic purposes. It has the possibility to show the following, how the heat pump works, how the refrigerant circulates inside the heat pump, and what happened with the refrigerant in elements of a heat pump like a compressor, evaporator, condenser, expansion valve. There is also the possibility to show the dependence between the coefficient of efficiency and the temperature of the heat source or heat sink.

Keywords Heat pump · COP · Superheat

W. Luboń (✉) · G. Pełka · J. Kotyza · D. Malik
Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Mickiewicz Ave. 30, 30-059 Kraków, Poland
e-mail: lubon@agh.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_50

1 Introduction

The development of renewable energy sources contributes to increased interest in new appliances such as heat pumps. The market research carried out in 2016 by the Polish Association for Heat Pump Technology and Development (PORT PC) shows that the size of the market of electrically driven heat pumps has almost tripled over the last six years. Figure 1 shows the heat pump market in Poland in 2010–2015 [1].

Heat pumps, however, are complicated devices and require a high level of knowledge and a well-executed installation of the heat sources and heat distribution system. A very high impact on the work of the heat pump and its efficiency is due to the realization of heat sources and the heat distribution system [2]. Unfortunately, many installations of heat sources and heat sinks are badly made. As a result, the heat pump is inefficient or even damaged. That is why it is so important for education in the field of heat pumps. In the AGH-UST Laboratory of Renewable Energy Sources and Energy Saving in Miękinia, training in the field of heat pumps is already provided. Training includes the subject of heat sources (ground, air, waste heat), cooling circuits in the heat pump and the realization of heat distributing system. For this purpose, in the Laboratory in Miękinia work on creating a new infrastructure that can be used for both teaching and research purposes are in progress.

One of the new pieces of equipment is a heat pump with a stabilized temperature of heat sources and heating system. The photo of the heat pump is presented in Fig. 2. This stand allows for research into the impact of superheating on the

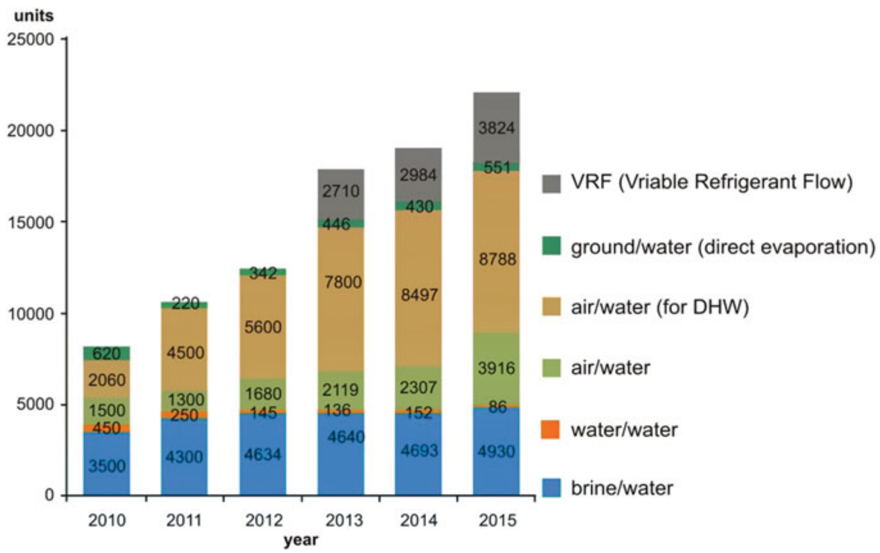


Fig. 1 The sales of heat pumps in Poland

efficiency of the heat pump—COP. Many air source heat pumps have huge problems with defrosting. With this heat pump it is possible to research the influence of refrigerant volume on the efficiency in heating mode and ability to defrost and work in cooling mode. This heat pump also gives to the opportunity to research the algorithm of defrosting. The new heat pump shows the refrigerant flow and what happens with refrigerant in the individual components of the heat pump. The heat pump is built with a lamella heat exchanger as an evaporator, a plate heat exchanger as a condenser, thermostatic expansion valve (bi-flow type) and rotary compressor. The heat pump has a 4-way reversing valve which reverses the refrigerant flow direction and then the heat pump can work as an air conditioner.

The heat pump has the possibility to stabilize the temperature of the heating system. A variable-speed fan is also used with a lamella heat exchanger, which enables the stabilization of the temperature on the heat source side. Stabilization of temperature on both sides allows the presentation of how the efficiency of the heat pump changes when the temperature difference between the heat source and heating system increase. Temperature stabilization on the side of the heat source allows how installations with an air–water heat pump should be projected to be shown. When the temperature of heat sources decreases, the efficiency of the heat pump does so too along with heating power. This relationship is very important in the design of the heating system with an air–water heat pump. All components of heat pumps are clearly visible and which helps in the presentation of the principle of heat pump operation. The didactic stand has small dimensions and is mobile. The heat pump can be switched on and off using computer software, where all of the operating parameters of the heat pumps are presently displayed. Important

Fig. 2 Didactic air–water type heat pump. A heat pump with temperature stabilization on the side of the heat source and heating system

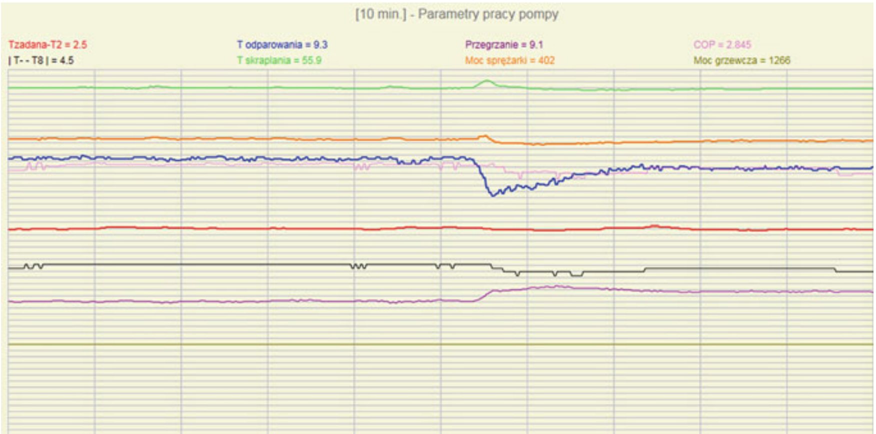


Fig. 3 Visualization of the heat pump circuit with all operating parameters

parameters are archived and displayed in graphs. Examples of data from the measurement cycle when superheat was changing are shown in Fig. 3.

2 Measurements

Research on the new heat pump was carried out to present the importance of superheating refrigerant in the refrigeration cycle. Superheat is a measured value and is the difference between two temperatures. The role of the expansion valve is to control superheating at a set level. Superheat is measured as the difference between the actual temperature of the refrigerant vapor and the saturation temperature of the refrigerant at that same point. When superheating of refrigerant is too low, it means the refrigerant is not fully evaporated and the compressor can be flooded. In cases where the superheating is too high, the evaporating point decreases and the mass flow of refrigerant also decreases. The effect of this on the cooling and heating power is to cause a drop. A high value of superheating also means that the compressor will get too hot causing its sump oil to overheat, slowly break down and lose its viscosity (lubricating effect) [3, 4]. All this results in the uneconomical operation of the heat pump. It means the operation with a low coefficient of performance.

For testing, the heat pump was filled with 0.5 kg of refrigerant. The volume of the evaporator and condenser pipes was included in the filling [5]. During the other research, the heat pump was tested with a higher and lower amount of refrigerant in reference to calculations made. A higher amount of refrigerant caused power consumption by the compressor to increase while if the amount of refrigerant was too low, it caused the temperature of evaporation to decrease. In extreme situations, the refrigerant wasn't fully condensed. Ultimately, the amount of refrigerant was as made in the calculations.

The correct choice of refrigerant has a big influence energy efficiency of heat pump in both cooling and heating function. Choosing the refrigerant the following criteria should be taken into account, like [6]:

- Pressure: At a given temperature the condensation pressure is different for different refrigerants. In high temperature, the pressure can too high what needs better components of heat pomp.
- Critical temperature: Critical temperature of a refrigerant is the temperature above which the refrigerant cannot be liquefied irrespective of the pressure.
- Environmental impacts of refrigerant: Environmental aspects are increasingly being taken into consideration. Refrigerants can thus also be ranked according to their impact on the stratospheric ozone layer (the Ozone Depletion Potential, ODP) or as greenhouse gases (the Global Warming Potential, GWP) [7, 8].

Many other factors are also involved in making decision about the refrigerant, such as costs associated with the investment, the required size of the installation and the safety and permissions [9]. This heat pump was projected with R134a refrigerant.

This refrigerant can be used for sytem requesting very high water temperatures (about 70 °C) but COP decreases proportionally to the increase of temperature (even about 3% each K). Has also a good theoretical COP but worse system performance caused by low heat transfer capability and high pressure drops. What is important R134a requires more heat exchange surface for given ΔT on the heating side and bigger compressor what is related with higher cost of investment [10].

Measurements of superheat were read directly from the controller of the heat pump (This data are displayed on computer software). To confirm the values of superheat, a digital kit of manometers was also used (testo 570-4). The expansion valve was factory set. The study of the effect of superheat on the coefficient of performance and achieved heating power was carried out for superheat: 2, 5 and 9 K. Set superheat values were not extreme values. During the measurements, the heat pump was working at the stable temperatures of the heat source. Also the difference between outlet temperature and inlet temperature on the side of the heat system was the same during all of the test. The stable operating parameters throughout the whole study on the side of heat source and heat system allows the influence of superheat on heating power and coefficient of performance to be discerned. The heat pump was working within parameters A23W46. The temperature of the air entering the evaporator was about 23 °C. The temperature of water flowing out from the condenser was about 46 °C, and difference between water temperature flowing out and flowing into the condenser was about 5 °C. These parameters are similar to a heat pump preparing hot domestic water. All parameters for the extreme values of superheat 2.1 and 9.3 are shown on the visualization of the heat pump in Fig. 4.

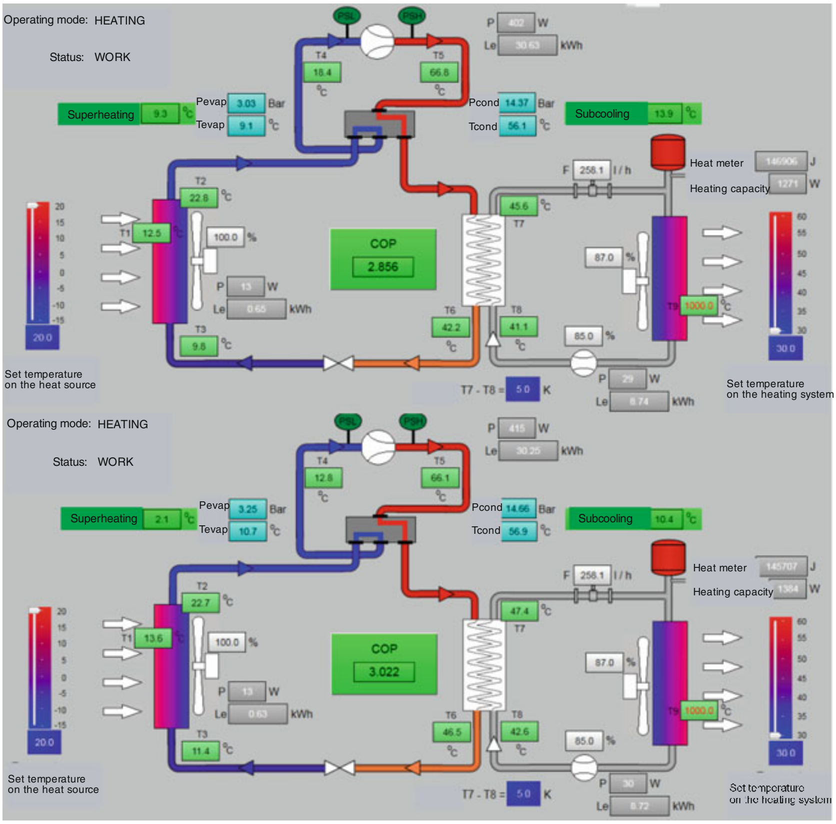


Fig. 4 Visualization of the heat pump circuit with all operating parameters

3 Results

The highest value of heating power 1384 W was obtained with a superheat of 2.1 K. According to this operating parameter, the heat pump has a coefficient of performance 3.02. The lowest value of heating power 1271 W was obtained with a superheat of 9.3K. According to this operating parameter, the heat pump has a coefficient of performance 2.86. The coefficient of performance was counted in reference to present standard EN 14511 [11]. Calculations included the power consumption of the circulation pump on the side of the heating system and power consumption of the fan on the side of the heat source. Reducing the superheat of the refrigerant caused an increase in the power consumption of the compressor. With a superheat 2.1 power consumption was 415 W, and with a superheat of 9.3 power consumption was 402 W. As a result of decreasing superheat, the evaporation temperature also increased. This also meant that the condensing temperature of the

Table 1 Heat pump operating parameters with tested values of superheat

Superheat [–]	Heating capacity [W]	Evaporating temperature [°C]	Power consumption [W]	COP [–]
9.1	1271	9.1	402	2.86
5.3	1299	10.2	405	2.9
2.1	1384	10.7	415	3.02

refrigerant decreased in reference to water temperature leaving the condenser. Important data from the whole test are collected and presented in Table 1.

4 Summary

The research has confirmed that when the superheat of refrigerant increases, the heating power and coefficient of performance of the heat pump decreases. By reducing the superheat, the mass flow of refrigerant was increased and this increased the power consumption of the compressor. In spite of the increasing power consumption of the compressor, the COP increased. Decreasing the superheat resulted in more efficient heat pump operation. A low value of superheat in the case of air source heat pumps is risky and the compressor could work with a wet refrigerant.

Acknowledgements The paper was prepared under AGH-UST statutory research grant No. 11.11.140.031.

References

1. http://www.ehpa.org/about/news/article/poland-a-spectacular-growth-of-the-air-heat-pump-market-in-2015/
2. Gorecki, W., et al.: Efficient use of renewable energy sources. Solgen (2015)
3. http://www.temperzone.com.au/Temperzone/media/Training/Superheat/PDF%27s/Superheat-Explained-V1-2.pdf
4. Dabiri, A.E., Rice, C.K.: A compressor simulation model with corrections for the level of suction gas superheat. Reserachgate.net (1981)
5. Ullrich, H.J.: Technika Chłodnicza. Poradnik. IPPU Masta, Gdańsk (1999)
6. http://www.industrialheatpumps.nl/en/how_it_works/refrigerants/
7. http://swep.net/refrigerant-handbook/5.-refrigerants/sd5/
8. Brown, S.J., Yana-Motta, S.F., Domanski, P.A.: Comparitive analysis of an automotive air conditioning systems operating with CO_2 and R134a. Int. J. Refrigerat. **25**, 19–32 (2002)

9. Hosoz, M., Direk, M., Yigit, K.S., Canakci, M., Turkcan, A., Alptekin, E., Sanali, A.: Performance evaluation of an R134a automotive heat pump system for various heat sources in comparison with baseline heating system. Appl. Therm. Eng. **78**, 419–427 (2015)
10. http://www.ehpa.org/uploads/media/13_20100520_EHPA_Zamana_Heat_Pump_Compressors_Overview_-_ECT_01.pdf
11. EN 14511-2014: Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling. Test conditions

An Innovative Air—Water Heat Pump with Ecological Refrigerant

Grzegorz Pełka, Wojciech Luboń, Daniel Malik, Krzysztof Kołton and Wojciech Kołton

Abstract The heat pump market is growing year on year and more than 20,000 units were sold in 2015 alone. The majority were air to water heat pumps for heating or for only warming up domestic hot water utilizing inside air. The project ordered by Kołton S.C. company, co-funded by Regional Operating Programme 2014–2020 of the Lesser Poland Region, was conducted in the AGH-UST Educational and Research Laboratory of Renewable Energy Sources and Energy Saving in Miękinia and had the following goals: defining the type of air-water heat pumps, determining the refrigerant, design, developed and testing the prototype. According to EU F-gas regulations, the use of refrigerant with high GWP (Global Warming Potential) will be limited. It was one of the reasons to develop a heat pump using an environmentally friendly and natural refrigerant—R290. The type of construction used in the heat pump is monobloc, which simplifies the installation. It uses components dedicated for R290, such as a scroll compressor, evaporator and condenser, 4-way valve, electronic expansion valve, etc. The first tests of the device gave the following results: for an air temperature of 2 °C and a water temperature of 35 °C the heating power was 13.2 kW and COP was 3.69. Further tests will be conducted to optimize the parameters of the heat pump and the controlling algorithm.

Keywords Air-water heat pump · Ecological refrigerant · COP

G. Pełka (✉) · W. Luboń · D. Malik
Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
e-mail: gpelka@geol.agh.edu.pl

W. Luboń
e-mail: lubon@agh.edu.pl

D. Malik
e-mail: dmalik@geol.agh.edu.pl

K. Kołton · W. Kołton
PPHU KOŁTON Wojciech Kołton, Krzysztof Kołton, Orawka 149a, 34-480 Jabłonka, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_51

1 Introduction

To protect the ozone layer, hydro-fluorocarbons (HCFC) refrigerants, such R22, were withdrawn from use. In the EU, HCFC's have been totally banned since 1 January 2015, because of their Ozone Depleting Potential (ODP) indicator higher than 0 [1, 2].

Although hydro-fluorocarbons (HFCs), such as R134a or R410A (as a mixture), can solve the issue of ozone layer protection, the Global Warming Potential (GWP) of these refrigerants is still very high, so it is necessary to limit their usage and they also will be phased out in the next few years [3]. One of the alternatives for HCFC and HFC are natural refrigerants. Hydrocarbons, such as R290 (propane), has a similar thermodynamic property to R22, with zero Ozone Depleting Potential (ODP) and very low GWP. For that reason R290 is the candidate for the next generation refrigerant with a wide range of applications, from commercial and domestic air conditioning systems to heat pumps [4, 5].

Currently, a lot of research is being conducted to test and implement heat pumps with R290 refrigerant. International projects, such as Next Generation Heat Pump for Retrofitting Buildings (GReenHP) and Next Heat Pump Generation Project (NxtHPG) aim to develop components for ecological heat pumps [5–8].

In Poland, the heat pump market is developing and, as shown in Fig. 1, the market is still growing. The main dynamic growth is enjoyed by air/water heat pumps (100% growth compared 2014 and 2015). For units sold, the biggest share is occupied by domestic hot water heat pumps [9]. The anti-smog law which is being introduced in some Polish voivodeships may change the amount and quality of

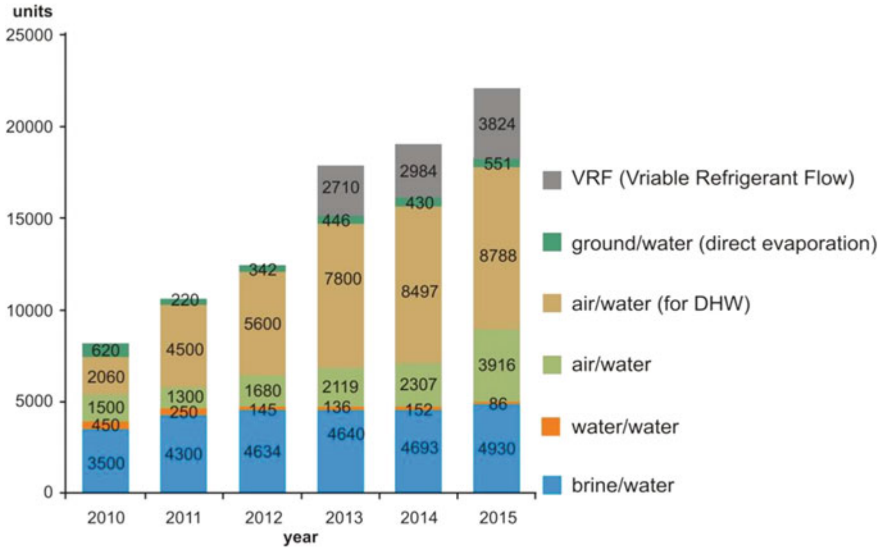


Fig. 1 Polish heat pump market in the years 2010–2015 [9]

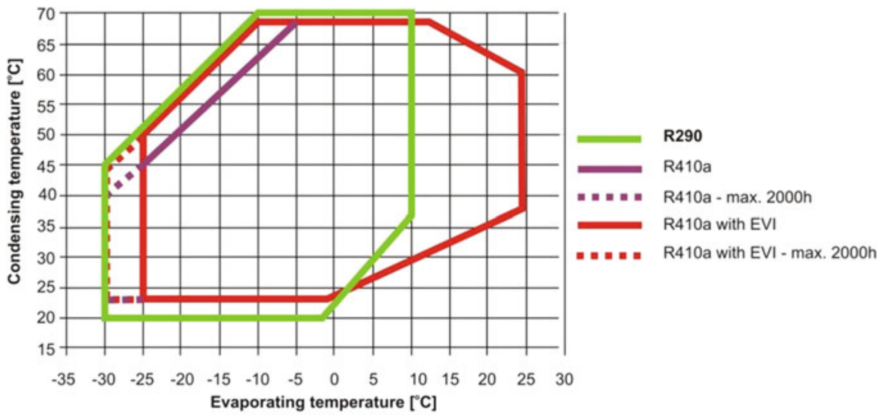


Fig. 2 Operating envelopes of the scroll compressors and various refrigerants [23]

solid fuel boilers sold and also be an impulse for the usage other heat sources, i.e. heat pumps.

The Educational and Research Laboratory of Renewable Energy Sources and Energy Saving in Miękinia is a unit of Faculty of Geology, Geophysics and Environment Protection AGH-UST, which conducts didactic activity and research around the RES. The realized project, ordered by Kołton S.C. company, had the following goals: defining the type of air-water heat pumps, determining the refrigerant, design, developing and testing the prototype.

2 Propane as a Refrigerant

Propane belongs to the family of organic saturated hydrocarbons, it is colorless and odorless. This compound occurs in oil and natural gas deposits and is characterized by favorable thermodynamic properties similar to ammonia and R22 in the field of refrigeration applications. However, after the development of CFCs and HCFCs in 1928, it was neglected because of its flammability [10–15].

Propane used in refrigeration should be highly pure (the purity higher than 99.5%) [16].

Thermodynamic properties of propane:

- Low compression end temperatures compared to R22, which allows for a better cooling of the medium, and causes less wear on compressor components that do not need to operate at extremely high temperatures.
- Comparable value of cooling capacity coefficient (COP) with R22.
- Definitely greater unit capacity (volume) of the R290 refrigerant than R22. This means that filling this installation factor is considerably lower than for factors such as R22. In the case of a very well-designed installation, the propane

quantity can be up to 30% less than R22, which results in significant savings and reduced overall refrigerant costs.
- Low dynamic viscosity, resulting in low flow resistance in the loop.
- Comparable temperature of the critical point of R290 as R22.
- Propane forms in solutions with mineral oils, which facilitate the transfer of oil between the compressor and the refrigeration system.

According to PN-EN 378-1: 2008 [17], propane is a refrigerant classified as a lower toxicity class A and a higher flammability class 3-A3. According to the standard, refrigerant is class A (lower toxicity), when refrigerant with a time weighted average concentration not having an adverse effect on nearly all workers who may be exposed to it day after day for a normal 8-h workday and a 40-h workweek whose value is equal to or above 400 ml/m^3.

Single compound refrigerant is classified in class 3 (higher flammability) if the following conditions are met:

- exhibits flame propagation when tested at 60 °C and 101.3 kPa;
- has a lower flammable limit LFL $\leq$ 3.5 vol.%; or it has a heat of combustion that is $\geq$19,000 kJ/kg.

According to PN-EN 378-1:2008, the location of all elements that contain flammable refrigerant outside (as monobloc heat pumps are designed) above ground level (for public space), the filling limit is 5 kg. If the device was to be mounted below ground level, the filling limit would be 1 kg.

3 Energy Performance Parameters of Heat Pumps

Heat pumps are devices which have high work efficiency during the heating process. For determining the efficiency of heat pumps the following factors are used:

- COP (Coefficient of Performance)—calculated according to PN-EN 14511 [18] or according to the previous EN 255 standard. It is defined as a ratio of heating output divided by the electrical power input. It is measured in determined conditions of temperatures of heat source and heat sink. To calculate COP, the electrical power required from all components such as the compressor, controller, circulation pumps or fans of heat sources and sink are taken into account. For the circulation pump on the side of the heat sink, the electrical power demand needed to overcome the hydraulic resistance of the condenser is taken into account. This coefficient characterizes the heat pump's work in the strictly defined conditions of the temperature of the heat source and heat sink.
- SCOP (Seasonal Coefficient of Performance) is calculated according to PN-EN-14825 [19]. This coefficient describes the annual average efficiency factor of heat pumps. SCOP shows how efficient a specific heat pump will be in a designated heating season and for a given heating demand profile. Seasonal

Coefficient of Performance can be estimated at the design stage of building and this calculation can be used to predict the future exploitation cost. SCOP is used to optimize a heating installation with heat pumps.

- SPF (Seasonal Performance Factor) is defined as the ratio of heat production and electricity consumption during the specified period. There are several types of SPF, which account for some additional elements of the installation such as the pump of a central heating system, additional electric heaters, etc. [20–22]. SPF is result of measurements, not calculations based on assumptions.

For testing the performance of the heat pump and cataloguing data, COP is used.

4 Development of an Air to Water Heat Pump with a Natural Refrigerant

The main assessment of the project:

- Monobloc air to water heat pump—it expands the product offer for installers—the clients of the company,
- Outdoor type heat pump—no refrigerant in the indoor side (safety requirements),
- Offer a fully ecological product with no F-gas restrictions,
- Deliver the product with a high envelope of the operation, especially in low evaporation temperatures.

During development, the device took into consideration the guidelines of the contracting company, good practise and best available techniques—BAT [8] and the standard EN 378-1:2008 [17].

At first, a schematic drawing was made. A few configurations of the device were taken into consideration, one of which is in Fig. 3. After acceptance, the 3-D model was made (Fig. 4) with an arrangement of all the components. The main components used in the construction of the prototype are:

- scroll compressor dedicated for R290,
- brazed plate heat exchanger as a condenser,
- coil evaporator,
- electronic expansion valve,
- suction line accumulator,
- 4-way reversing valve,
- Filter/dehumidifier,
- safety and control elements as a pressure switches, pressure transducers, temperature sensors, motor protection switch, etc.,
- fan with EC motor,
- circulating pump
- check valves and other specified in Fig. 3.

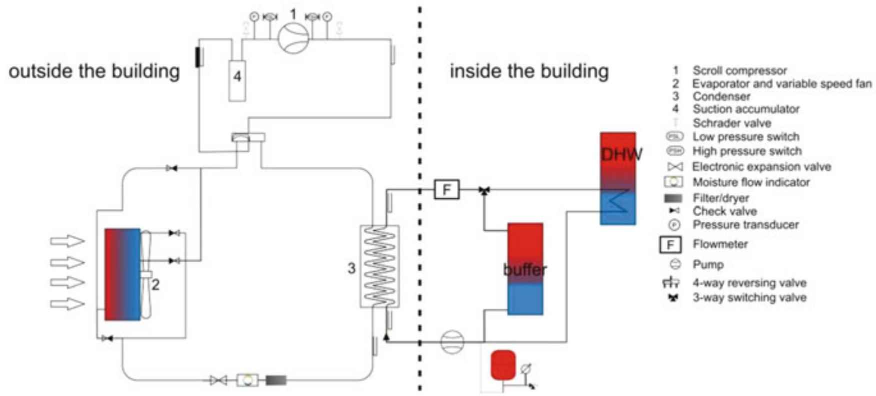


Fig. 3 Schematic drawings of the cycle of the heat pump

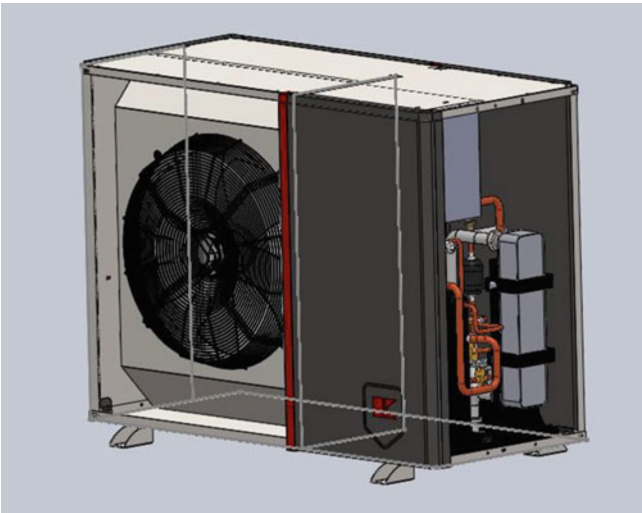


Fig. 4 3-D model of the heat pump

The scroll compressor used in the prototype has a wide operating envelope for a low evaporating temperature, compared to the envelope for the R410a optimized compressor with enhanced vapor injection (EVI). But the producer of these compressor limits the working time for such a low evaporating temperature to 2000 h during the compressor lifetime. For the R407c optimized compressor with EVI the permitted condensing temperatures are lower than for R290 optimized compressor [23]. Heat pumps using R410a or R407c without EVI have a lower range of operation at low evaporating temperatures. For higher than 10 °C evaporating temperatures, R410a and R407c compressors have wider operating envelopes but for heating purposes it isn't very useful (Fig. 2).

5 Testing of the Prototype

The prototype (Figs. 5 and 6) was tested in stabilized conditions of heat source and heat sink. For stabilization of the heat source parameter, a chamber with modulated temperature and relative humidity was used. For the stabilization of heat sink parameters, a system composed of a buffer tank, mixing 3-way valve with an actuator and the driver was used. For the heating capacity measurements, a heat meter APATOR Faun with PT-500 temperature sensors and single-jet dry water meter impulse transmitter with B metrological class was used. For power consumption a FiF Le03MP power meter with metrological class 1 (according IEC61036) was used. The data from the meters were collected via RS485 and Modbus RTU protocol and compiled in a database. The first test results are shown in Table 1. Heat pump tested in the air temperature 2 °C and outflow water temperature 35 °C reach heating capacity 13.2 kW and the COP equal 3.69. For an air temperature of 7 °C and an outflow water temperature of 40 °C, it has a heating capacity of 14.8 kW and the COP was 4.19.

Fig. 5 Prototype of the heat pump

Fig. 6 Prototype in the testing chamber

Table 1 First results of the tests

		Air temperature [°C]					
		7			2		
		Heating capacity [kW]	Power input [kW]	COP	Heating capacity [kW]	Power input [kW]	COP
Water outlet temperature [°C]	35	–	–	–	13.20	3.58	3.69
	40	14.82	3.54	4.19	12.81	3.67	3.49

6 Summary

The initiation of the heat pump prototype with a R290 refrigerant was successful. The energy parameters, such as heating capacity, power input and COP, are rewarding. The device is still being analyzed in the stabilized conditions of the Laboratory in Miękinia. Improvements to the controlling algorithm are also being conducted.

Acknowledgements The paper was prepared under AGH-UST statutory research grant No. 11.11.140.031 in cooperation with PPHU Kołton Wojciech Kołton, Krzysztof Kołton.

References

1. Dobrzyński, M.: Rewolucje w czynnikach chłodniczych. Przemysł Spożywczy, tom 67 (2013)
2. Technical information, Daikin: R-32 Czynnik chłodniczy następnej generacji do klimatyzatorów i pomp ciepła (2015)
3. Gao, B., Chen, Z., Gao, Q.: Research of R290 compressor effect on RAC system charge amount. In: International Compressor Engineering Conference. Paper 2096 (2012). http://docs.lib.purdue.edu/icec/2096
4. Lampugnani, G., Zgliczynski, M.: R290 as a substitute of R502 and R22 in commercial refrigeration and air conditioning. In: International Compressor Engineering Conference. Paper 1087 (1996). http://docs.lib.purdue.edu/icec/1087
5. Palm, B.: Heat pumps working with propane. Next Heat Pump Generation Project. The final workshop of the Next Heat Pump Project (NxtHPG), Milan (2016)
6. Zottl, A.: Project final report. Next Generation heat pump for retrofitting buildings, GReenHP (2016)
7. Fraccari, E.: Compressor technology outlook in the HP market. A tiered approach. In: European Heat Pump Summit Symposium +EXPO, Nuremberg (2015)
8. Maul, J.: Environment-friendly heating with R290 heat pumps. ATMOEUsphere—solutions for Europe—natural refrigerants (2013)
9. PORT PC: Spektakularny wzrost rynku powietrznych pomp ciepła w 2015 roku (2015). http://portpc.pl/port-pc-spektakularny-wzrost-rynku-powietrznych-pomp-ciepla-w-2015-roku/
10. Choudharia, C.S., Sapalib S.N.: Performance investigation of natural refrigerant R290 as a substitute to R22 in refrigeration systems. Energy Proc. **109**, 346–352 (2017)
11. Yu, Ch.Ch., Teng, T.P.: Retrofit assessment of refrigerator using hydrocarbon re-frigerants. Appl. Thermal Eng. **66**, 507–518 (2014)
12. Miyara, A.: Condensation of hydrocarbons—a review. Int. J. Refrig. **31**, 621–632 (2008)
13. Granryd, E.: Hydrocarbons as refrigerants—an overview. Int. J. Refrig. **24**, 15–24 (2001)
14. Palm, B.: Hydrocarbons as refrigerants in small heat pump and refrigeration systems—a review. Int. J. Refrig. **31**, 552–563 (2008)
15. Shrivastava A.P., Choudhari Chandrakishor, S.: Evaluation of refrigerant R290 as a replacement to R22. Int. J. Innovative Res. Sci. Eng. **2**(3) (2016)
16. Technical documentation Inventec—R290, http://www.inventec.dehon.com/fr/chimie-fine/intermediaires-de-synthese/19/r290/224.html. Last accessed 04 June 2017
17. PN- EN 378-1:2008 Instalacje ziębnicze i pompy ciepła—Wymagania dotyczące bezpieczeństwa i ochrony środowiska—Część 1: Wymagania podstawowe, definicje, klasyfikacja i kryteria wyboru
18. PN-EN 14511-3:2013-12—Klimatyzatory, ziębiarki cieczy i pompy ciepła ze sprężarkami o napędzie elektrycznym, do grzania i ziębienia—Część 3:Metody badań
19. PN-EN 14825:2016-08 - Klimatyzatory, agregaty do chłodzenia cieczy i pompy ciepła ze sprężarkami o napędzie elektrycznym, do grzania i ziębienia—Badanie i ocena w warunkach niepełnego obciążenia oraz obliczanie wydajności sezonowej
20. Lachman, P.: Metodyka obliczenia OZE z pomp ciepła zgodnie z najnowszymi wytycznymi UE, InstalReporter, 03/2013, pp. 42–47 (2013)
21. Miara, M., Gunther, D., Kramer, T., Oltersdorf, T., Wapler, J.: Heat pump efficiency: analysis and evaluation of heat pump efficiency in real-life conditions (2011)

22. Nordman, R., Zottl, A.: SEPEMO-build—a European project on seasonal performance factor and monitoring for heat pump systems in the building sector (2011)
23. Technical documentations of scroll compressors, Copeland, http://www.emersonclimate.com. Last accessed 04 June 2017

Modelling of PV Power Station Exploitation Process, Supporting Wastewater Treatment Plant Energetic System

Kurpaska Sławomir, Knaga Jarosław, Bernacik Robert and Nęcka Krzysztof

Abstract The paper presents a new method for determining the indicator of energy demand coverage from PV micro power station. For verification process we applied this method in wastewater treatment plants. The investigated parameter was the electricity demand of these facilities. The developed method is based on two indicators $W_{I(t)}$ and $W_{P(t)}$, respectively the insolation and the power demand index. Mean annualized data were used to develop the insolation index, while the power demand index was based on actual power demand of wastewater treatment plant. Once the load profile has been defined, it has been modified by the signum function to the day/night interval, and then the power demand indicator has been determined. The intersection point of these two indexes developed on a common basis can be interpreted as a degree of energy demand coverage of objects with known load profile. Described author's methodology was verified in the first six months of the first half of the year in the rural wastewater treatment plant, which is integrated with a 100 kW PV micro power station. The energy demand of the plant treatment in each month exceeded the model's value for about 10–17%. That was caused by 30% PV power station oversizing.

Keywords Insolation · Micro PV power station · Insolation index
Power demand index

1 Introduction

2.122 million dam^3 of industrial and municipal waste water were generated in Poland in 2015, which required treatment before throwing into flowing water or land. In the municipal sewage treatment plant more than 1.254 million dam^3 were treated, accounting nearly 33 m^3 rok^{-1} for the statistical inhabitant. This value was changing slightly over the past ten years. Wastewater treatment plants are mostly

K. Sławomir · K. Jarosław (✉) · B. Robert · N. Krzysztof
Agricultural University in Kraków, Ul. Balicka 116B, 30-149 Kraków, Poland
e-mail: Jaroslaw.knaga@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_52

used in local government units as well as in other industrial facilities that produce large quantities of wastewater or have a specific chemical composition. Inhabitants bear the costs of sewage disposal which is currently governed by the City council resolutions. They are very diverse and vary from less than 2 PLN to over 19 PLN [2], with a significant share of electricity charges. The energy consumption of different stages of wastewater treatment depends mostly on the applied technology. Literature review shows that average energy consumption in conventional solutions can vary from 0.27 kWh m^{-3} (China), 0.33–0.60 kWh m^{-3} (USA) and 0 kWh m^{-3} (Australia) to 0.30–1.89 kWh m^{-3} (Japan) [3–7]. Regardless of the technology of wastewater treatment, the amount of energy consumed in this type of facility is characterized by low variability during the day, month or year. Variations in power demand daily profile are negligible and are partly dependent on residents preference, sewage collection, or weather conditions. Application of renewable energy power generators in such local facilities, can provide tangible benefits not only in environmental but also financial terms. It is enough to mention that in the cost of municipal sewage treatment plants the charge for electric power can be higher than 30% [8–10].

The research shows that most of the treatment plants were designed solely with regard to the quality of wastewater treatment without proper attention to energy demand. It depends mostly on the type of treatment plant, the aeration system, the required quality of the wastewater as well as the robustness of the service provided by the operators.

The most environmental friendly renewable energy sources are photovoltaic systems that use available solar radiation. However they are sources characterized by high variability of available energy in the daily the annual period. Therefore, there is a need of actions to maximize the use of the available solar radiation potential.

Currently methods and models used for PV power station size selection are based on the annual energy consumption, which is a technical criterion and a full-power cost analysis, which is an economic criterion [11, 12].

Among the most commonly encountered technical criteria taken into account for the calculation of the photovoltaic modules active area are: limit of the maximum power of photovoltaic power station to the power peak, ordered from the electricity supplier, increased by the average power consumed by electrical appliances installed in the treatment plant and elaboration of energy demand coverage within a specified period of time. The optimal size of the PV station is determined by the dependence of the energy demand coverage (ε) on the surface of the power plant. The optimum area of PV power is the point at which the characteristic $\varepsilon = f(A_{PV})$ collapses, which means that the differential value of this function decreases. At this point, the installed PV power is characterized by best use to cover own needs.

On the other hand, the analysis of the effectiveness of the planned undertaking is often carried out on the basis of the following economic indicators [13–15]:

- Simple payback period (SPBP),
- Payback period (PBP),
- Net present value of the (NPV),
- Net present value ratio (NPVR),
- Internal rate of return (IRR),
- Dynamic generation cost (DGC).

The choice of a specific photovoltaic system in a wastewater treatment plant should always be based on objective criteria. It is commonly believed that such a criteria is a effects surplus over inputs.

There are many reports of using the PV power station to support the coverage of electricity demand in sewage treatment plants [16, 17]. However, there is still a lack of clear methodology to determine the degree of coverage of electricity demand for PV plants and to determine the optimum installed power that would result solely from the technical criterion.

2 Goal and Scope of the Paper

The aim of the study was development of method, determining the degree of energy demand coverage by photovoltaic (PV) power station, using a single criterion (technical criterion). The developed method can be the basis for optimizing the selection of PV micro size for specific applications.

Electricity consumption and production data from the local PV system installed in the municipal waste water treatment plant located in the rural areas of the Tarnów district were used for model evaluation. Research and analysis was conducted for the first half of 2017. In this range, the electricity consumption, the sewage treatment plant, and the insolation data from the meteorological station closest to the treatment plant were examined.

3 Method

Developed model was based on two indicators. First, the indicator of the demand for the average power of sewage treatment plants and the second insolation index—the density of the solar flux falling on the reception area inclined from the existing PV power system, for verification of the correctness of the developed methodology. The model was referred to a common time base and its general idea was presented as a graphical algorithm in Fig. 1.

The background of the model was development of a daily demand profile for the average power of the sewage treatment plant P = f (t) and the average insolation profile at the site of the PV station I_S = f (t), for the common hour time basis. Then,

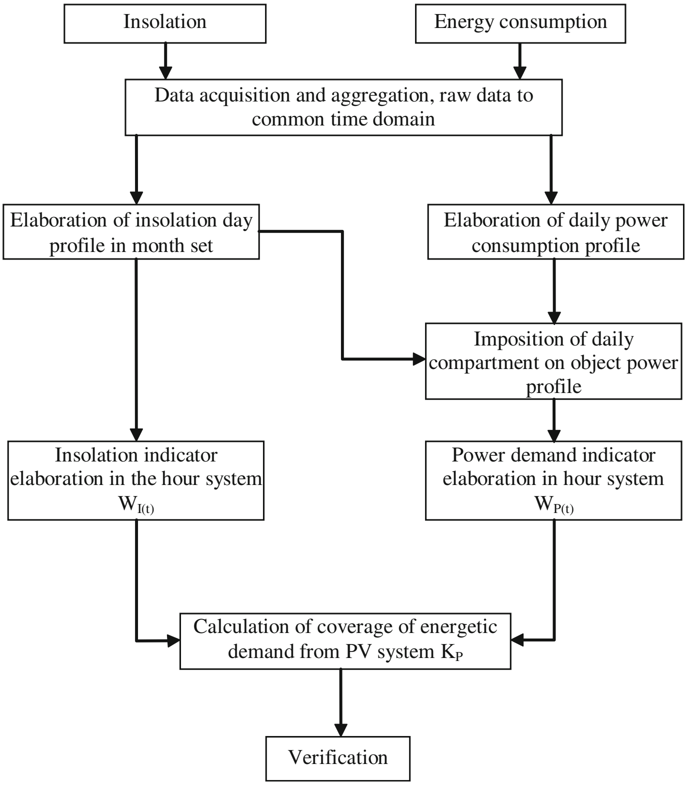


Fig. 1 Model structure

the relation describing the power profile P = f (t) was modified by the signum function to form.

$$P_M = P \cdot \mathrm{sgn}\,(t) \tag{1}$$

where:

Sgn (t) = 1 for the daily interval,
Sgn (t) = 0 for sunrise and sunset,
Sgn (t) = −1 for night interval.

Whereas the notion of sunrise and sunset does not refer to a period of full hour as the determined average power per day profile only.

The power demand index of the object is defined as the ratio of the sum of hourly power in a given time period to the sum of power hourly averaged over the daily profile (2). However, the sum of hourly power in a given time interval is calculated symmetrically with respect to the sunrise:

$$W_{P(t)} = \frac{\sum_{i=12}^{12-n} P_{m,i} + \sum_{i=12}^{12+n} P_{m,i}}{\sum_{1}^{24} P_{m,i}} \tag{2}$$

where:

P_i power of daily profile for the object,
$P_{m,i}$ hourly power of the modified daily profile for the object in mth month.

The value of this indicator was determined for the average day of the month.

In turn, the insolation index is defined as the ratio of the hourly insolation mean in a given time interval to the mean of the maximum insolation (3). Where the mean hourly insolation in a given time interval is calculated from 2 h evenly spaced from the Sun, and the mean maximum insolation is determined from the study period considered;

$$W_{I(t)} = \frac{\left(I_{Sm,(12-i)} + I_{Sm,(12+i)}\right) \cdot \frac{1}{2}}{I_{Smax}} \tag{3}$$

where:

$I_{Sm,\ (12\text{-}i)}$, $I_{Sm,\ (12+1)}$ insolation in the ith hour defined with respect to the sun's zenith,
I_{Smax} maximum insolation determined from the daily profile for the first six months.

The intersection of the developed index characteristics $W_{I(t)}$ and $W_{P(t)}$ will determine the percentage of electrical demand for the facility in subsequent months and resulting from the technical criterion taking into account only the daily power and demand profile.

Verification of the method was based on data from the PV plant operating in the wastewater treatment plant.

4 Data Analysis

Analysis of the results of the research began with the preparation of the daily demand profile for average power through the sewage treatment plant (Fig. 2) in a monthly layout. The waveforms for each month of the profile are characterized by a uniform load (neutral) excluding the month of May, where we observe a clear reduction in daytime power demand (tendency towards a negative profile for solar radiation).

In most of the profiles (January, February, March, April, June), there are two slight peak power requirements that are appropriate for the midday hours from 11th

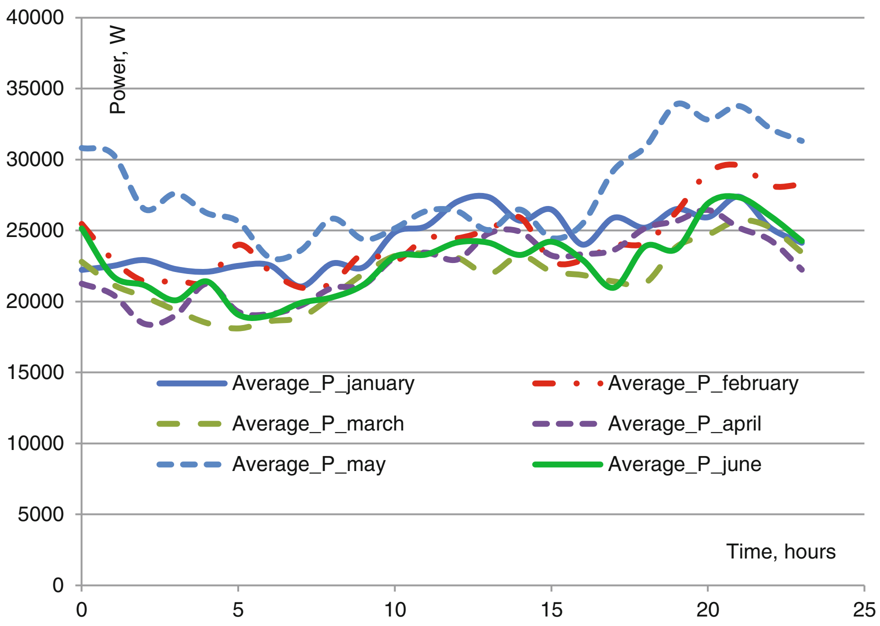


Fig. 2 Daily consumption profiles of average electric power in sewage treatment plant, in monthly set

to 14th and evening hours 20–21. This demand for electricity is typical of rural sewage treatment plants, which process waste water on a regular basis, without pre-storage of wastewater at night, to promote better use of PV electricity. It should also be noted that the average power requirement for treatment plants was 24 kW, at less than three times the maximum power, which is 70 kW.

Subsequently, the developed demand profiles for average power were multiplied by the signum function (1), which allowed to mark day and night intervals on the profile, compared to the day of the average month. After modifying the average power profile, according to the Eq. (2), its index was determined as shown in the graph below (Fig. 3).

Irrespective of the month in each case, there is a maximum which falls on the average day length for the average day of the month. This maximum is interpreted as the potential daily value of the electricity demand for individual months at the theoretically very high (reaching infinity) of installed PV power. For three months; January, February, and March rates are negative, what indicates that more energy is needed in the night range than during the day in a proportion 2/1. In particular it has been shown on the example of the January, when 2/3 of the curve (Fig. 3) is in the range of indicator positive values, whereas 1/3 is negative. In April, May and June, greater demand for electricity is in the day rather than the night. In the month of June with the longest daily interval, we can theoretically cover 65% of electricity from PV micro power plant.

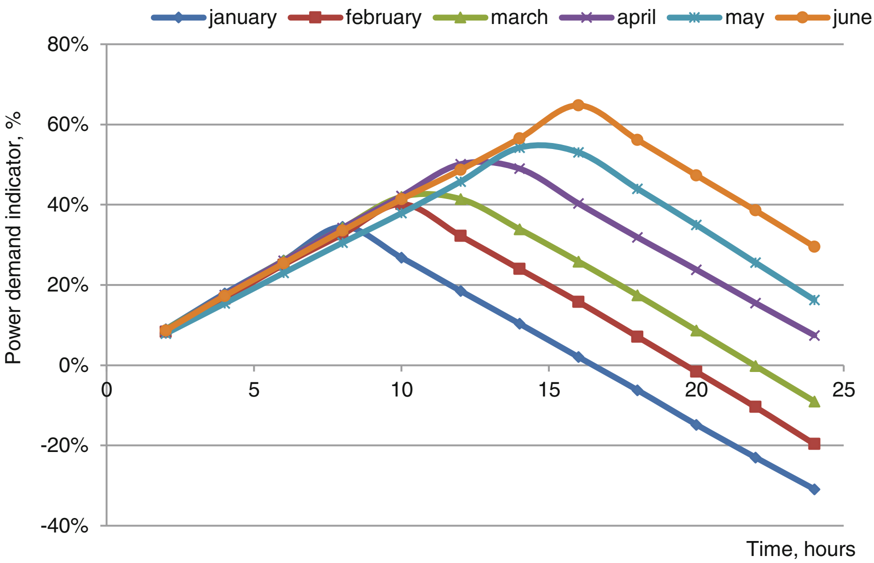


Fig. 3 Daily consumption index in sewage treatment plant $W_{P(t)}$, including months of the first half-year

Moreover, the nature of the daily profile can be relatively easily recognized from the graph (Fig. 3). If the profile is neutral like in case of the months January, February, March, April or June, the first points forming curve, which create the angle 45° to time axis up to the maximum ratio of power demand indicator (Fig. 3). Also, the characteristics of evenly distributed 45° fall in the second part of the profile until the dusk. On the other hand, in the course of this indicator for May has a slight deviation, observed in the form of milder raising and slight shift of the maximum towards time increasing values. It should be noted that these conclusions are consistent with the analysis presented in accordance with the graph (Fig. 2).

In the second part of the paper an analysis of insolation was carried out at the location of the PV microelectronic plant, using the average year data from the meteorological station in Tarnów, which is 23 km away and the closest to the solar power station. After the aggregation of insolation data to the daily profile for each month, the insensitivity index $W_{I(t)}$ was determined according to the Eq. (3), which is graphically graphed (Fig. 4).

The insolation index for all waveforms was determined at the maximum average I_{Smax} insolation level at 640 W/m^2 for the months analyzed, what represents 60% of the maximum instantaneous solar radiation density at the installation site. Practically in all waveforms of the indicator (Fig. 4), a certain regularity can be observed, which indicates a fairly fast and even decrease of this index to the level of 5–8%. On the other hand, some differences in the course of these indicators can be observed for May and June, which comes down to the fact that the characteristics are practically overlapping with a small deviation in the form of weaning in the

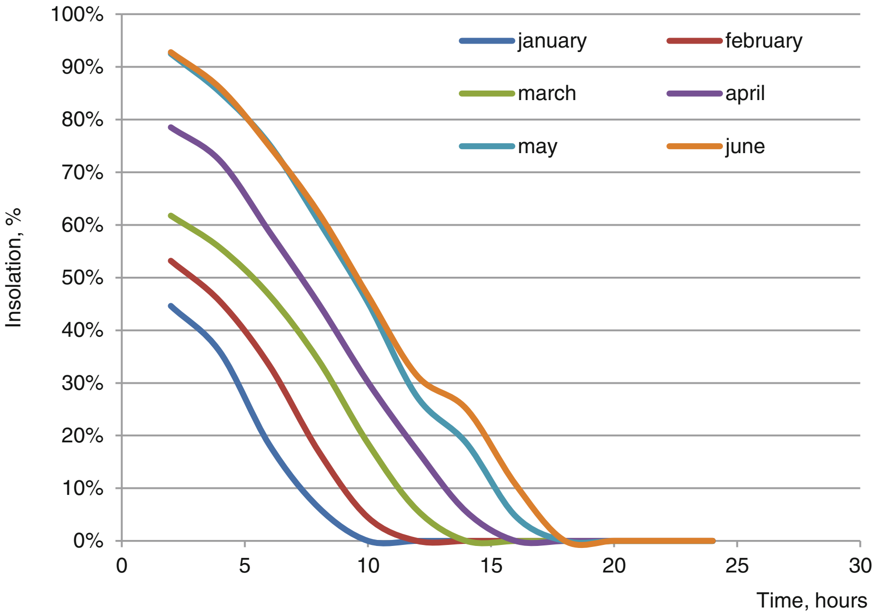


Fig. 4 Daily insolation index $W_{I(t)}$, including months of the first half-year

range of 20–30%, which may indicate an observed increase in insolation after the east and just before sunset.

The developed indicators $W_{I(t)}$ and $W_{P(t)}$ have a common time domain, so they can be applied to a common graph and read points of mutual intersection determining the value of the coverage of energy demand in a given month. The application was presented on the example of the two months of February and June as shown in the graph (Fig. 5). The graph shows that the coverage of the energy needs of PV plants is 27% for February and 44% for June.

From the graph (Fig. 5), it is still relatively easy to deduce that the maximum displacement for the $W_{P(t)}$ indicator towards time decreasing values by changing the profile will increase the degree of coverage of the wastewater treatment plant with the electricity generated from the PV farm. It is also easy to analyze the potential use of a waste water storage tank in the night. In the case of a storage tank with capacity to store wastewater over four hours, the use of PV energy can be increased to 60% in June and 40% in February. It should be noted that the developed methodology based on two indicators $W_{I(t)}$ and $W_{P(t)}$ is easy to interpret. However, in the case of storage of electricity from PV independently of the form of stored energy requires recalculation of the indicators and load profile electrical systems of analyzed objects.

At the last stage of the study, the model was validated for the first half of the year as shown in the graph (Fig. 6).

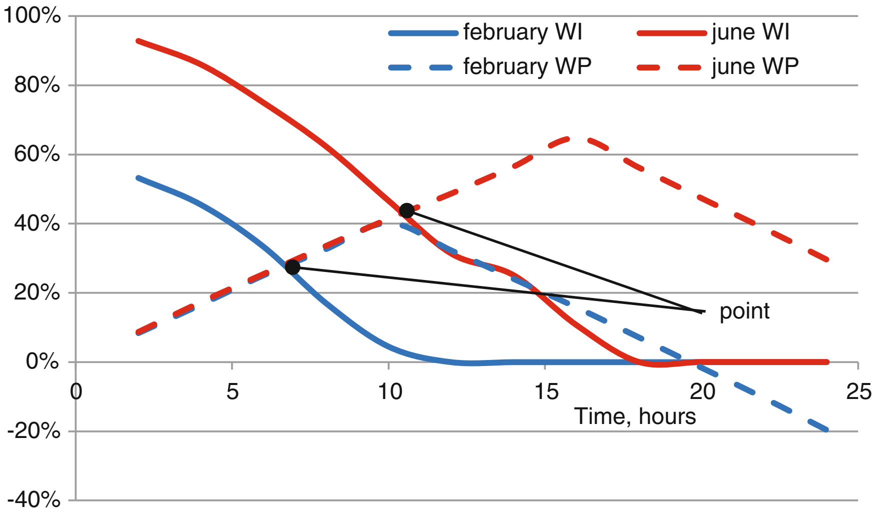


Fig. 5 Calculation of energy demand covering index by PV power station of sewage treatment plant (February, June)

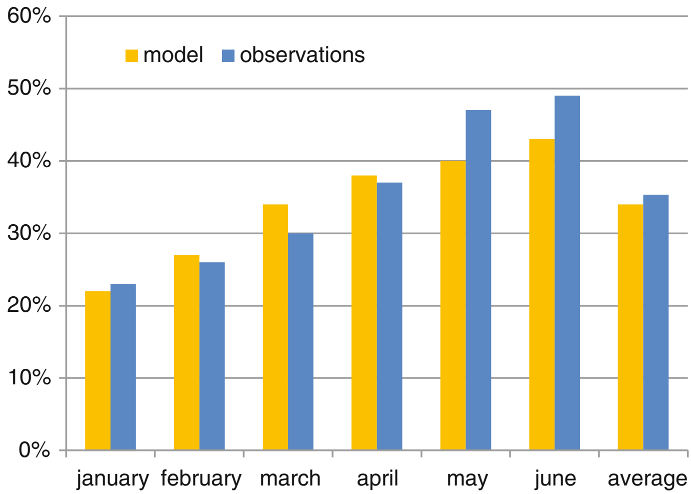


Fig. 6 List of indexes designated from working model of mikro-PV power station

The biggest errors of the model were observed for May and June respectively 17 and 14%, what undoubtedly results from the oversized PV power system with the temporary power 100 kWp. The analysis shows that the power of PV station should not exceed 75 kWp. In contrast, in the first four months of 2017 4–5-day breakdowns occurred, resulting in underestimation at the level of real coverage of energy in the range of 13–15%. It can be stated that in this case the model underestimates the degree of energy coverage in the range of 10–17%, what was caused by oversizing of the PV power station by 30%, and from the fact that in this paper we used the averaged year insolation data.

5 Conclusions

1. Elaborated model served to specify the energy demand coverage in sewage treatment plant and is a first such solution, in which the maximum sunlight portion was designated on level about 640 W/m^2. That is 60% of maximum temporary solar flux density in power station placing.
2. The power demand profile modification by sgn(t) allowed elaboration of simply power profile index, in which the extremum is the possible value of the energy demand grade from PV power station, assuming installed power rising to infinity.
3. Developed models for May and June do not estimate levels of coverage at 17 and 14%, what is undoubtedly caused by an oversized PV power station with a power of 100 kWp, and the analysis showed that the power of PV station should not exceed 75 kWp.
4. Underestimation of real coverage at the level of 13–15% in the four months of 2017 resulted from the breakdowns occurrence lasting for about 4–5 days duration.

The investigation of developed methodology allowing to model the degree of energy demand coverage from PV microelectronics will be continued, not only on a larger scale but also on other load profiles.

References

1. Główny Urząd Statystyczny. Bank Danych Lokalnych. (Central Statistical Office. Local Data Bank). http://stat.gov.pl/bdl/app/strona.html?p_name=indeks
2. Izba Gospodarcza "Wodociągi Polskie" 2017. http://www.cenywody.pl/
3. Bodik, I., Kubaská, M.: Energy and sustainability of operation of a wastewater treatment plant. Environ. Prot. Eng. **39**, 15–24 (2013)
4. Pitas, V., Fazekas, B., Banyai, Z., Karpati, A.: Energy efficiency of the municipal wastewater treatment. J. Biotechnol. **150**(Supplement), 163–164 (2010)
5. Kneppers, B., Birchfield, D., Reviewer, M.L., Easton, L., Collins, N., Wilson, D., et al.: Energy-water relationships in reticulated water infrastructure systems. Water Supply (kWh/Capita) (2009)
6. Mizuta, K., Shimada, M.: Benchmarking energy consumption in municipal wastewater treatment plants in Japan. Water Sci. Technol. **62**(10), 2256–2262 (2010)
7. Longo, S., d Antoni, B.M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., et al.: Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. Appl. Energy **179**, 1251–1268 (2016)

8. Prognoza kosztów utrzymania i eksploatacji oczyszczalni ścieków w Lubiszynie. Załącznik do Uchwały Rady Gminy Lubiszyn Nr XIX/135/2012 z dn.30.10.2012r
9. Boruszko, D., Miłaszewski, R., Piotrowski, P.: Ocena ekonomicznej efektywności komunalnej oczyszczalni ścieków w gminie Sokoły. Middle pomeranian scientific society of the environment protection annual set the environment protection. vol. 15, pp. 1086–1097 (2013)
10. Rauba, E., Rauba, K.: Analysis of possibilities for fulfillment of water services costs recovery principle for the example of wastewater treatment plants located the north-eastern Poland. Ochrona Środowiska i Zasobów Naturalnychn **40**, 542–548 (2009)
11. Szul, T., Knaga, J., Nęcka, K.: Multi-criterion optimisation of photovoltaic systems for municipal facilities TEKA Komisji Motoryzacji i Energetyki Rolnictwa **13**(2), 67–72 (2013)
12. Knaga, J., Nęcka, K.: Analysis of solar energy for the purpose of implementation of photovoltaic systems for a drinking water intake station. Logistyka **5**, 199–206 (2015)
13. Bławat, F.: Analiza Ekonomiczna. Wydawnictwo Politechniki Gdańskiej. Gdańsk (2010)
14. Jerzemowska, M. (red.): Analiza ekonomiczna w przedsiębiorstwie. PWE. Warszawa (2006)
15. Johnson, H.: Ocena projektów inwestycyjnych. Maksymalizacja wartości przedsiębiorstwa. LIBER. Warszawa (2000)
16. Chae, K.-J., Ren, X.: Flexible and stable heat energy recovery from municipal wastewater treatment plants using a fixed-inverter hybrid heat pump system. Appl. Energy **179**(1), 565–574 (2016). https://doi.org/10.1016/j.apenergy.2016.07.021
17. Chae, K.J., Kang, J.: Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. Energy Convers. Manage. **75**, 664–672 (2013). https://doi.org/10.1016/j.enconman.2013.08.028

Use of Straw as Energy Source in View of Organic Matter Balance in Family Farms

Maciej Kuboń, Sławomir Kocira, Anna Kocira and Danuta Leszczyńska

Abstract The paper presents possibilities of using straw as an energy source with reference to the organic matter balance. We carried out the survey in 30 family farms by means of calculation of the amount of the produced straw and its management trends. We determined that 7 farms were selling all produced straw for energy purposes and in the remaining ones, straw was used in animal production or ploughing up. In farms, which were selling straw for energy purposes, a negative organic matter balance was reported. Ploughing up of straw would allow obtaining a positive value of the OMB [Organic Matter Balance] in 5 out of 7 farms. The calculations enabled us to state that designation of straw for energy purposes in farms, which use it in agricultural production or ploughing up, would cause reduction of organic matter balance to negative values in majority of these farms. Therefore, straw may be designated for energy purposes only in these farms, where the organic matter balance (without straw) is at a satisfactory level or after—crops designed for ploughing up are cultivated. Statistical analysis proved that despite an additional income from selling straw, both the final production and standard gross margin do not differ significantly from those obtained in farms which use straw in agricultural production.

Keywords Biomass · Organic matter balance · Farms

M. Kuboń (✉)
University of Agriculture in Krakow, 30149 Krakow, Poland
e-mail: maciej.kubon@ur.krakow.pl

S. Kocira
University of Life Science in Lublin, 20950 Lublin, Poland

A. Kocira
State School of Higher Education in Chelm, 22100 Chelm, Poland

D. Leszczyńska
Institute of Soil Science and Plant Cultivation-State Research Institute, 24100 Pulawy, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_53

1 Introduction

Within the last 20 years, many studies on the use of straw for energy purposes have been written in Poland [1, 2]. The papers the most often deal with advantages resulting from replacing traditional energy sources with energy from biomass [3]. According to Jarosz et al. [4] each agricultural biomass may be used for energy purposes if basic function of agriculture, namely production of food, is performed [5]. However, in only few papers, a reference to the second crucial aspect can be found, namely to the impact of use of straw as an energy source on the organic matter balance in soil.

According to Kopiński and Kuś [6] the soil organic matter balance made for evaluation purposes on the agricultural land in Poland was negative in Poland in 2007–2009 and it was at the average of -0.49 t ha^{-1}. Data for the country or region are mainly approximate. The most important it to balance the organic matter in a farm to the positive value and the best if it is between 0.4 and 1.5 t ha^{-1} AL [arable land] [7]. The objective of the paper is to evaluate the impact of straw consumption in the investigated farms (for agricultural and energy purposes) on the organic matter balance in a farm and economic effects of a farm expressed with the standard gross margin and final production.

2 Materials and Methods

The material used in analyses comes from the research carried out in 2009–2012 on the area of the entire country as a part of the scientific project executed by the ITP [Institute of Technology and Life Sciences] Warsaw Branch (NCBiR [the National Centre for Research and Development] No 1204306/2009) titled "Technological and ecological modernization of the selected family farms". The analysed data from 30 family farms. The collected data according to the methodology presented in Wójcicki's paper [8]. The organic matter balance was calculated after Kopiński and Kuś [6] assuming the coefficient from the Code of Good Agricultural Practice [9].

The analysed farms were divided into two groups:

- farms which use straw as an energy source,
- farms which do not use straw as an energy source.

The Shapiro–Wilk test was performed for the normal distribution of data. The test which was carried out proved that the variables: intensity of production organization ($p = 0.4711$), organic matter balance ($p = 0.2037$) and standard gross margin ($p = 0.0501$) have a normal distribution. The animal livestock ($p = 0.0095$) and final production ($p = 0.0000$) variables do not have a normal distribution. The research on uniformity of variance with Levene's test proved no homogeneity of variance for the standard gross margin ($p = 0.0004$) and final production

($p = 0.0013$) variables. Therefore, U Mann-Whitney's test was applied for analysis of significance of differences at $\alpha = 0.05$.

3 Results and Discussion

Grains constituting 50% of AL prevailed in the structure of crops in the investigated farms (Fig. 1). A great participation of meadows and pastures in the structure of crops, which is 20.4%, proves a developed animal production. Root crops (mainly sugar beets) and legume plants were cultivated in these farms. Rape was the least cultivated plant and it covered only 2.1% of the agricultural land area.

The area of the agricultural land in the analysed farms was between 12.10 and 85.00 ha and was at the average of 38.28 ha (Table 1). It was 3 times higher than the national average, which in 2012 was 10.14 ha. Some farms did not have permanent grassland (meadows and pastures). The average livestock expressed in LSU per 100 ha of AL was 94.1. One farm did not carry out the animal production and the highest livestock was 149.2 LSU 100 ha^{-1} and was compliant with recommendations set forth in the Code of Good Agricultural Practice [9]. Intensity of production organization in the investigated group of farms had an average variability (coefficient of variability 36%) and was between 117 and 954 point $farm^{-1}$. Economic effects of management expressed with the final production and standard gross margin were very varied and were at the average of 7.098 PLN thousand ha^{-1}, and the standard gross margin was 2.292 PLN thousand ha^{-1}.

The organic matter balance was very varied (coefficient of variability = 127%) and was between −0.59 and 1.27 t ha^{-1} AL. The surface area of grain cultivation

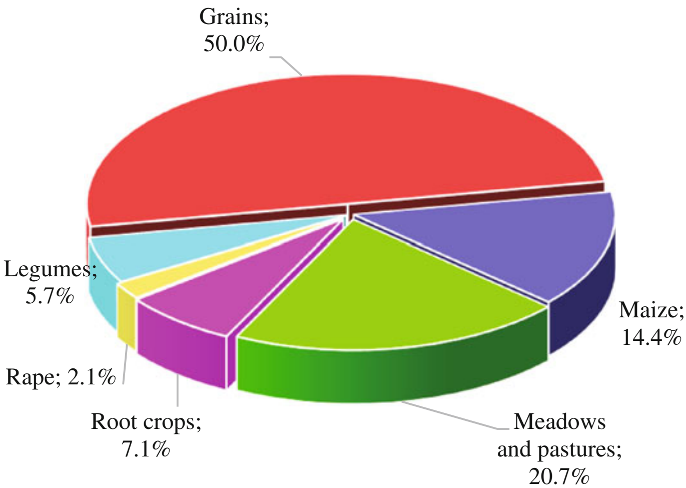


Fig. 1 Crop structure in the investigated farm group

Table 1 General characteristic of the investigated farms

Specification	Unit	Average	Minimum	Maximum	Coefficient of variability (%)
Surface area of AL	ha farm^{-1}	38.28	12.10	85.00	48
Arable land	ha farm^{-1}	30.34	4.06	61.00	93
Permanent grassland	ha farm^{-1}	7.93	–	32.55	58
Livestock	LSU 100 ha^{-1}	94.1	–	149.2	51
Intensity of production organization	point farm^{-1}	498	117	954	36
Final production	PLN thousand ha^{-1}	7.098	2.299	26.991	63
Standard gross margin	PLN thousand ha^{-1}	5.292	1.531	11.522	41

Table 2 Organic matter balance and straw production and its use

Specification	Unit	Average	Minimum	Maximum	Coefficient of variability (%)
Organic matter balance	t ha^{-1} AL	0.43	−0.59	1.27	127
Surface area of grain cultivation	ha farm^{-1}	19.13	3.39	55.50	72
Straw yield	t ha^{-1} AL	2.91	0.20	6.14	50
Straw designed for energy purposes	t ha^{-1} AL	0.59	–	3.94	209
Straw used in animal production and ploughed up	t ha^{-1} AL	2.32	–	9.14	90

was at the average of 19.13 ha at the coefficient of variability which was 72%. The average yield of straw per 1 ha of arable land (AL) was 2.91 t. In 7 farms straw was compacted and sold for energy purposes. In the remaining 23 farms, straw was designed for ploughing up or used in animal production. At the average 0.59 t ha^{-1} AL of straw was designed for sale and 2.32 t ha^{-1} AL was used in animal production or ploughed up (Table 2).

In 7 investigated farms a negative organic matter balance was the outcome of selling straw.

Figure 2 presents the change of the organic matter balance from the factual state (sale of straw) to the theoretical state (ploughing up straw instead of selling it). If straw had been left on the field in 5 farms, the organic matter balance would have been positive. Only in two farms, it would have a negative value. In those two farms, it was necessary to introduce organic matter to soil in the form of after-crop.

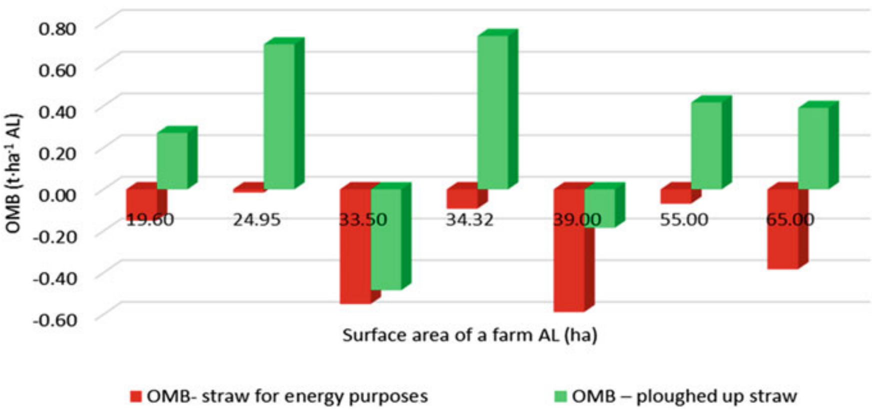


Fig. 2 Change of organic matter balance with its negative value in farms

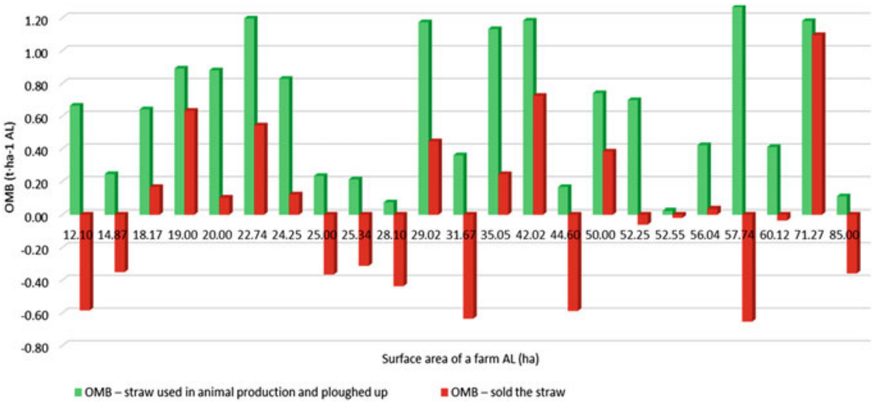


Fig. 3 Change of organic matter balance with its positive value in farms

In the remaining 23 farms organic matter balance was positive (Fig. 3) and in case of sale of straw for energy purposes in 11 farms it would decrease to negative values and only in 5 farms it would be at the level between 0.4 and 1.5 t ha^{-1} AL. In 5 farms straw may be designed for sale without negative effects for managing organic matter in a farm. In their papers Jarosz et al. [4] and Kopiński and Kuś [6] also pay attention to the necessity of satisfaction, in the first place, of the needs related to agricultural production (production of food) and only then surplus of straw may be devoted for energy purposes. On the other hand, Wójcicki [10] indicates the fact that only rape straw and a small part of wheat and rye straw may be used as an energy source. It results from the universal use of straw in various production technologies used in agricultural farms. Bielski and Jasiński [11] point at the possibility of using surplus of straw in the power industry.

Statistical analysis which was carried out with U Mann-Whitney's non-parametric test, proved significant differences in the intensity of production organization ($p = 0.0081$), livestock ($p = 0.0108$) and organic matter balance ($p = 0.0001$) between farms which sell straw for energy purposes and farms which use straw in agricultural production. Statistical analysis did not prove any significant differences between the investigated groups of farms for the final production ($p = 0.7314$) and standard gross margin ($p = 0.4327$).

4 Conclusion

The analysis of the obtained data allowed a statement that in farms, which were selling straw for energy purposes a negative organic matter balance was reported. Ploughing up of straw would have allowed obtaining a positive value of OMB in 5 out of 7 farms.

Made calculations allowed us to state that designation of straw for energy purposes in farms, which use it in agricultural production or ploughing up, would cause in majority of these farms a reduction of organic matter balance to negative values. Therefore, straw may be designated for energy purposes only in these farms, where the organic matter balance (without straw) is at a satisfactory level or after—crops designed for ploughing up are cultivated.

Statistical analysis proves that despite an additional income from selling straw, both the final production and standard gross margin do not differ significantly from those obtained in farms which use straw in agricultural production.

References

1. Niedziółka, I., Szpryngiel, M., Kachel-Jakubowska, M., Kraszkiewicz, A., Zawiślak, K., Sobczak, P., Nadulski, R.: Assessment of the energetic and mechanical properties of pellets produced from agricultural biomass. Renew. Energy **76**, 312–317 (2015)
2. Lisowski, A., Bulinski, J., Gach, S., Klonowski, J., Sypula, M., Chlebowski, J., Kostyra, K., Nowakowski, T., Struzyk, A., Swietochowski, A., Dabrowska-Salwin, M., Stasiak, P.: Biomass harvested at two energy plant growth phases for biogas production. Ind. Crops Prod. **105**, 10–23 (2017)
3. Malaga-Tobola, U., Tabor, S., Kocira, S.: Productivity of resources and investments at selected ecological farms. Agric. Agric. Sci. Proc. **7**, 158–164 (2015)
4. Jarosz, Z., Faber, A., Borzęcka-Walker, M., Pudełko, R.: Estimating and regionalisation of biomass potential from cereal production. Stowarzyszenie Ekonomistów Rolnictwa i Agrobiznesu, Roczniki Naukowe **16**, 99–103 (2014)
5. Krolczyk, J.B., Latawiec, A.E., Kubon, M.: Sustainable agriculture—the potential to increase wheat and rapeseed yields in Poland. Pol. J. Environ. Stud. **23**(3), 663–672 (2014)
6. Kopiński, J., Kuś, J.: Influence of organization changes in agriculture on the management of organic matter in soil. Problemy Inżynierii Rolniczej **2**, 47–54 (2011)
7. Kocira, S.: Technical and technological modernisation of family farms in the process of implement-ing sustainable agriculture. TWN Libropolis, Lublin (2013)

8. Wójcicki, Z.: Technologiczna i ekologiczna modernizacja wybranych gospodarstw rodzinnych. Cz. I. Program, organizacja i metodyki badań. IBMER, Warszawa (2009)
9. Duer, I., Fotyma, M., Madej, A.: Kodeks Dobrej Praktyki Rolniczej. Ministerstwo Rolnictwa i Rozwoju Wsi, Ministerstwo Środowiska, Warszawa (2004)
10. Wójcicki, Z.: Renewable energy versus rural environment protection. Infrastruktura i Ekologia Terenów Wiejskich PAN oddział w Krakowie **2**(1), 33–48 (2006)
11. Bielski, S., Jasiński, A.M.: Analysis of local agricultural biomass resources in łasin community. Stowarzyszenie Ekonomistów Rolnictwa i Agrobiznesu, Roczniki Naukowe **16**, 28–33 (2014)

Storage of Heat Excess from a Plastic Tunnel in a Rock—Bed Accumulator: Tomato Yield and Energy Effects

Sławomir Kurpaska, Hubert Latała and Paweł Konopacki

Abstract The paper presents the outcome of experimental research which was carried out in real conditions on tomato production in a plastic tunnel. Plastic tunnels with dimensions of 9 × 30 were covered with double PE plastic with an air insulation layer. Devices responsible for microclimate inside the facility were controlled with a climate computer. Two facilities where tomatoes were cultivated in the April–October cycle were analysed. A rock-bed accumulator was installed in one of the tunnels. The system of heat accumulation comprised elements which suck hot air from the upper part of the facility and the system which distributes heated air to the plant zone. Heat storage in the accumulator was performed with the use of an autonomous control system. This system, based on the algorithm, controlled both the charging and discharging process including the set parameters of the microclimate inside the facility. The energy effects (the amount of heat, parameters of the microclimate inside the tunnel), issues concerning drying and humidification of air pressed through the stone bed and the amount and quality of tomato yield were analysed. The effects of accumulation were calculated into fuel consumption and the reduction of hazardous substance emitted to atmosphere was calculated. Moreover, the obtained effects in the form of plant yield were presented.

Keywords Rock-bed accumulator · Tunnels · Tomato · Effects

S. Kurpaska (✉) · H. Latała
Department of Production Engineering and Power Energy, University of Agriculture, Kraków, Poland
e-mail: rtkurpas@cyf-kr.edu.pl

H. Latała
e-mail: hubert.latala@urk.edu.pl

P. Konopacki
Institute of Horticulture, Skierniewice, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_54

1 Introduction

Plant cultivation under controlled conditions (facilities under covers) stimulates to apply innovations related to the reduction of energy consumption and optimal control of plant growth factors (temperature, relative air humidity, solar radiation and feeding plants with carbon dioxide). It is known that searching for technical solutions used in the production processes should be integrally related to the improvement of the product quality and reduction of its costs. Undoubtedly, reduction of production costs in facilities under covers may be performed, inter alia, by using the excess of heat from the inside of the facility for heating the object. This issue, for crops under covers, concerns both the type of the object structure and its equipment. Many scientific centres have undertaken research concerning the impact of the object structure, efficiency of heat storage in the storage bed including aspects of the heat demand. From the point of view of the facility structure, Abreu et al. [1] analysed the impact of its structure (single tunnel, blocked) on the effect of cultivated tomatoes. Condori et al. [2] presented results of their research related to the use of heat from the inside of the prototype greenhouse for drying vegetables (sweet pepper, garlic). Moreover, similar issues concerning the use of waste heat from the inside of the facility were analysed by Fuller and Charters [3] determining possibilities of using this heat from a production plastic tunnel for drying grapes. Li et al. [4] carried out research in order to determine daily temperature changes, relative moisture and solar radiation and for analysis of microclimate characteristic in naturally vented greenhouses. Kothari and Panwar [5] developed an analytical thermal model in a greenhouse in order to estimate parameters of the internal microclimate. The issue of the heat balance including processes which take place in a greenhouse enforced by the heating system and solar radiation getting inside the facility was analysed by Geol et al. [6]. On the other hand, Kendirli [7] analysed setting towards the geographical directions various structures of greenhouses, concluding that for the northern latitude the east-west orientation improves effectiveness of the solar energy use. Singh and Tiwari [8] analysed the total heat demand and the amount of heat obtained from solar radiation for five different types of greenhouse structures. Parra et al. [9] developed a mathematical model for determination of the natural ventilation intensity, where they determined a percentage share in the amount of the exchanged air in relation to locations of vents. Papadakis [10] carried out investigation of natural ventilation by analysis of tracking gases showing a limit velocity of wind at which also temperature difference between the inside of the facility and the surroundings should be included. Teitel et al. [11] analysed the impact of the wind direction and velocity on the air flow type in vents of a greenhouse [12]. From the range of heat excess storage carried out a series of experiments in the accumulator, where the steel pipes system was installed (positioned in a loop shape) placed in the ground. Kurklu [13] in his review paper presented constructional solutions of heat accumulators which use phase changes of material (salt hydrates, paraffin and polyethylene glycol) along with determination of potential heat effects of their use in a greenhouse.

The presented review of research works shows clearly that the use of heat excess from the inside of the facility, which was formed from solar radiation, in the process of heating a horticultural facility is one of the solutions which are used for the microclimate change. This issue is an object for the research carried out in plastic tunnels located in the University of Agriculture facilities and the Institute of Horticulture in Skierniewice [14]. In the process of heat storage, both thermal processes as well as mass exchange processes occur (condensation, evaporation) through changes of steam concentration in air. Therefore, determination of these effects which were formed during pressing air to the rock-bed storage is an essential problem. Plant reaction to the introduced innovations is a separate issue. Analysis of these issues will be the main objective of the paper.

2 Material and Method

Research was carried out in two plastic tunnels: in one of them (in the half of its length separated with an additional wall) a rock—bed accumulator was installed. Tunnels with dimensions of 9 $\times$ 30 m were covered with a double PE plastic; there was air in the space between the plastic layers. Parameters of the microclimate of plants were maintained at the level recommended in the cultivation technology. Both facilities had identical control systems of vents location. Figure 1 presents the schematic representation of the measurement stand.

In the tunnel with a heat accumulator (Fig. 1a), air from the inside of the facility was supplied through the perforated pipes system and pressed into the rock-bed accumulator. The accumulator comprises three sections with an effective area of: one section −38.5 and two section 18.7 m^2 each and the height of the rock layer of 0.7 m. The air pressing system consists of perforated pipes located in the upper part of the tunnel (1) through which a vent (W) pressed air into perforated pipes (2) located on the bottom of the rock-bed accumulator (porphyry rock with

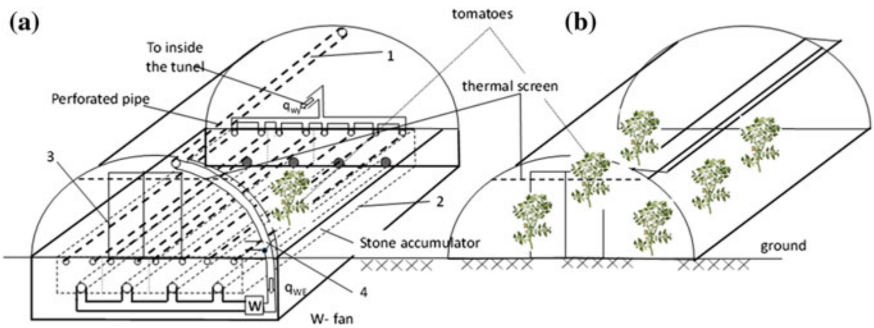


Fig. 1 Schematic representation of measurement stand: **a** Tunnel with heat accumulator and **b** control tunnel

dimensions within the range of 30–63 mm). Air, upon fighting over the flow resistance flew into the inside of the facility thanks to the perforated pipes installed in the surface layer of the bed connected with the connection pipe (3). The following sensors were used in the measurements: air temperature—with PT 1000 measure, air moisture—TS110 transducer, wind velocity—with MAX 40H time anemometer, solar radiation intensity with LP PYRA 02AV pyranometer, air flow—with Air Mini 64 measures. The Original Computer Measurement System which with 120 s sampling time monitored and archived the measured parameters was used in the tests. This system was also used for controlling the system operation through the developed algorithm. The control was carried out through a change of location of flap valves installed at the air inflow to particular sections and charging and discharging heat from the rock accumulator.

2.1 Description of Experiments

The considered system of the rock-bed accumulator may operate in the charging and discharging system of the accumulator. In the charging process, the control of the flap valve location item 4 in Fig. 1a takes place with an algorithm, where a difference in temperature between temperature over a protection screen and the temperature in the accumulator (Δt_1) as well as the temperature flowing out of the accumulator and temperature inside the facility was a controlling parameter (Δt_2). The charging process was carried out when Δt_1 = 2 K and for the discharging process the minimum temperature of 18 °C was assumed; the difference between the temperature of the rock-bed accumulator and the temperature of the air which was flowing out from the accumulator is Δt_2 = 4 K. Standard treatments were carried out during experiments. Plants were cultivated on ballots filled with the mixture of peat and tree bark. The plant fertigation process (irrigation and fertilization) was carried out with a fertilizing mixer and the concentration of the fertilizers was compliant with the production technology requirement.

2.2 Theoretical Analysis

By marking the average air temperature inside the facility with Twew and by omitting the air stream exchanged by means of ventilation, an equation describing the air temperature change inside the facility assumes the following form:

- tunnel with the heat accumulator:

$$V_{p1} \cdot \rho_1 \cdot c_{w1} \frac{dT_{wew1}}{d\tau} = q_{R1} \pm q_{ak} - q_{TR1} - q_{str1} \pm q_{vent1} \quad (1)$$

- tunnel without the heat accumulator:

$$V_{p2} \cdot \rho_2 \cdot c_{w2} \frac{dT_{wew2}}{d\tau} = q_{R2} - q_{TR2} - q_{st2r} \pm q_{vent2} \tag{2}$$

The sign (±) in the Eq. (1) stands for the case of pressing air into the accumulator—the accumulator loading cycle (−) and the case of supplying air from the accumulator to the inside of the facility—accumulator discharging cycle (+).

The simplifying assumptions were assumed in the analysis:

– a uniform heat stream used for plant transpiration (identical compaction, plant variety and size): $q_{TR1} = q_{TR2}$,
– a relative small difference in density($r_1 = r_2$), relative air heat ($c_{w1} = c_{w2}$), identical air volume inside the facility $V_1 = V_2$,
– a uniform heat stream which gets inside the facility through a transparent shield ($q_{R1} = q_{R2}$).

The total effect of the accumulator operation (*DQ*) is included with the difference of temperature inside the facility as a result of supplying heat from the accumulator and varied ventilation of the facility. Therefore, after including assumptions, transformation and simplification we finally obtain:

$$\Delta Q = U \cdot F_{osł}(T_{wew2} - T_{wew1})d\tau \tag{3}$$

Time intervals of 10 min were assumed for analysis. The obtained thermal effect was calculated into savings in fossil fuel (coal with calorific value of Wu = 18.9 MJ/kg was taken into analysis, thus, the fuel mass may be calculated from the relation:

$$m_{pal} = \frac{\Delta Q}{W_u \cdot \eta} \tag{4}$$

where, particular symbols stand for: *U*—coefficient of heat transfer through a shield, W/(m^{2}K) (the analysis assumed U = 5.3 W/(m^2/K).; F_{ost}—the shield surface, m^2; T_{wew1}, T_{wew2}—air temperature inside the facility with (T_{wew1}) and without (T_{wew2}) heat accumulator, °C, *h*—boiler performance. It was assumed that *h* = 0.7.

In the analysis, with the use of standard psychrometric relations, deficiency of partial pressure of water steam (vpd) inside the facility was also calculated. For the analysed sizes statistical analysis of differences at the level of significance a = 0.05 was carried out.

3 Results and Discussion

Investigations were carried out in April–October and tomato was a tested plant. The presented values of experimental factors were calculated as average 10-min values from measurements made with a sampling frequency of 2 min. Figure 2 presents the course of ambient conditions during the accumulator charging cycle.

As it is presented, during the charging process, the scope of changes of the measured values was within: air temperature outside the facility from 4.9 to 26.4 °C, relative moisture 35.4–91.1%, solar radiation intensity 72–555 W/m^2 and the wind velocity 0–16.1 m/s. During experiments the area of the accumulator was within 7.5–75.9 m^2, the pressed air stream 0.26–0.42 m^3/s, and the charging time from 4 min to almost 23.6 h. The lower value of the active area (11.1 m^2) of the accumulator than the surface area of the section (18.7 m^2) results from the fact that

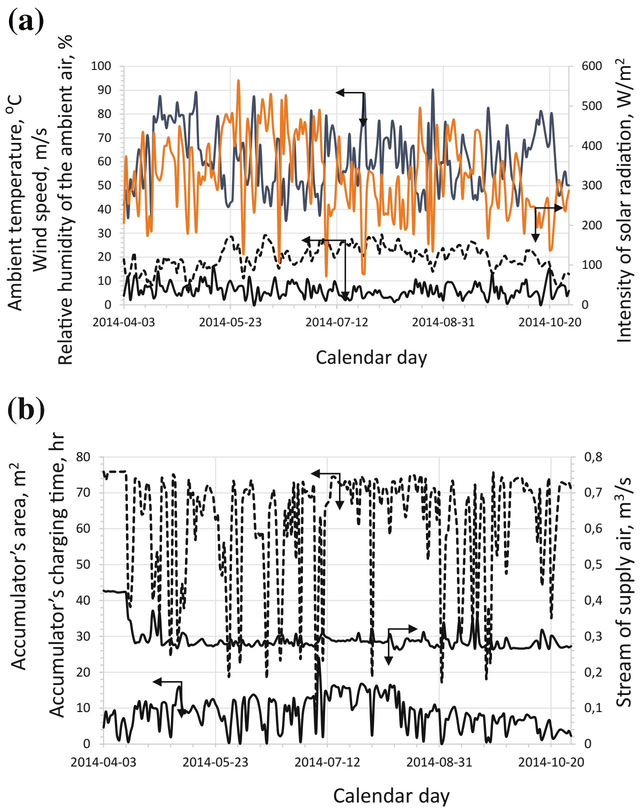


Fig. 2 Course of ambient conditions **a** and accumulator operation conditions and pressed air stream **b** during its charging

in the average value (10 min) based on which the surface area of the accumulator was calculated, the charging process was carried out only for 4 min.

Figure 3 presents the course of comparable values of the surroundings and the rock-bed accumulator operation during its discharging.

As it is presented, during this process, the scope of changes of the measured values was within: air temperature outside the facility from 0.4 to 20.8 °C, relative moisture 69.9–99.5%, solar radiation intensity 0–100.8 W/m^2 and the wind velocity 0–10.6 m/s. During experiments the area of the accumulator was within 38.5–75.9 m^2, the pressed air stream 0.32–0.453 m^3/s, and the discharging time from 0.1 to almost 20.3 h.

By comparing both processes we may notice that the charging process of the accumulator was initiated almost 2-weeks in advance before the process of discharging.

Figure 4 presents the course of temperature and relative air moisture and the calculated deficiency of water steam pressure (vpd) inside the investigated tunnels (with and without the rock-bed accumulator) for the time where the process of charging the accumulator was carried out.

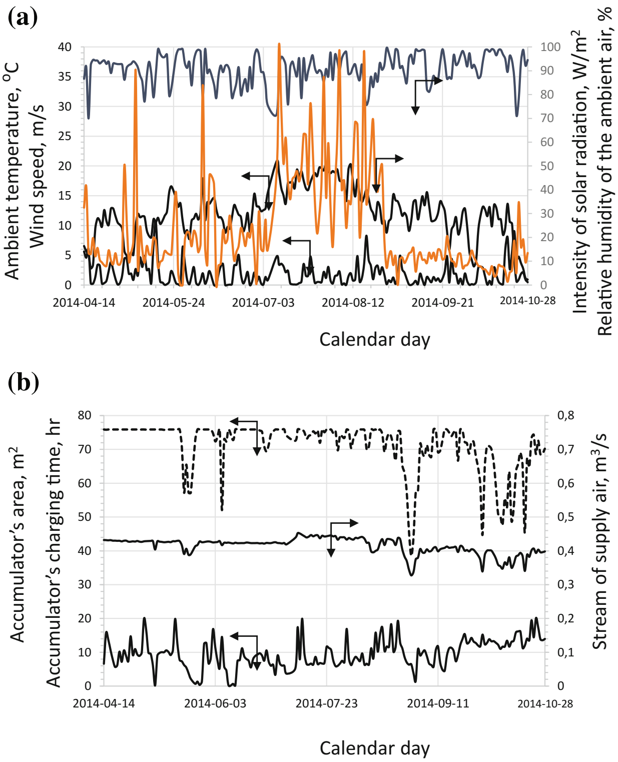


Fig. 3 Course of ambient conditions **a** and accumulator operation conditions and pressed air stream **b** during its discharging

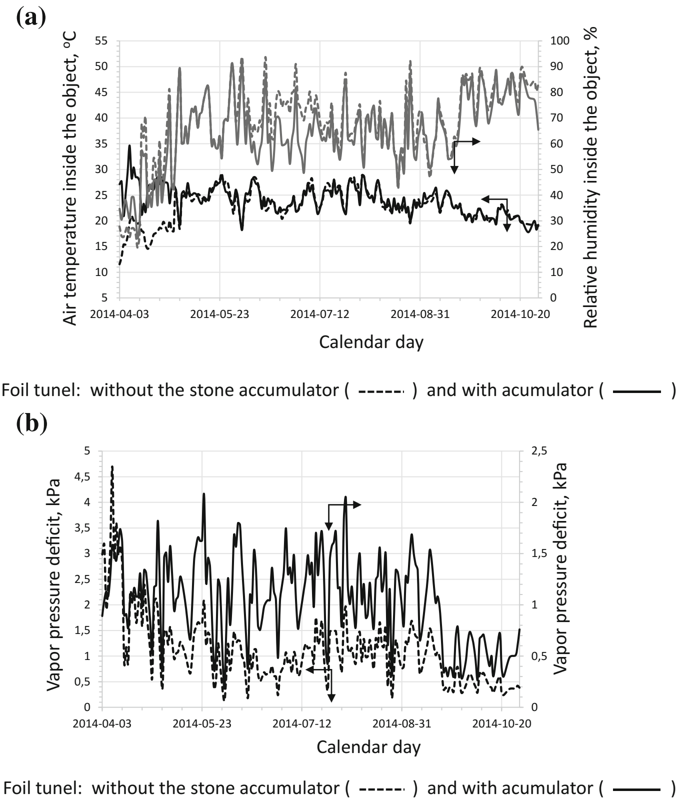


Fig. 4 Course of temperature and air relative moisture **a** and calculated value of water steam pressure deficiency **b** in investigated tunnels with and without accumulator during charging process

The course of the obtained values shows that in the investigated ambient conditions, the average value of the measured parameters in the tunnel with the heat accumulator was equal to: the air temperature 22.8 °C, air relative moisture 63.6%, and it was 1.07 kPa. On the other hand, for the facility without the bed accumulator, these values were respectively: 24.2 °C, 70.1% and 1.13 kPa. The statistical analysis proved that both temperature and moisture inside the facility differ statistically between each other: in case of vpd parameter, these differences are not statistically significant.

The above values in the accumulator discharge process were presented in Fig. 5.

The course of the obtained values shows that in the investigated ambient conditions, the average value of the measured parameters in the tunnel with the heat accumulator was equal to: the air temperature 17.1 °C, air relative moisture 87%, and it was 0.25 kPa. On the other hand, for the facility without the rock-bed

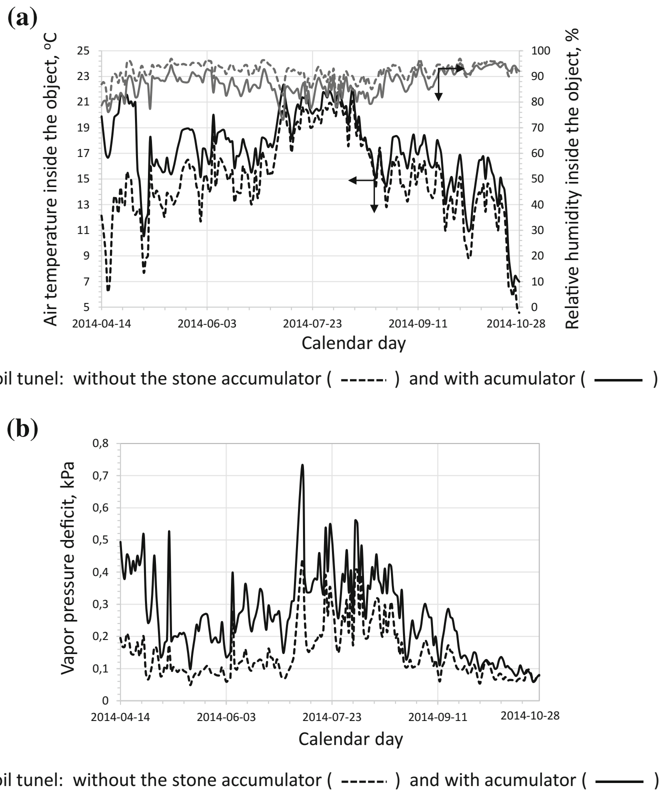


Fig. 5 Course of temperature and air relative moisture **a** and calculated value of water steam pressure deficiency **b** in the investigated tunnels with and without accumulator during discharging process

accumulator, these values were respectively: 14.8 °C, 92.1% and 0.13 kPa. The statistical analysis proved that the presented values differ statistically between each other.

Using the expired equations momentary savings in heat and accumulated savings in fuel were calculated. The analysis was carried out for the accumulator discharging process and the surface area of the tunnel which is 135 m^2. The obtained results were presented graphically in Fig. 6.

The obtained values reflect the amount of additional heat which should be supplied inside the facility in case there is a need to obtain there microclimate parameters. As one can see, the scope of changes in the amount of the saved heat is within 0.1—606 MJ of heat. In the entire cycle of cultivation almost 1625 kg of fuel (fine coal type) was saved. It corresponds to the reduction to atmosphere: 13.8 kg, CO_2—2.39 t; CO—30.5 kg; SO_2—10.4 kg and NO_x at the level equal to 2.2 kg.

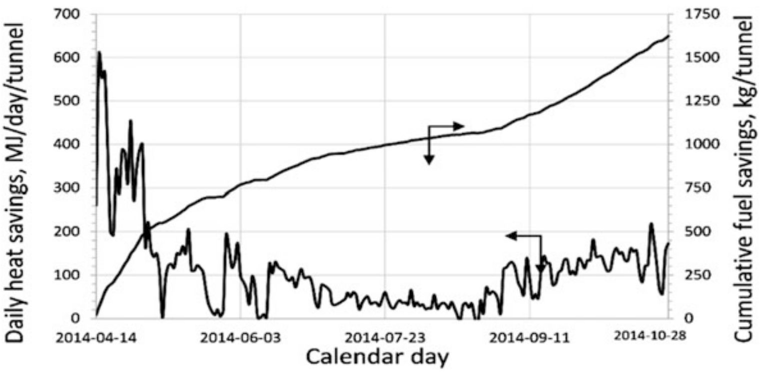


Fig. 6 Momentary and accumulated values of savings in heat and fuel during process of discharging the accumulator

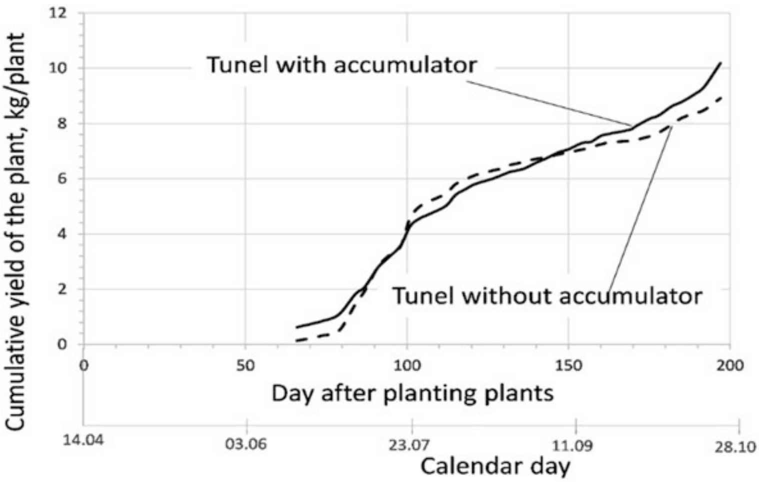


Fig. 7 Effects of plant yield in facility with and without rock-bed accumulator

The obtained effects of use of the rock-bed accumulator in the facility calculated into the commercial yield of tomatoes was graphically presented in Fig. 7.

It may be observed that in calculation in the facility with the heat accumulator, in comparison to the control facility, almost by 14% higher yield of cultivated tomatoes was obtained. In total, per one plant in the tunnel with a heat accumulator, approx. 10.2 kg and in the tunnel without the heat accumulator approx. 8.9 kg of tomatoes were obtained. The analysis which was carried out proved that these differences are statistically significant.

4 Conclusions

1. In the investigated facilities, average differences between the inside temperature (for the charging and discharging process) are from 1.4 to 2.3 K, between the relative moisture from 4.5 to 6.5% and deficiency of water steam pressure is from 0.06 to 0.11 kPa. Only during the charging process, differences in the deficiency of water steam are not statistically significant.
2. During the cultivation cycle in order to maintain the microclimate parameters at night the same as occur during the accumulator operation to the facility, approx. 12 kg of coal should be supplied to a unit surface area of the tunnel.
3. An annual reduction in the emission of noxious substances to atmosphere in the discharging cycle for the investigated facility with the surface area of 135 m^2 were: Dust—13.8 kg, CO_2—2.39 t; CO—30.5 kg; SO_2—10.4 kg and NO_x at the level equal to 2.2 kg.
4. In comparison to the control facility, in the tunnel with the heat accumulator almost by 14% higher yield of cultivated tomatoes was obtained: differences in the yield are statistically significant.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Abreu, M.J., Ferreira, V.C., Sottomayor, A., Vargues, A.C., Meneses, J.F.: Evaluation of greenhouse structures for tomato spring crops in the entre douro e Minho region of Portugal. Acta Hort. **559**, 169–176 (2001)
2. Condori, M., Echazu, R., Saravia, L.: Solar drying of sweet pepper and garlic using the tunnel greenhouse drier. Renew. Energy **22**(4), 447–460 (2001)
3. Fuller, R.J., Charters, W.W.S.: Performance of a solar tunnel dryer with microcomputer control. Sol. Energy **59**(4–6), 151–154 (1997)
4. Li, A., Huang, L., Zhang, T.: Field test and analysis of microclimate in naturally ventilated single-sloped greenhouses. Energy Build. **138**(1), 479–489 (2017)
5. Kothari, S., Panwar, N.L.: Steady state thermal model for predicting microclimate inside the greenhouse. J. Inst. Eng. (India). Agric. Eng. **88**(2007), 52–55 (2007)
6. Geoola, F., Kashti, Y., Peiper, U.M.: A model greenhouse for testing the role of condensation, dust and dirt on the solar radiation. J. Agric. Eng. Res. **71**(4), 339–346 (1998)
7. Kendirli, B.: Structural analysis of greenhouses: a case study in Turkey. Build. Environ. **41** (7), 864–871 (2006)
8. Singh, R.D., Tiwari, G.N.: Energy conservation in the greenhouse system: a steady state analysis. Energy **35**(6), 2367–2373 (2010)
9. Parra, J.P., Baeza, E., Montero, J.I., Bailey, B.J.: Natural ventilation of parral greenhouses. Biosyst. Eng. **87**(3), 355–366 (2004)
10. Papadakis, G., Mermier, M., Meneses, J.F., Boulard, T.: Measurement and analysis of air exchange rates in a greenhouse with continuous roof and side openings. J. Agric. Eng. Res. **63** (3), 219–227 (1996)

11. Teitel, M., Tanny, J., Yakir, D.B., Barak, M.: Air flow patterns through roof openings of a naturally ventilated greenhouse and their effect on insect penetration. Biosyst. Eng. **92**(3), 341–353 (2005)
12. Ozgenger, L., Ozgener, O.: Energetic performance test of an underground air tunnel system for greenhouse heating. Energy **35**(10), 4079–4085 (2010)
13. Kurklu, A.: Energy storage applications in greenhouses by means of phase change materials (PCMs): a review. Renew. Energy **13**(1), 89–103 (1998)
14. Kurpaska, S., Latała, H., Rutkowski, K., Hołownicki, R., Konopacki, P., Nowak, J., Treder, W.: Storing heat surplus from a plastic tunnel in a rock—bed storage. Inżynieria Rolnicza, Nr **2**(136), 157–167 (2012). (in Polish)

Geophysical Methods in the Recognition of Geothermal Resources in Poland—Selected Examples

Michał Stefaniuk, Tomasz Maćkowski and Anna Sowiżdżał

Abstract Seismic and magnetotelluric methods are most frequently used under Polish conditions predominant by low temperature geothermal associated with sedimentary complexes and crystalline rocks. The application of those methods to recognizing of geological structure and differentiation of petrophysical parameters is presented in the work. The examples of hydrogeothermal investigation in sedimentary complexes of Polish Lowlands and crystalline rocks of Sudetes area are used. The results demonstrate that seismic structural interpretation and seismic inversion can effectively support the selection of areas optimal for future geothermal investments inside sedimentary complexes. Simultaneously, such methods can be important for determination of hydrogeothermal parameters of particular aquifer. Results of seismic inversion can be applied to porosity estimations. Within the crystalline rocks non—seismic methods are usually used, mainly different variants of magnetotelluric method. This method allows to recognize resistivity distribution in geological medium. Geothermal reservoirs inside crystalline rocks are usually connected with fractured tectonic zones conducting warm and mineralized water. Such zones appear as low resistivity at the background of predominant, radically high resistivity rocks.

Keywords Geothermics · Geophysical methods · Geothermal parameters
Seismics · Magnetotellurics

M. Stefaniuk (✉) · T. Maćkowski · A. Sowiżdżał
AGH University of Science and Technology, Krakow, Poland
e-mail: stefaniu@agh.edu.pl

T. Maćkowski
e-mail: mackowsk@agh.edu.pl

A. Sowiżdżał
e-mail: ansow@agh.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_55

1 Introduction

Geophysical methods are widely applied in geothermal issues. Low temperature geothermal associated mainly with sedimentary complexes and partly with crystalline rocks is predominant under Polish geological conditions. In this situation most frequently seismic and magnetotelluric methods are used. In the study of the structure and lithology of regular sedimentary complexes the most effective is the seismic reflection method. The results demonstrate that geophysical methods such as seismic structural interpretation and seismic inversion can effectively support the selection of areas optimal for future geothermal investments. Simultaneously, such methods can be important for determination of hydrogeothermal parameters of particular aquifer. Seismic inversion can be applied to porosity estimations. The application of non—seismic methods in recognition of sedimentary basins is rather supplementary. The magnetotelluric continuous profiling method was used for studying of near salt dome geological structure in the area of Polish Lowlands [1, 2, 3]. The spatial study with use of magnetotelluric soundings as well as magnetotelluric continuous profiling were applied to support seismic survey in recognition of hydrogeothermal condition in Kompina area [4]. Within the crystalline rocks non–seismic methods are usually used, mainly different variants of magnetotelluric method. This method is based on analysis of resistivity differentiation of geological medium with use of broad frequency range of natural or artificial electromagnetic field. Geothermal reservoirs inside crystalline rocks are usually connected with fractured tectonic zones filtrated by hot and mineralized water. Such zones appear as low resistivity at the background of predominant, high resistivity igneous or metamorphosed rocks.

In the work application of mentioned above methods to recognizing of geological medium structure and differentiations of petrophysical parameters is presented. The examples of hydrogeothermal investigation in sedimentary complexes of Polish Lowlands and crystalline rocks of Sudetes area are used. Seismic structural interpretation and seismic inversion were applied for determination of hydrogeothermal parameters of Lower Cretaceous and Lower Jurassic aquifers located in the Mogilno-Łódź Trough, central part of the Polish Lowlands (Fig. 1). Magnetotelluric continuous profiling was used to recognizing of tectonic zone conducting hot waters inside granitic Karkonosze Massif.

2 Geological Condition of Geothermal Resources Occurrence in Poland

Poland is characterized by low-temperature geothermal resources, defined as heat obtained from the geothermal fluid in the ground at temperatures of 150 °C or less. These kind of geothermal resources are typically used in direct-use applications, such as district heating, greenhouses, balneotheraphy etc. Geothermal resources are strictly geologically determined. Poland is situated at the interface between three main European geostructural units: the Precambrian East European Platform, the Paleozoic units of Central and Western Europe (Caledonian and Variscan) and the Carpathian range (part of the Alpine system). Each of these structures is characterized by distinct geothermal conditions. Sedimentary rocks cover almost whole territory of Poland, main exception is the area located in south-west of Poland (Sudetes Mts.) where mostly crystalline (igneous and metamorphic) rocks occur.

Geothermal energy in Poland is accumulated in four geothermal provinces: Polish Lowlands, Carpathians, Carpathians Foredeep and Sudetes Region. Each of these provinces is characterized by different geological conditions and different geothermal water parameters. The most prospective regions for geothermal energy development in Poland are connected with **Polish Lowlands** and **Podhale area** (Western Carpathians). Water in these areas are characterized by favorable temperatures (even above 90 °C) and relevant value of discharges of wells (to several hundred m^3/h). Low discharges of wells is the fundamental problem in the rest of analyzed regions (Carpathian and Carpathian Foredeep).

The principal resources of geothermal waters in the **Polish Lowlands** are accumulated in the Mesozoic groundwater horizons. Geothermal waters are accumulated first of all in the Lower Jurassic and Lower Cretaceous formations but significant resources of geothermal energy are accumulated also in the Upper Jurassic, Middle Jurassic, Upper Triassic and Lower Triassic formations [5, 6]. Polish Lowlands is one of the most prospective area for geothermal energy utilization in Enhanced Geothermal System [7]. Reservoirs favorable for EGS - Carboniferous and Lower Triassic sandstones located in the central part of Poland (the Mogilno-Łódź Trough region and a small part of the Kujawy Swell and Fore-Sudetic regions).

In Carpathian Foredeep the aquifers of the Cenomanian, Upper Jurassic, Devonian-Carboniferous and Miocene are most prospective. However, in these aquifers, the most favorable parameters for location of geothermal intakes occur in small areas and depth intervals. The Cenomanian aquifer is an exception, as high discharges (to 250 m^3/h) can be expected over the whole area of its occurrence (central part of Carpathian Foredeep). Zones with increased potential discharges of wells are sporadically encountered in the Upper Jurassic (tens m^3/h) aquifer and in the Miocene aquifer (above 100 m^3/h). The best hydrogeological and geothermal parameters that indicate the possibility of using the Miocene geothermal water occur in the depth interval 500–1500 m bsl. The remaining depth intervals seem to reveal low prospective because of low temperatures or weak hydrogeological parameters that determine low discharges of geothermal water intakes [8].

In the **Carpathians** the best reservoir and exploitation properties for geothermal waters utilization occur in the inner Carpathian—Podhale, represented by: favorable reservoir parameters and lithology, usually high yields and regional extent of the aquifer as well as recent recharge and low TDS. Podhale is a region in the Western Carpathians where geothermal waters are utilized recently and will be utilized in the future, preferably for heat generation but also for recreation and balneotherapy purposes. The reservoir rocks for geothermal waters are mainly Triassic carbonates, sometimes Jurassic sandstones and carbonates. The most prospective aquifer (subject of exploitation) occurs within the Middle Triassic limestones and dolomites and in overlying Middle Eocene carbonates at the depths of 1–3.7 km [9].

In the remaining part of the Carpathians reservoir parameters are much worse. Relatively low geothermal potential was found both in the flysch cover and in the geothermal aquifers of the Mesozoic-Paleozoic basement as well.

Definitely different geothermal conditions are present in the Sudetic Geothermal Region. **The Sudetic region** in SW Poland including the Sudetes Mts and the Fore-Sudetic Block limited to the NE by the Odra fault is an exception as compared to the rest of Poland's geological setting. Instead of large sedimentary basins of the Polish Lowland and the Carpathian foredeep or folded flysch formations of the external Carpathians, the Sudetes Mts consist mainly of old crystalline rocks covered with younger sediments. Precambrian and Lower Palaeozoic gneisses and schists with not uncommon marble intercalations were intruded by Upper Carboniferous granitoids which form among others the core of the Karkonosze-Izera massif. In synclinal structures the crystalline rocks are covered with Phanerozoic sediments (Silurian-Quaternary). Geothermal waters occur in this region only in the crystalline formations. Most of the fragmentary hydrogeothermal investigations carried out so far in the Polish part of the Sudetes were limited to zones of occurrence of thermal waters utilized for therapeutic purposes, or to a few areas in which prospection has been carried out for such waters [10, 11]. However, the Sudetic region is characterized by favorable thermal conditions. In Cieplice, water with temperature 86.7 °C was obtained from the depth 2002.5 m. For this reason, the Cieplice area located in the Sudetic geothermal region was a subject of a study to identify a perspective location for the HDR project in Poland [12] as well as to identify an appropriate location of binary systems [13].

3 Example of Seismic Data Interpretation in the Mogilno-Łódź Trough

The quality of seismic imaging is good in the shallow part of the newest seismic sections in the interval of Cretaceous and Jurassic measures occurring (up to 1000 ms—Fig. 2). The contacts of seismic reflections in the form of wedging could be seen that are connected among others with vanishing of Lower Cretaceous geothermal aquifer in the marginal part of study area (w—Fig. 2). In the deeper part of the trough seismic reflecting boundary connected with the roof of this aquifer (K2sp—Fig. 2) is clearly visible as a result of significant differentiation of acoustic impedances between carbonate sediments of Upper Cretaceous and porous sandstones of Lower Cretaceous. The good quality of seismic data in this interval allows to perform seismic inversion and evaluate variability of reservoir sandstones porosity.

Fig. 1 Location of geophysical survey for geothermal resources in Poland. 1—Example of seismic survey in Mogilno–Łódź trough; 2—example of magnetotelluric survey in Cieplice—Zdrój area

The seismic signatures typical for carbonate reefs are clearly legible in the Upper Jurassic sediments (r—Fig. 2). The reefs are created on the local anticlinal elevations connected with salt pillows occurring deeper in the Zechstein measures. Evident vanishing of reflections inside reef forms is observed, only chaotically dispersed parts of reflections of small amplitudes is visible. The seismic reflections in Oxfordian sediments are continuous outside reef forms. Reef forms occurrence causes lateral differentiation of seismic wave velocity that influence destructively on seismic imaging of deeper part of cross-section (em—Fig. 2). The characteristic narrow zones of noise level increase and breaks in reflections continuity are observed on seismic sections below the reefs bottoms. This seismic artefacts suggest occurrence of tectonic dislocations in Triassic and Zechstein measures. The seismic boundary between carbonate measures of Upper Jurassic and clastic sediments of Middle Jurassic is clear in the area of Mogilno—Łódź Trough and appear as reflection of high negative amplitude. However, there is little indication in seismic image of deeper seismic reflection connected with the roof of Lower

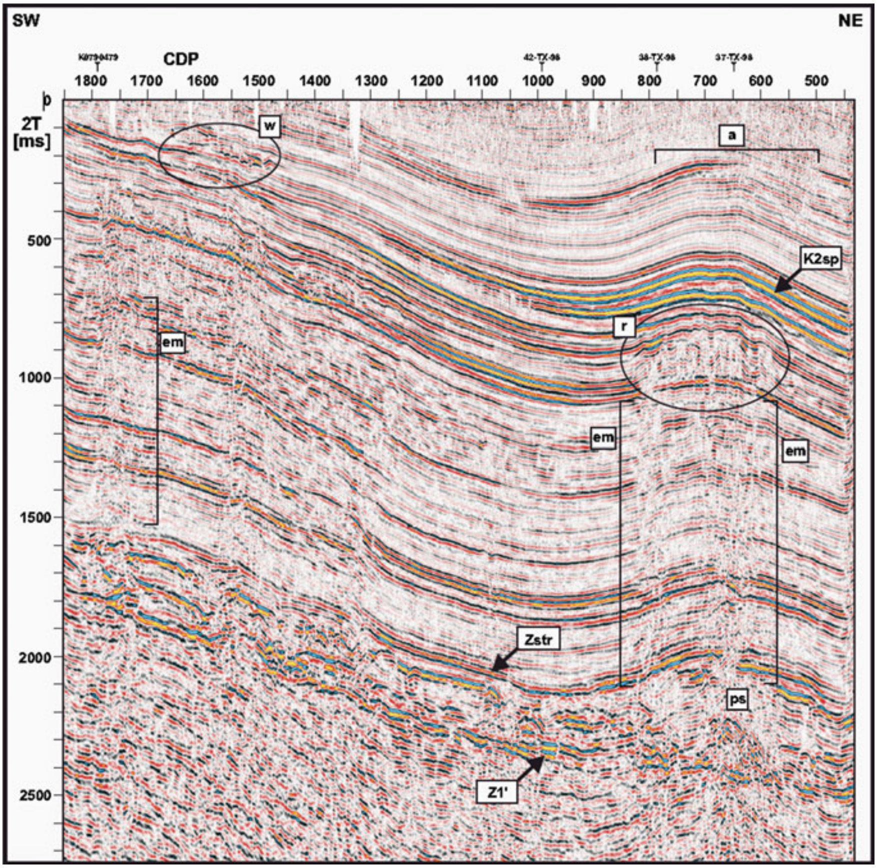


Fig. 2 Example of seismic cross-section from Mogilno–Łódź through

Jurassic geothermal aquifer, that is caused by relatively low contrast of acoustic impedance between clastic sediments of Middle and Lower Jurassic.

Strong seismic reflections of regional spread in the all area of Mogilno—Łódź Trough occur inside Triassic sediments and appear on important lithological boundaries Stratigraphically this reflections are connected with roofs of Keuper, Mushelcalc and Middle Bundsandstein. In the seismic image of Zechstein the zone of clear increasing of thickness of evaporitic sediments creating form of salt pillow is observed between reflections Zstr and Z1′, in the NE part of area (ps—Fig. 2). The process of forming of this salt structure generated the local elevations of younger sediments among others, mentioned above geothermal aquifers of Lower Cretaceous and Lower Jurassic (a—Fig. 2).

4 Recognizing of Tectonic Zones Inside Crystalline Rocks, Example from Karkonosze Granitic Massif

The area of the Sudetes comprising south-western part of Poland is considered to be prospective for geothermal water connected with zones of deep tectonic breaks and granitic massifs (Fig. 3). Thermal water and mineral water reservoirs in the Polish Sudetes Mts. are connected with near fault fractured carriers in high resistivity igneous and metamorphic rocks. Thus, they manifest themselves as low-resistivity zones [14, 15]. Magnetotelluric continuous profiling were used for location and recognition of fault zones filtrated by thermal and mineral waters in Sudetes area. The example of application of this method to the survey made in well-known area of thermal waters occurring inside the Granitic Karkonosze Complex close to the Cieplice-Zdrój town in Jelenia Góra Depression area (Fig. 3). The presented profile is located inside outcrops of granitic massif and cuts the zone of crossing faults (Fig. 4). The ascension filtration of thermal waters in this area is connected with fractured fault zone. The structure of the zone marks of evident resistivity

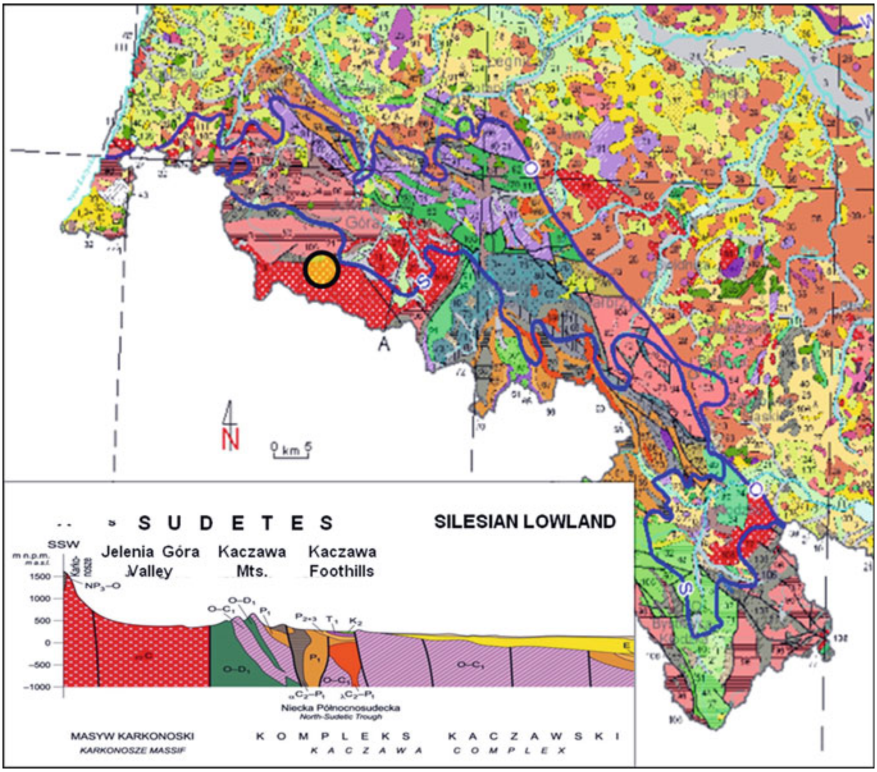


Fig. 3 Location of magnetotelluric survey in Cieplice–Zdrój area at the background of geological map of Sudetes Region. The map and cross-section: [19]

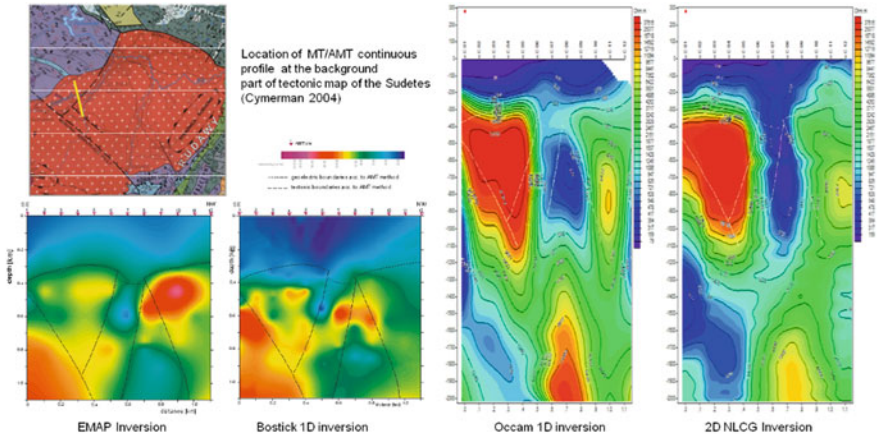


Fig. 4 Results of magnetotelluric survey made in Cieplice—Zdrój area

differentiation along the cross-sections computed with all of used algorithms of 1D inversion i.e. EMAP [16] and Occam [17] as well as with 2D inversion with use of non-linear conjugate gradients [18]; (Fig. 4). The presence of water in fractures inside fault zone causes remarkable decreasing of resistivity of geological medium. This effect is amplified by high water mineralization (salinity) and its higher temperature. As the result the resistivity is lowered up to range of 100 Ωm in tectonic zone, whereas normal resistivity of crystalline rocks used to reach several thousand Ωm. The roof of high—resistivity ingenuous rocks is covered by complex of relatively low—resistivity comparable with resistivity of tectonic zone. The thickness of this complex locally reaches 300–400 m.

5 Summary

Seismic and magnetotelluric methods are mainly applied in geothermal survey in Poland. Seismics is predominant in tasks related to sedimentary complexes of Polish Lowlands in structural interpretation as well as in recognizing of hydrogeothermal aquifer parameters. The role of magnetotelluric survey is auxiliary in that area. Different variants of magnetotelluric method are mainly used in recognition of zones of geothermal waters occurrence inside crystalline formations of Sudetic area. This waters generally filtrate through zones of open fractures accompanying extensional faults. Fractures filled by mineralized and hot water sufficiently decrise resistivity of geological medium. The anomalous resistivity zones could be determine by magnetotelluric soundings interpretation. As a conclusion it could be stated that application of geophysical survey can effectively support the selection of places for location of geothermal installations.

Acknowledgements This work was made in the framework of statutory research of Department of Fossil Fuels, contract no.: 11.11.140.031.

References

1. Czerwiński, T., Stefaniuk, M.: Badania magnetotelluryczne w rozpoznawaniu wgłębnj budowey wysadu. W: Wiesław Bujakowski (red.) Termiczna charakterystyka górotworu w rejonie wysadów solnych. Wyd. IGSMiE PAN, s: 93–102 (2003)
2. Stefaniuk, M., Czerwinski, T.: MT continuous profiling in structure and lithology recognition: Poland's case studies. In: 67th EAGE (European Association of Geoscientists & Engineers) conference & exhibition, 13–16 June 2005 Madrid, extended abstracts, pp. 1–4 (2005)
3. Stefaniuk, M., Czerwiński, T., Klityński, W., Wojdyła, M.: Zastosowanie metody magnetotellurycznych profilowań ciągłych w badaniach strukturalnych. Kwartalnik AGH Geologia, t. 34, z. 1, s: 43–69 (2008)
4. Bujakowski, W., Barbacki, A., Czerwińska, B., Pająk, L., Pussak, M., Stefaniuk, M., Trześniowski, Z.: Integrated seismic and magnetotelluric exploration of the Skierniewice, Poland, geothermal test site. Geothermics; 2010 vol. 39, issue 1: The European I-GET Project: Integrated Geophysical Exploration Technologies for Deep Geothermal Reservoirs, pp. 78–93 (2010)
5. Górecki, W., Sowiżdżał, A., Hajto, M., Wachowicz-Pyzik, A.: Atlases of geothermal waters and energy resources in Poland/environmental earth sciences **74**(12) (2015). ISSN 1866–6280
6. Sowiżdżał, A., Hajto, M., Górecki, W.: The most prospective areas for geothermal energy utilization for heating and power generation in Poland. In: Proccedings European Geothermal Congress 2016. Strasbourg, France (2016)
7. Sowiżdżał, A.: Possibilities of petrogeothermal energy resources utilization in central part of Poland. Appl. Ecol. Environ. Res. **14**(2), 555–574 (2016)
8. Sowiżdżał, A.: Characterization of geothermal reservoirs parameters in Polish part of Carpathian Foredeep. Carpathian J. Earth Environ. Sci. **10**(2), 237–246 (2015)
9. Górecki, W (ed.) et al.: Geothermal Atlas of the Eastern Carpathians. AGH KSE, Kraków (2013)
10. Dowgiałło, J.: The Sudetic geothermal region of Poland. Geothermics **31**, 343–359 (2002)
11. Ciężkowski, W.: Kierunki rozwoju i możliwości wykorzystania geotermii głębokiej na Dolnym Śląsku Instytut Górnictwa. Politechnika Wrocławska, Wrocław (2011)
12. Wójcicki, A., Sowiżdżał, A., Bujakowski, W. (eds.): Evaluation of potential, thermal balance and prospective geological structures for needs of closed geothermal systems (Hot Dry Rocks) in Poland. Warszawa/Kraków (2013). (in Polish)
13. Bujakowski, W., Tomaszewska, B. (eds.) et al.: Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary system in Poland, MEERI PAS, Kraków, 305 (2014)
14. Wojdyla, M., Farbisz, J., Klitynski, W., Stefaniuk, M.: Experimental exploration of geothermal and ore mineralized zones in Sudetes Mts in Poland with the use of AMT method. In: 70th EAGE conference & exhibition incorporating SPE EUROPEC, Rome 2008, Extended abstracts & exhibitors' catalogue. EAGE European Association of Geoscientists & Engineers, S. [1–5], P214 (2008)
15. Stefaniuk, M., Farbisz, J., Wojdyła, M., Sito, Ł.: Badania magnetotelluryczne na Dolnym Śląsku – nowe możliwości wykorzystania metody magnetotellurycznej w geologii strukturalnej, złożowej, poszukiwaniach wód mineralnych i termalnych. W: Mezozoik i kenozoik Dolnego Śląska: LXXXI zjazd Polskiego Towarzystwa Geologicznego; red. A. Żelaźniewicza, J. Wojewody & W. Ciężkowskiego; Polskie Towarzystwo Geologiczne.— Wrocław: WIND, 2011. s. 169–193 (2011)

16. Bostick, F.: A simple almost exact method of magnetotelluric analysis. In: Ward S. (ed.) Workshop on Electrical Methods in Geothermal Exploration. United States Geological Survey, Contract no.14080001-G-359, pp. 174–183 (1977)
17. Constable, S.C., Parker, R.L., Constable, C.G.: Occam's inversion: a practical algorithm for generating smooth models from electromagnetic sounding data. Geophysics **52**, 89–300 (1987)
18. Rodi, W., Mackie, R.L.: Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics **66**(1), 174–187 (2001)
19. Marks, L., Ber, A., Gogolek, W., Piotrowska, K., (sci.eds.): Geological map of Poland. Polish Geological Institute, Warsaw (2006)

Modeling and Simulation of Biomass Drying Using Artificial Neural Networks

Sławomir Francik, Bogusława Łapczyńska-Kordon, Renata Francik and Artur Wójcik

Abstract Willow (*Salix viminalis*) is a moist material after the crops. Therefore, the content of water in this type of material has to be lowered by drying before any further mechanical or thermal processing, in order to increase its calorific value. The process of drying is energy-intensive. Thus it is advisable to search for optimal methods and parameters of drying. The optimisation requires evolving a model that is based on the crucial parameters of the process. One of the possible solutions is to apply models of Artificial Neural Networks. Artificial Neural Networks belong to the group of methods of artificial computational intelligence and are often used in modelling various phenomena and processes. The aim of this work was to develop models using Artificial Neural Networks to describe the process of convective drying of the willow woodchips. As a result of presented work we obtained neural models describing alterations of water content, changes of the temperature and the mass of the chips. The presented models are highly accurate. We used experimentally obtained data in order to validate the models. It is important to underline that the data were not applied while the artificial neural networks were being developed. Subsequently, the models were used to simulate the process of drying what allowed us to define the optimal parameters of drying willow woodchips characterised by different moisture content.

Keywords Biomass · Willow (*Salix viminalis*) chips · Drying
Model · Artificial neural networks

S. Francik (✉) · B. Łapczyńska-Kordon · A. Wójcik
Department of Mechanical Engineering and Agrophysics, Faculty of Production and Power Engineering, University of Agriculture in Krakow, Krakow ul. Balicka 120, 30-149 Kraków, Poland
e-mail: slawomir.francik@urk.edu.pl

R. Francik
Chair of Organic Chemistry, Department of Bioorganic Chemistry, Jagiellonian University Medical College, Krakow, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_56

1 Introduction

Recently, the Renewable Energy Sources have become one of the major objects of interest. That results from continuously increasing need for energy all over the world. The exhaustion of conventional sources of energy, such as oil, coal, and natural gas, and the pollution of environment triggered off dynamic development of research aimed at identifying pure sources of energy that could be more effective and more efficient—Renewable Energy Sources (RES). Renewable energies are energy sources that are continuously replenished by nature. They can be derived either directly (for example thermal, photo-chemical, and photo-electric), or indirectly (such as wind, hydropower, and photosynthetic energy stored in biomass) from the Sun. They can also be obtained from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). It is estimated that RES could potentially deliver the amount of energy that would comprise the amount 3000 times larger than the current world-wide need for energy. According to the reports we will observe 2.7-fold increase of the global RES-based production of electrical energy from 2010 till 2035 [1].

Biomass is one of the commonly used sources of renewable energy [2]. This term is used for all organic material originating from plants, trees and crops, and is essentially the collection of the Sun energy that is processed, converted and stored in the form of the products of photosynthesis. Biomass energy is renewable and sustainable. Its characteristics are comparable to the characteristics of fossil fuels. Biomass can be directly burned to obtain energy, it can also be converted to various liquid or gas fuels (biofuels) [1].

Solid biofuels are another type of biomass that is frequently exploited. One of the examples is wood obtained from plantations maintained for energetic purposes (for example Short Rotation Woody Crops). Wood biomass and the one derived from energy-related plants is often converted into briquettes or pellets and constitutes their primary ingredient [3–6].

The entire process of production of briquettes and pellets requires a few steps employing several technological processes that eventually lead to obtaining a high quality product [3, 7].

The biomass used in the production is initially broken into pieces. Unfortunately, the obtained chips are often characterised by high moisture content. Therefore, in order to proceed with the following technological procedures, it is prerequisite to make the chips undergo thorough drying processes [8–10].

2 Modelling the Drying of Woodchips

Development of various models is the object of numerous research projects. A vast number of scientists, who focus their work on Renewable Energy Sources, predicate their research on creating suitable models. The issues concerning modelling that is related to RES were profoundly reviewed in [11].

Drying is an energy-intensive process what results in high costs. Therefore, the optimisation of the process of drying is pivotal in the aspect of cost minimisation. In such a case applying a model describing the process of drying is inevitable. Moreover, due to the complexity of the process it is necessary to create many different models of drying of biomass that are adjusted to various conditions. Hence a lot of effort is put in research aimed at elucidating the biomass drying process (including drying of woodchips), creation of the most accurate models and their optimisation [10, 12–17].

One of the types of willow—*Salix viminalis* is one of the most commonly used types of trees in the biomass production. First its sprouts are broken into pieces in the process of chipping. Subsequently, they are dried. The models of drying of willow woodchips were proposed and described in many scientific articles and reports [8, 9, 18–20].

According to the information available in the literature Artificial Neural Networks (ANN) are one of the newest modelling tools. They belong to the group of methods known as Computational Intelligence which, in turn, constitutes a subtype of Artificial Intelligence. The beginning of ANN development is assumed to fall on development of a mathematical model of neurone by McCulloch and Pitt in 1943 and introduction of the concept of adaptation of connections between network nodes in the process of learning neural networks by Hebb. The first simulation program of the ANN was made by Rochester in 1956 year. In the 1958 was created the first neurocomputer (Perceptron) by Rosenblatt and Wightman. Presently, there is no scientific field where the ANN was not used [21].

So far ANN were used in the models of many processes, including the processes of drying of food products, such as grains [22, 23], barberry (Berberis) fruits [24], apples [25] or onion [26]. Moreover, ANN were also used in modelling the drying of wood [27–30].

One of the criteria taken into account during the validation of mathematical models is accuracy. According to the literature, the models based on ANN are significantly more accurate than any other types of existing mathematical models [22, 23, 25, 26, 28, 30]. The results presented in our previous papers also provided some further proofs for this notion [31–38].

3 The Aim and the Scope

The work presented in the manuscript was aimed at formulating a comprehensive tool useful in simulation and optimisation of the processes of convective drying of the willow (*Salix viminalis*) woodchips that applies Artificial Neural Networks.

In order to achieve the main goal of our work we independently formulated three neural models representing the overall process of convective drying of the willow woodchips:

– neural model of the changes observed in the content of water in the chips,
– neural model of the changes of temperature of the chips,
– neural model of the changes of the mass of the chips.

The previously described model of the changes observed in the water content in the chips [34] and the model of the changes of temperature of the chips [33] were modified and updated for the purposes of this work.

4 Materials and Methods

All the three above-mentioned neural models were based on the experimentally obtained data measured and recorded during the process of convective drying. The analyses were performed using the biological material extracted from the willow *Salix viminalis*. The material was dried in a form of chips that were approximately 2 cm long. The samples were extracted directly before the beginning of the drying in order to avoid any additional effects of unintended, uncontrolled, spontaneous drying of the samples. The values of their mass differed among all samples and were dependent on the differences in the length of their diameter.

Prior to the drying process the examined material was weighted using an electronic scale WPE 300 (accuracy 0.01 g). The woodchips were dried using a convective dryer (ELKON KC 100 N) with the drying agent flow, in the temperature 40, 50, 60 and 70 °C. The drying process was ended when the equilibrium moisture content was established. The measurements of the mass, temperature or the moisture content in the samples were carried out every 5 min. The temperature was measured using a thermocouple NiCr-NiAl that was located inside a woodchip and its accuracy was up to 0.01 °C.

20 samples were dried in each individual case of given conditions (temperature values: 40, 50, 60 and 70 °C). The obtained data were sufficient to go to the next step, namely the process of ANN learning based on 6060 patterns.

The major goal was to create neural models quantitatively describing the process of convective drying of willow woodchips. Prior to the design of the neural models three semantic models were developed:

– the model of the changes of water content in the woodchips

$$Y_1 = f(X_1, X_2, X_3, X_4, X_5, X_6)$$

– the model of the changes of the temperature of the woodchips

$$Y_2 = f(X_1, X_2, X_5)$$

– the model of changes of the mass of the woodchips

$$Y_3 = f(X_1, X_2, X_3, X_4, X_5, X_6, Y_2)$$

where:

X_1 time of drying [min.]
X_2 temperature of the air [°C]
X_3 length of the sample (initial) [mm]
X_4 diameter of the sample (initial) [mm]
X_5 average content of water (initial) [kgH_2O/kg d.m.]
X_6 initial mass of the sample [g]
Y_1 content of water [kgH_2O/kg d.m.]
Y_2 temperature of the sample [°C]
Y_3 mass of the sample [g].

The development of the models was performed using a specialised software Statistica Neural Networks. The entire collection of 6060 patterns obtained as a result of the measurements was randomly divided into three categories: 3636 learning patterns, 1212 validation patterns and 1212 test patterns. In order to develop as accurate models as possible we applied the procedure of multiple repeats since the process of ANN learning proceeds stochastically. 100 ANNs were designed for each of the three, above-mentioned models. The architectural characteristics of the designed ANNs differed between each other (different number of layers in the network, different number of neurons in each layer, different activation functions). We kept only 10 most accurate models using the software Statistica Neural Networks. Subsequently, we chose the networks that were characterised by the lowest value of root mean square error (RMS), calculated for the validation data (patterns):

$$RMS = \sqrt{\frac{\sum \left(Y_{i,ANN} - Y_{i,OBS}\right)^2}{n}}$$

where:

$Y_{i,ANN}$ the initial value of a variable obtained as a result of neural modelling,
$Y_{i,OBS}$ the initial value of a variable obtained as a result of measurements,
n the number of patterns (reflecting the amount of input data).

5 Results and Discussion

As a result of the research three neural models were obtained. All of the models belonged to a class of feedforward artificial neural networks being multilayer perceptron (MLP). We distinguished the following most accurate models:

- the model of changes of the content of water in the woodchips: a four-layer neural network consisting of 6 neurons in the input layer, 15 neurons in the first hidden layer, 14 neurons in the second hidden layer and 1 output neuron (MLP 6:6-15-14_1:1),
- the model of changes of the temperature of the woodchips: a four-layer neural network consisting of 3 neurons in the input layer, 9 neurons in the first hidden layer, 5 neurons in the second hidden layer and 1 output neuron (MLP 3:3-9-5-1:1),
- the model of changes of the mass of the woodchips: three-layer neural network consisting of 7 neurons in the input layer, 9 neurons in the hidden layer and 1 output neuron.

The obtained neural models are highly accurate. The RMS calculated for the ANN describing changes of the content of water in the woodchips was 0.0179 [kgH_2O/kg d.m.]. In the case of the ANN describing changes of temperature RMS equalled 2.65 [°C] and in the case of the ANN describing changes of the mass RMS was 0.0634 [g]. In each case the RMS was calculated for the collection of validation data that had been separated before the beginning of the development of the main model. The validation patterns were not included in the data used in the learning process.

Figures 1, 2 and 3 present examples of the trends in changes of the content of water, temperature and the mass of the woodchips obtained for the validation data.

The analyses of changes of the content of water, the temperature and the mass of the woodchips as a function of the time of drying also prove high accuracy of the obtained models. The comparison of the values calculated in each neural model with the values measured during the experiments (collection of validation data) shows that they are consistent. Thus not only do we infer about the high quality and the accuracy of the proposed models but we also interpret that the models can be generalised.

Figure 4 is showing a scheme representing the functional links in the developed neural models. Entering the values of the input variables results in generating the values of the output variables as a response of the ANN what, in consequence, allows simulation of the process of drying of the willow woodchips and its further optimisation.

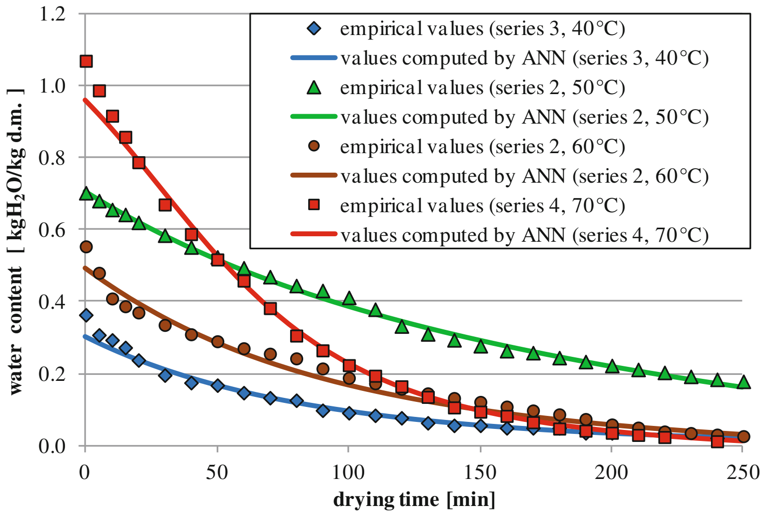


Fig. 1 Example trajectories of water content changes depending on time for empirical values and values computed using the model ANN (validation data set)

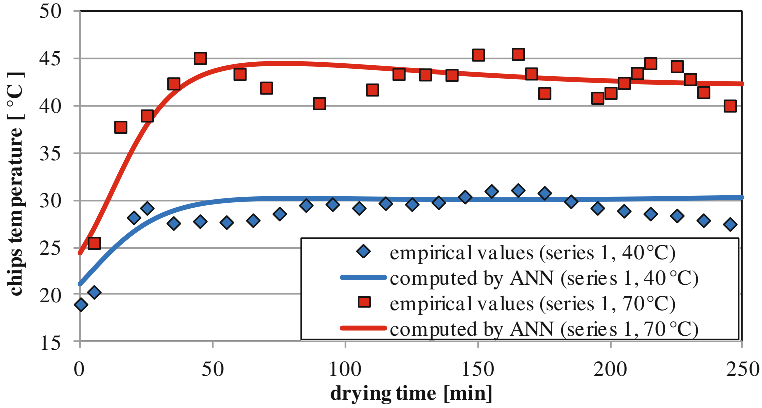


Fig. 2 Example trajectories of chips temperature changes depending on time for empirical values and values computed using the model ANN (validation data set)

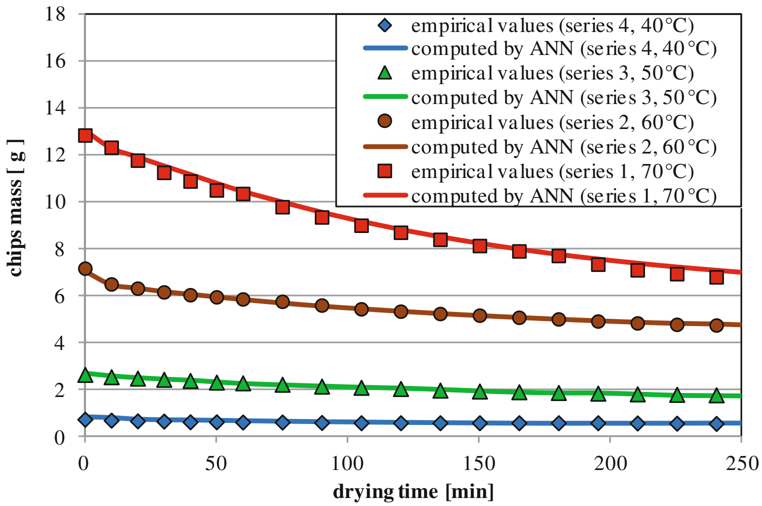
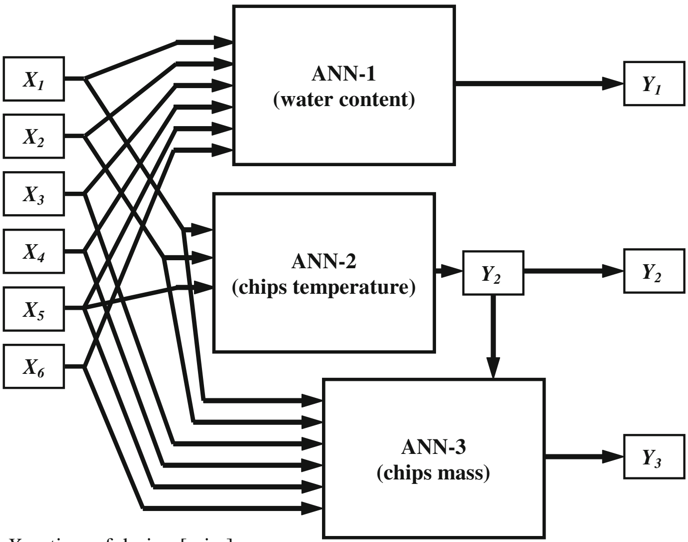


Fig. 3 Example trajectories of chips mass changes depending on time for empirical values and values computed using the model ANN (validation data set)



X_1 – time of drying [min.]
X_2 – temperature of the air [°C]
X_3 – length of the sample (initial) [mm]
X_4 – diameter of the sample (initial) [mm]
X_5 – average content of water (initial [kgH_2O/kg d.m.]
X_6 – initial mass of the sample [g]
Y_1 – content of water [kgH_2O/kg d.m.]
Y_2 – temperature of the sample [°C]
Y_3 – mass of the sample [g]

Fig. 4 A scheme of functional links in the three proposed neural models

6 Conclusions

First of all, the analysis of the results, which encompass the changes of the water content in the willow woodchips in time and the changes of the temperature and the mass of the samples as a function of time, proves that proposed neural models are correct in the aspect of logic. It is manifested by the fact that the recorded changes of the listed values are consistent with the theoretically predicted changes of the values representing the content of water, the temperature and the mass in time in the case of the solid samples during the process of their heating. The models were also empirically verified as correct. The estimated root mean square error values are very low. These values were obtained by comparing the experimentally measured values with the values generated in the model based on the Artificial Neural Networks.

The obtained models are a subclass of feedforward artificial neural networks known as multilayer perceptron. We distinguished four-layer models with 2 hidden layers and three-layer models with 1 hidden layer. Combining the three described models together is essential for delivering a complete description of the process of drying of the willow woodchips, simulating the process, which in turn is critical for the proper optimisation.

Further research is going to be aimed at developing and engineering a software or a computer application that will use the obtained models in order to automatically simulate the process of drying of the willow woodchips what would be used in the optimisation of the process.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Ellabban, O., Abu-Rub, H., Blaabjerg, F.: Renewable energy resources: current status, future prospects and their enabling technology. Renew. Sustain. Energy Rev. **39**, 748–764 (2014)
2. Kubica, K., Jewiarz, M., Kubica, R., Szlęk, A.: Straw combustion: pilot and laboratory studies on a straw-fired grate boiler. Energy Fuels **30**(6), 4405–4410 (2016)
3. Wrobel, M., Fraczek, J., Francik, S., Slipek, Z., Mudryk, K.: Influence of degree of fragmentation on chosen quality parameters of briquette made from biomass of cup plant *Silphium perfoliatum* L. In: Engineering for Rural Development (2013), pp. 653–657
4. Mudryk, K., Fraczek, J., Slipek, Z., Francik, S., Wrobel, M.: Chosen physico-mechanical properties of cutleaf coneflower (*Rudbeckia laciniata* L.) shoots. In: Engineering for Rural Development (2013), pp. 658–662
5. Ivanova, T., Kolarikova, M., Havrland, B., Passian, L.: Mechanical durability of briquettes made of energy crops and wood residues. In: Engineering for Rural Development, vol. 13 (2014), pp. 131–136
6. Kolarikova, M., Ivanova, T., Havrland, B.: Energy balance of briquettes made of hemp (*Cannabis sativa* L.) cultivars (Ferimon, Bialobrzeskie) from autumn harvest to produce heat for household use. In: Engineering for Rural Development, vol. 2 (2013), pp. 504–508

7. Swietochowski, A., Lisowski, A., Dabrowska-Salwin, M.: Strength of briquettes and pellets from energy crops. In: Engineering for Rural Development (2016), pp. 547–551
8. Gigler, J.K., van Loon, W.K.P., Seres, I., Meerdink, G., Coumans, W.J.: Drying characteristics of willow chips and stems. J. Agric. Eng. Res. **77**(4), 391–400 (2000)
9. Gigler, J.K., Van Loon, W.K.P., Vissers, M.M., Bot, G.P.A.: Forced convective drying of willow chips. Biomass Bioenerg. **19**(4), 259–270 (2000)
10. De Fusco, L., Jeanmart, H., Blondeau, J.: A modelling approach for the assessment of an air-dryer economic feasibility for small-scale biomass steam boilers. Fuel Process. Technol. **134**, 251–258 (2015)
11. Iqbal, M., Azam, M., Naeem, M., Khwaja, A.S., Anpalagan, A.: Optimization classification, algorithms and tools for renewable energy: a review. Renew. Sustain. Energy Rev. **39**, 640–654 (2014)
12. Jirjis, R.: Storage and drying of woodfuel. Biomass Bioenerg. **9**(1–5), 181–190 (1995)
13. Johansson, A., Fyhr, C., Rasmuson, A.: High temperature convective drying of wood chips with air and superheated steam. Int. J. Heat Mass Transf. **40**(12), 2843–2858 (1997)
14. Le Lostec, B., Galanis, N., Baribeault, J., Millette, J.: Wood chip drying with an absorption heat pump. Energy **33**(3), 500–512 (2008)
15. Peters, B., Bruch, C.: Drying and pyrolysis of wood particles: experiments and simulation. J. Anal. Appl. Pyrol. **70**, 233–250 (2003)
16. Gebreegziabher, T., Oyedun, A.O., Hui, C.W.: Optimum biomass drying for combustion—a modeling approach. Energy **53**, 67–73 (2013)
17. Sridhar, D., Madhu, G.M.: Drying kinetics and mathematical modeling of *Casuarina equisetifolia* wood chips at various temperatures. Periodica Polytech. Chem. Eng. **59**(4), 288–295 (2015)
18. Gigler, J.K., Van Loon, W.K.P., Sonneveld, C.: Experiment and modelling of parameters influencing natural wind drying of willow chunks. Biomass Bioenerg. **26**(6), 507–514 (2004)
19. Pakowski, Z., Adamski, R., Kokocinska, M.: Cross-fiber dry wood darcy permeability of energetic willow *Salix viminalis* v. Orm. Drying Technol. **27**(12), 1379–1383 (2009)
20. Pakowski, Z., Krupinska, B., Adamski, R.: Prediction of sorption equilibrium both in air and superheated steam drying of energetic variety of willow *Salix viminalis* in a wide temperature range. Fuel **86**(12–13), 1749–1757 (2007)
21. Francik, S., Ślipek, Z., Frączek, J., Knapczyk, A.: Present trends in research on application of artificial neural networks in agricultural engineering. Agric. Eng. **20**(4), 15–25 (2016)
22. Farkas, I., Reményi, P., Biró, A.: A neural network topology for modelling grain drying. Comput. Electron. Agric. **26**(2), 147–158 (2000)
23. Khazaei, J., Daneshmandi, S.: Modeling of thin-layer drying kinetics of sesame seeds: mathematical and neural networks modeling. Int. Agrophys. **21**, 335–348 (2007)
24. Gorjian, S., Tavakkoli Hashjin, T., Khoshtaghaza, M.H.: Designing and optimizing a back propagation neural network to model a thin-layer drying process. Int. Agrophys. **25**, 13–19 (2011)
25. Khoshhal, A., Dakhel, A.A., Etemadi, A., Zereshki, S.: Artificial neural network modeling of apple drying process. J. Food Process Eng. **33**(Suppl. 1), 298–313 (2010)
26. Jafari, S.M., Ganje, M., Dehnad, D., Ghanbari, V.: Mathematical, fuzzy logic and artificial neural network modeling techniques to predict drying kinetics of onion. J. Food Process. Preserv. **40**(2), 329–339 (2016)
27. Assidjo, E., Yao, B., Kisselmina, K., Amané, D.: Modeling of an industrial drying process by artificial neural networks. Braz. J. Chem. Eng. **25**(3), 515–522 (2008)
28. Ge, L., Chen, G.S.: Control modeling of ash wood drying using process neural networks. Optik **125**(22), 6770–6774 (2014)
29. Ozsahin, S., Aydin, I.: Prediction of the optimum veneer drying temperature for good bonding in plywood manufacturing by means of artificial neural network. Wood Sci. Technol. **48**(1), 59–70 (2014)

30. Watanabe, K., Matsushita, Y., Kobayashi, I., Kuroda, N.: Artificial neural network modeling for predicting final moisture content of individual Sugi (*Cryptomeria japonica*) samples during air-drying. J. Wood Sci. **59**(2), 112–118 (2013)
31. Mudryk, K., Francik, S., Fraczek, J., Slipek, Z., Wrobel, M.: Model of actual contact area of rye and wheat grains with flat surface. In: Renewable and Sustainable Energy Reviews (2013), pp. 292–296
32. Fraczek, J., Francik, S., Slipek, Z., Knapczyk, A.: Application of artificial neural networks in modelling the contact area of grain seeds. Agric. Eng. **20**(4), 27–37 (2016)
33. Łapczyńska-Kordon, B., Francik, S., Frączek, J., Ślipek, Z.: Modeling drying shrinkage for selected root vegetables using neural networks (in Polish). Inżynieria Rolnicza/Agric. Eng. **13**, 303–311 (2006)
34. Łapczyńska-Kordon, B., Francik, S.: Neural model of changes in water content in willow chips during convection drying (in Polish). Inżynieria Rolnicza/Agric. Eng. **11**(109), 143–148 (2008)
35. Łapczyńska-Kordon, B., Francik, S., Ślipek, Z.: Neural model of temperature changes during convection drying of energy willow chips (in Polish). Inżynieria Rolnicza/Agric. Eng. **11** (109), 149–155 (2008)
36. Zlobecki, A., Francik, S.: Defining the damaging process of cereal grains on the basis of artificial neural network. Int. Agrophys. **15**, 219–223 (2001)
37. Francik, S., Fraczek, J.: Model development of the external friction of granular vegetable materials on the basis of artificial neural networks. Int. Agrophys. **15**, 231–236 (2001)
38. Wrobel, M., Fraczek, J., Francik, S., Slipek, Z., Krzysztof, M.: Modelling of unit contact surface of bean seeds using Artificial Neural Networks. In: Renewable and Sustainable Energy Reviews (2013), pp. 287–291

Analysis of Possible Application of Olive Pomace as Biomass Source

Sławomir Francik, Adrian Knapczyk, Renata Francik and Zbigniew Ślipek

Abstract The aim of the study was to determine the use of stored olive pomace as a solid biomass for energy purposes. The samples were collected from olive pomace pile stored for three years on Agricultural University in Cracow campus. Samples were taken from three heights and then standardized for each of them. Work has been done to compare energy properties such as calorific value, depending on the sampling depth of the material from the prism.

Keywords Pomaces · Storage · Energy properties · Calorific value Biomass

1 Introduction

Increasing global market of bioenergy requires new sources of biomass. Worldwide biomass market has approximately 14% of total energy production. In Europe, biomass is approximately 4% of total primary energy. Countries with fastest growing share of biofuels are United Kingdom, Germany and Scandinavian countries [1]. Biomass can originate from dedicated energy crop plantations or from industrial and agricultural waste [2–4].

S. Francik · A. Knapczyk (✉) · Z. Ślipek
Department of Mechanical Engineering and Agrophysics, Faculty of Production and Power Engineering, University of Agriculture in Krakow, Krakow ul. Balicka 120, 30-149 Kraków, Poland
e-mail: adrian.knapczyk91@gmail.com

S. Francik
e-mail: slawomir.francik@urk.edu.pl

Z. Ślipek
e-mail: zbigniew.slipek@urk.edu.pl

R. Francik
Chair of Organic Chemistry, Department of Bioorganic Chemistry, Jagiellonian University Medical College, Krakow, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_57

The European Union is a world leader in olive oil production. That production has an important share of Mediterranean countries' economy [5]. The amount of produced olive oil reaches 2 million tons per year. Industry that huge causes many problems with industrial waste management. Olive pomace are in the area of interest of many researchers [6–11]. The amount of produced olive pomace depends on used technology. Olive oil production process consist on three phases: crushing olives, grinding them and separating oil from pulp. Third phase is crucial, because it is where the final product is separated from waste. There are three technologies used for before mentioned separation—traditional centrifuge, two-phase centrifuge and three-phase centrifuge. These methods differs on work parameters and amount of extracted oil. The most common method (two-phase centrifuge) produces pomace with moisture above 20%, so it requires desiccation. Dried material is separated to pulp and stones. Stones are cleaned, additionally desiccated and grinded. Olive oil production waste consist on pulp and stones [1].

With that huge amount of waste produced by olive oil industry, storing pomace for further use should be taken into consideration. One of proposed methods is pelletizing, but unfortunately, olive pellet doesn't meet European quality norms. Therefore, it is necessary to mix it with another material (e.g. wooden remains from olive groves) to make it meet European regulations [12].

2 Aim of the Study

The aim of this study was to verify hypothesis that storing olive pomace affects its calorific value. Assumption was made that fresh pomace is homogenous regarding energetic parameters. From this it follows that differentiation between pile zones would be caused by storing process.

3 Materials and Methods

The samples were collected from olive pomace pile stored for three years on Agricultural University in Cracow campus. Pile was located on concrete plate, without any protection against environmental conditions. Shape and dimensions of the prism are shown on Fig. 1.

Olive pomace were product of industrial processing and stored for three years (Fig. 2).

Five 50 g samples were randomly taken from each height zone and then all samples from the same zone were unified by quartering.

The next step was to define the absolute humidity, which was measured using a dehumidifier. That method consist of measuring the weight of water vaporized from sample in standardized conditions—105 °C, for 24 h.

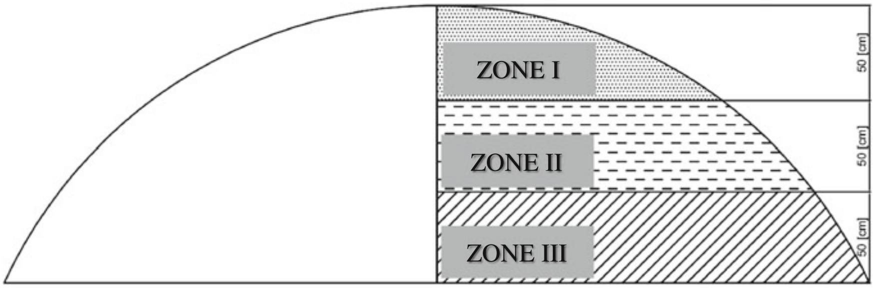
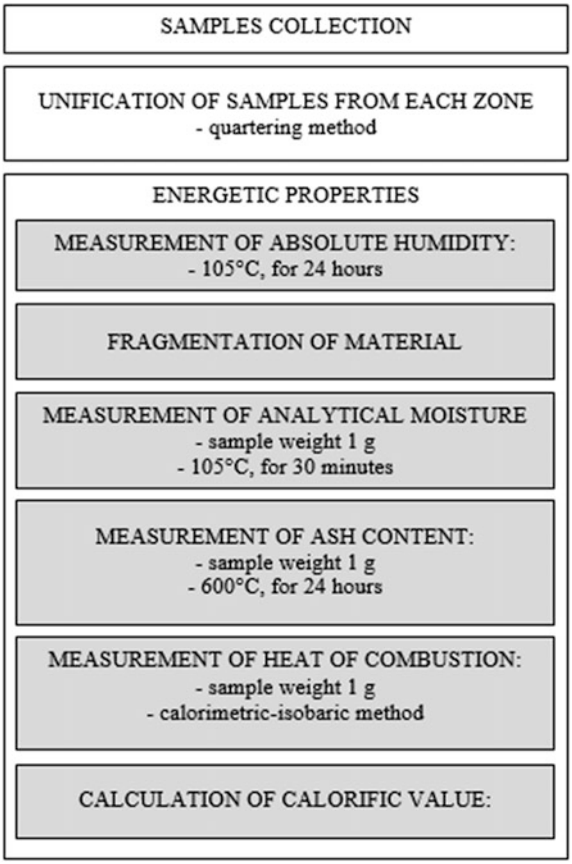


Fig. 1 Outline of pile cross-section

Fig. 2 Steps performed to complete the research



The absolute humidity was calculated from the formula [13]:

$$X = \frac{m_1 - m_2}{m_1} \cdot 100[\%]$$

where:

X absolute humidity [%]
m_1 fresh sample weight [g]
m_2 dried sample weight [g].

After drying, sample was crushed and saved for further research (Fig. 3).

To measure analytical moisture, 1 g samples were dried in 105 °C for 30 min. Calculations were made with the following formula [14]:

$$W^a = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100\%, [\%_{mas}]$$

where:

W^a analytical moisture [%]
m_1 empty bowl weight [g]
m_2 bowl weight with fresh sample [g]
m_3 bowl weight with dried sample [g].

Heat of combustion was measured with calorimetric method, using IKA automatic isoperibol calorimeter.

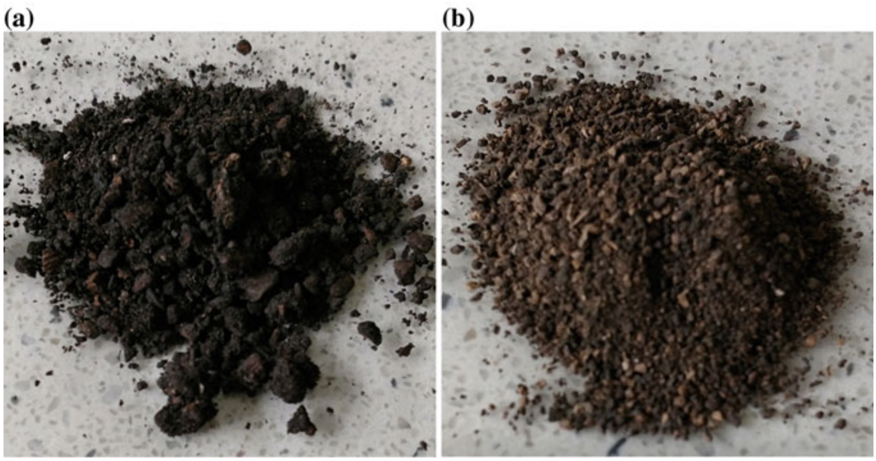


Fig. 3 Samples after **a** drying **b** crushing

Based on those measurements, calorific value was calculated using formula [15]:

$$Q_w = Q_s - \frac{r}{100}(8.94H^a - W^a)$$

where:

Q_w calorific value [kJ/kg]
Q_S heat of combustion [kJ/kg]
W^a analytical moisture [%]
H^a hydrogen content in the sample [%]
r enthalpy of vaporization of water, r = 2454 kJ/kg.

Because there was no possibility to measure hydrogen content in the sample, reference value was assumed Ha = 5.08 [16].

4 Statistical Calculations

To verify research hypothesis, data were analyzed with one-way ANOVA. The factor was prism zone from which each sample was taken.

ANOVA analyze is most often aimed to test differences between means. It is achieved by comparing (analyzing) their variances. In ANOVA test, null hypothesis is that means in analyzed groups don't differ.

The three main ANOVA assumptions are [17]:

1. the observations are independent,
2. the sample data have a normal distribution within factor levels and
3. the dependent variable's variances within each factor level are homogeneous (homoscedasticity).

Assumption that calorific value in each pile zone has normal distribution was verified using Shapiro-Wilk test. Assumption that variances in each group differ was verified using Levene test. After proving that those two assumptions are true, one-way ANOVA for calorific value was performed. Because null hypothesis was rejected, the need of performing post-hoc tests emerged. Tukey test, often called the honestly significant differences (HSD) method, was used.

All statistical calculations were performed using STATISTICA StatSoft, Inc., assuming level of significance $\alpha = 0.05$.

5 Results

Table 1 contains results of Shapiro-Wilk test for calorific value. For all three groups the probability (p) that null hypothesis is true (H0: distribution is normal) is greater that assumed level of significance ($\alpha = 0.05$). Therefore, there is no premise to reject null hypothesis, then distribution is normal.

Table 2 contains Levene test results for independent variable calorific value. Because probability (p) that null hypothesis is true (H0: variance is homogenous) is greater that assumed level of significance ($\alpha = 0.05$), there is no premise to reject null hypothesis and variance is homogenous.

The three main ANOVA assumptions were fulfilled, so the test was performed. Results are shown in Table 3. It was found that there is statistically significant difference between analyzed groups. Null hypothesis (H0: means in all groups are equal) was rejected.

After rejecting H0, the post-hoc Tukey test was performed to separate means into significantly different groups (Table 4). The results show that there is two groups:

Table 1 Results of Shapiro-Wilk test for calorific value

X-zone	Shapiro-Wilk test statistic W	*p*-value	Distribution
1	0.87406	0.30713	Normal
2	0.99998	0.99207	Normal
3	0.95118	0.57449	Normal

Table 2 Results of Levene test for calorific value

	MS Effect	MS Error	F	*p*	Variance
Calorific value	10,345.09	3902.630	2.650799	0.149635	Homogenous

Table 3 The results of one-way ANOVA for independent variable calorific value

Effect	Sum of squares (SS)	Degr. of freedom (D.F.)	Mean square (MS)	F	*p*
Intercept	1.775667E+09	1	1.775667E+09	91,148.67	0.000000
X-zone	1.569124E+06	2	7.845618E+05	40.27	0.000333
Error	1.168860E+05	6	1.948100E+04		

1. X-zone = 1 and X-zone = 2;
2. X-zone = 3.

Table 5 contains values of basic statistics for analyzed parameters. Figures 4, 5 and 6 depict confidence intervals for analyzed values.

Table 4 The results of post-hoc HDS Tukey test

Cell number	X-zone	{1} 14,909	{2} 14,823	{3} 15,749
1	1		0.745515	0.000958
2	2	0.745515		0.000643
3	3	0.000958	0.000643	

Table 5 Values of basic energetic parameters of olive pomace

X-zone	Heat of combustion	Calorific value	Ash content %
1	14,909 ± 194	13,795 ± 194 A	35.83 ± 0.98
2	14,823 ± 139	13,709 ± 139 A	28.75 ± 1.36
3	15,749 ± 41	14,635 ± 41 B	28.62 ± 1.65

Data are presented as means from independent measurements ± standard deviation (SD)
Different letters in the column calorific value indicate significant differences according to Tukey's test ($p < 0.05$)

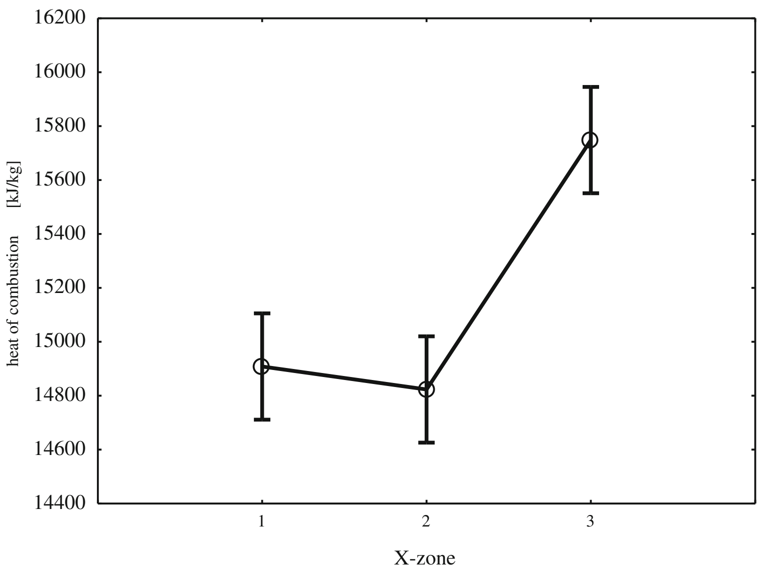


Fig. 4 Confidence intervals of heat of combustion for X-zones

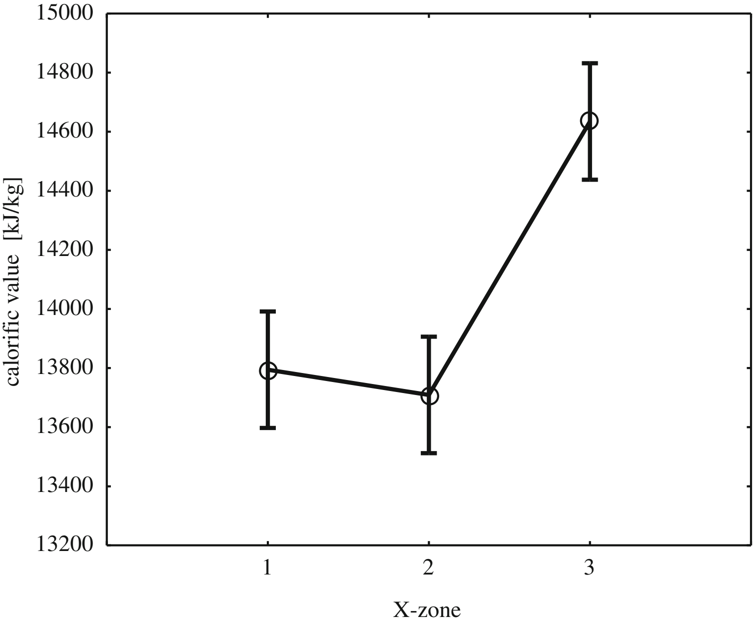


Fig. 5 Confidence intervals of calorific value for X-zones

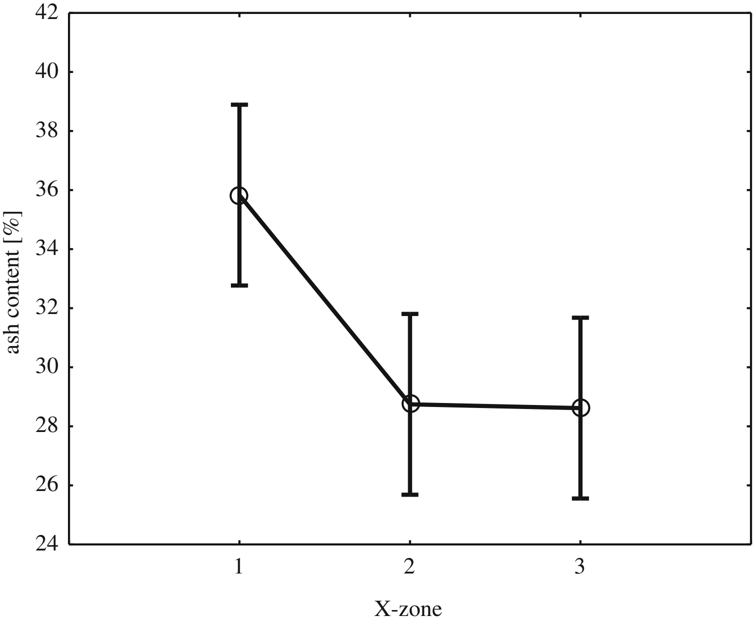


Fig. 6 Confidence intervals of ash content for X-zones

6 Conclusions

Conducted research revealed statistically significant difference in calorific value and heat of combustion between X-zones 1 + 2 and X-zone 3. This difference can only be explained by process of storing the pomace. Higher calorific value and heat of combustion in zone 3 is probably caused by atmospheric conditions.

It was also revealed that ash content in zone 1 was significantly higher than in deeper zones.

The further study on this topic will be aimed to quantify observed phenomenon.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Sanchez, J.M., Jimenez, J.A.P., Villanueva, M.J.D., Serrano, A., Núnez, N., Gimenez, J.L.: New techniques developed to quantify the impurities of olive stone as solid biofuel. Renew. Energy **78**, 566–572 (2015)
2. Mudryk, K., Fraczek, J., Slipek, Z., Francik, S., Wrobel, M.: Chosen physico-mechanical properties of cutleaf coneflower (*Rudbeckia laciniata* L.) shoots. In: 12th International Scientific Conference on Engineering for Rural Development, Engineering for Rural Development (2013), pp. 658–662. ISSN: 1691-3043
3. Wrobel, M., Fraczek, J., Francik, S., Slipek, Z., Krzysztof, M.: Influence of degree of fragmentation on chosen quality parameters of briquette made from biomass of cup plant *Silphium perfoliatum* L. In: 12th International Scientific Conference Engineering for Rural Development, Engineering for Rural Development (2013), pp. 653–657. ISSN: 1691-3043
4. Kubica, K., Jewiarz, M., Kubica, R., Szlek, A.: Straw combustion: pilot and laboratory studies on a straw-fired grate boiler. Energy Fuels **30**(6), 4405–4410 (2016). https://doi.org/10.1021/acs.energyfuels.5b02693
5. Bršćić, K., Poljuha, D., Krapac, M.: Olive residues-renewable source of energy. In: Management of Technology-Step to Sustainable Production, Sibenik, 10–12 June 2009, Croatia (2009)
6. Meziane, S.: Drying kinetics of olive pomace in a fluidized bed dryer. Energy Convers. Manag. **52**(3), 1644–1649 (2011). https://doi.org/10.1016/j.enconman.2010.10.027
7. Miranda, T., Arranz, J.I., Montero, I., Roman, S., Rojas, C.V., Nogales, S.: Characterization and combustion of olive pomace and forest residue pellets. Fuel Process. Technol. **103**, 91–96 (2012) SI. https://doi.org/10.1016/j.fuproc.2011.10.016
8. Haddadin, M.S.Y., Haddadin, J., Arabiyat, O.I., Hattar, B.: Biological conversion of olive pomace into compost by using *Trichoderma harzianum* and *Phanerochaete chrysosporium*. Biores. Technol. **100**(20), 4773–4782 (2009). https://doi.org/10.1016/j.biortech.2009.04.047
9. Plaza, C., Nogales, R., Senesi, N., Benitez, E., Polo, A.: Organic matter humification by vermicomposting of cattle manure alone and mixed with two-phase olive pomace. Biores. Technol. **99**(11), 5085–5089 (2008). https://doi.org/10.1016/j.biortech.2007.09.079
10. Haddadin, M.S., Al-Natour, R., Al-Qsous, S., Robinson, R.K.: Bio-degradation of lignin in olive pomace by freshly-isolated species of Basidiomycete. Biores. Technol. **82**(2), 131–137 (2002). https://doi.org/10.1016/S0960-8524(01)00171-7

11. Romero-Garcia, J.M., Nino, L., Martinez-Patino, C., Alvarez, C., Castro, E., Negro, M.J.: Biorefinery based on olive biomass. State of the art and future trends. Biores. Technol. **159**, 421–432 (2014). https://doi.org/10.1016/j.biortech.2014.03.062
12. Barbanera, M., Lascaro, E., Stanzione, V., Esposito, A., Altieri, R., Bufacchi, M.: Characterization of pellets from mixing olive pomace and olive tree pruning. Renew. Energy **88**, 185–191 (2016)
13. PN-EN ISO 18134-1:2017-03
14. PN-EN ISO 18134-3:2017-03
15. Cieślikowski, B., Juliszewski, T., Łapczyńska-Kordon, B.: Utilisation of bio-fuel technology by-products for power production purposes/Utylizacja na cele energetyczne produktów ubocznych technologii biopaliwowej (in Polish). Inżynieria Rolnicza **12** (2006)
16. Zabaniotou, A., Rovas, D., Libutti, A., Monteleone, M.: Boosting circular economy and closing the loop in agriculture: case study of a small-scale pyrolysis–biochar based system integrated in an olive farm in symbiosis with an olive mill. Environ. Dev. **14**(2015), 22–36 (2015). https://doi.org/10.1016/j.envdev.2014.12.002
17. John, J.M.M., Van Lishout, F., Gusareva, E.S., Van Steen, K.: A robustness study of parametric and non-parametric tests in model-based multifactor dimensionality reduction for epistasis detection. BioData Min. **6**, 9 (2013). https://doi.org/10.1186/1756-0381-6-9

Energetic Potential of Apple Orchards in Europe in Terms of Mechanized Harvesting of Pruning Residues

Arkadiusz Dyjakon and Krzysztof Mudryk

Abstract One of the new sources of biomass acquisition for energetic purposes are apple orchards. In apple orchards the biomass is generated mainly during the regular tree pruning. In the paper the energetic potentials (theoretical, technical and economic) for 28 EU countries are determined. The analysis was performed basing on the Eurostat database and accepted assumptions as well as considering the application of mechanized harvesting technology of pruned residues. Taking into account the size distribution area of the apple orchards in Europe, pruning losses and high heating value of wooden material the results indicated that the total energetic potentials are: 29.11 PJ/year for theoretical, 22.50 PJ/year for technical and 18.63 PJ/year for economic. However, these potentials are significantly scattered in Europe and vary from 5.90 PJ/year in Poland (economic potential) to 0.00 PJ/year for Malta. Moreover, ten countries cover the available economic potential in height of 87%. Finally, it was underlined that before the application of the mechanized harvesting technology of the pruning residues in the orchard by the farmer, the economic and market demand analysis should be performed to evaluate the profitability and market expectation.

Keywords Apple orchard · Pruning residue · Energetic potential
EU countries

A. Dyjakon (✉)
Institute of Agricultural Engineering, Wroclaw University of Environmental and Life Sciences, ul. Chelmonskiego 37a, 51-630 Wroclaw, Poland
e-mail: arkadiusz.dyjakon@upwr.edu.pl

K. Mudryk
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 b, 30-149 Krakow, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_58

1 Introduction

In Europe, because of environmental constrains and sustainable development strategy of agricultural areas, more and more attention is paid on the local potential of renewable sources of energy, especially less recognized and untypical biomass which could be used for heat generation. There are many paths of biomass acquisition from agricultural sector. The most popular and well documented biomass residue from agriculture in terms of energetic usage is straw. The other source of biomass having energetic potential are permanent crops (plantations and orchards). The biomass residue from permanent crops comes mainly from regular pruning of the trees which is carried out every year to maintain their proper growth and good fruits productivity. The created wooden residues might be collected and used for local heat production (see Fig. 1).

In general, main permanent crop areas in Europe are occupied by olive trees, vineyards and fruit trees (including apple trees) [1], in which total area of apple orchards accounts with ca. 450 thousands of hectares. This area represents a share in the permanent crops area of 4.2% [2].

Apple orchards, like many other permanent crops, are not evenly distributed along all countries in Europe. Some countries in Europe are more specialized in the production of olives and grapes (i.e. Spain, France, Italy), the other leads in fruits production such as apples (i.e. Poland) [3]. Figure 2 depicts the distribution of the total apple orchards area in top 10 leading countries in apples production in EU28. It can be seen that in these countries there are almost 400 thousands hectares of apple orchards which is close to 90% of the total area of this fruit in Europe. Moreover, the largest number of apple orchards is in Poland with the share of almost 32%.

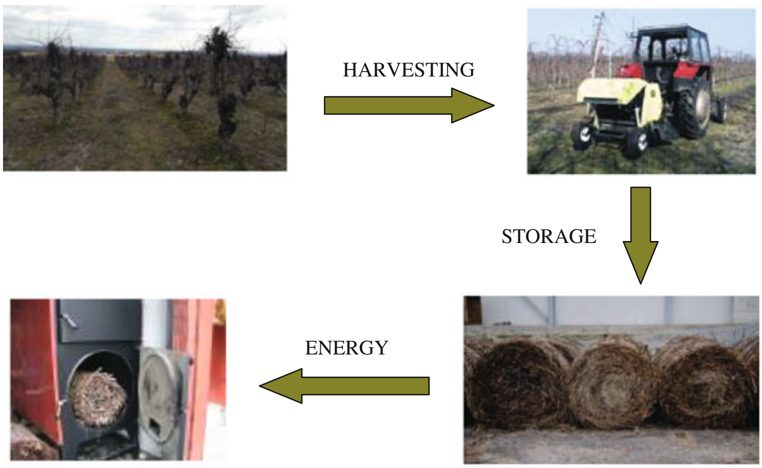


Fig. 1 Scheme of the pruning residue utilization for local heat production

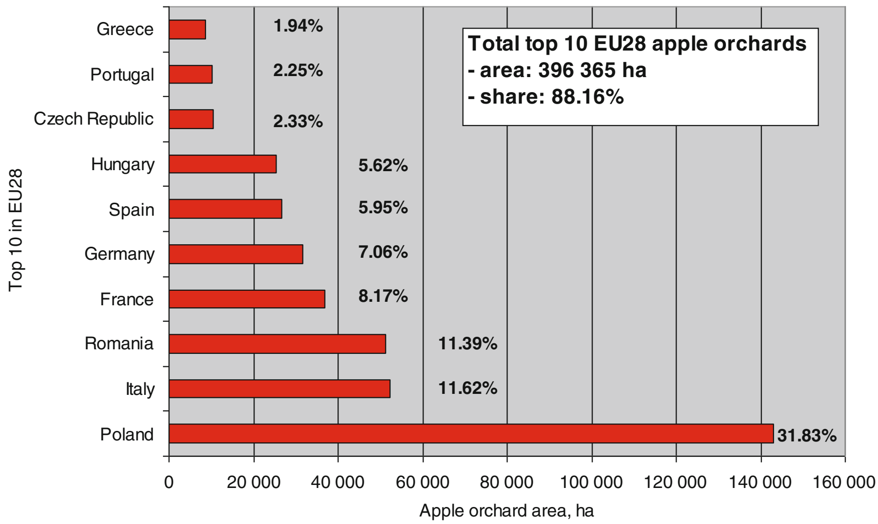


Fig. 2 The apple orchards area and its percentage share for a top 10 countries in Europe. *Source* Based on www.eurostat.eu

As a results, the apple orchards might introduce a certain amount of the wooden biomass (as a relatively cheap fuel) to the local market and limit the utilization of coal in the small and middle size boilers.

It should be marked that to enable the use of pruned biomass for energetic purposed, it must be first properly collected (harvested) in the orchard using adequate machinery [4, 5]. As for pruning harvesting the special machinery is required (baler or chipper with a pick-up system), the farmer must do some investments. Therefore, to make the investments profitable, the mechanized harvesting of the pruned biomass is limited, amongst the other parameters, by size of the orchard.

The aim of the work is to determine the energetic potential of the pruned biomass from apple orchards in Europe taking into account their size and theoretical, technical and economic possibilities of mechanized harvesting of this type of residue.

2 The Age and the Density of Apple Orchards

From commercial and technical point of view, the density of the apple trees in the orchards is very important, as it influences the harvesting technology, potential and thickness of the branches. According to the database available in Eurostat (from 2012) there are still almost 20% (ca. 85,000 ha) of the old apple orchards in Europe (see Fig. 3), in which more than 40,000 ha are older than 25 years and have tree density below 400 trees per hectare (see Fig. 4a).

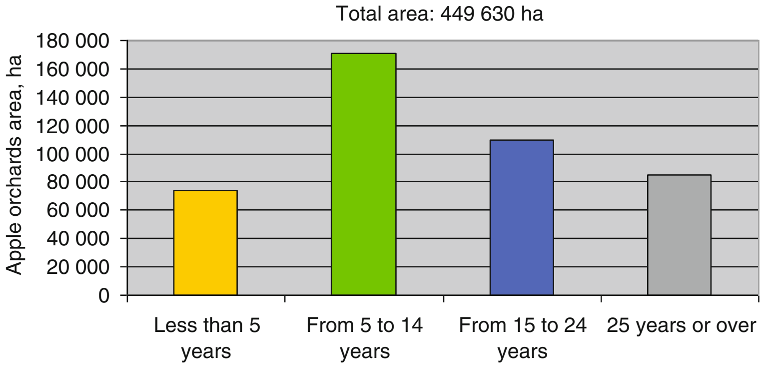


Fig. 3 The age of the apple orchards in Europe. *Source* Based on www.eurostat.eu

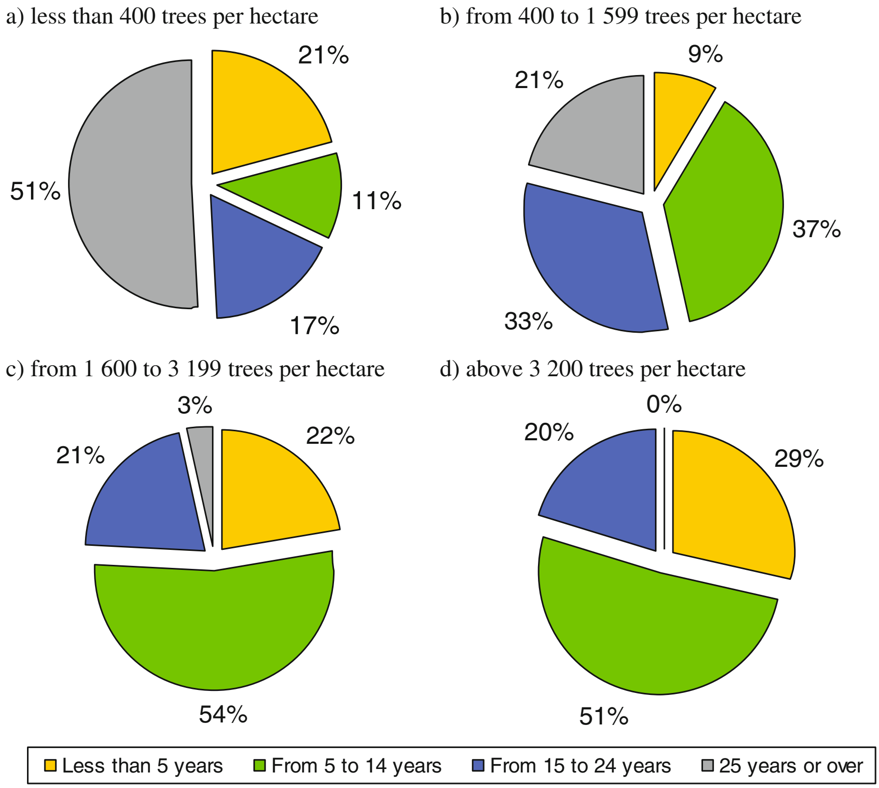


Fig. 4 The density and age of apple orchards in Europe. *Source* Based on www.eurostat.eu

However, the actual direction in permanent crops, like apple orchards, is the increase of the number of tress per hectare. In Fig. 4 the evolution of the apple trees density per hectare in Europe is shown. It indicates that the orchards type is changing from traditional (up to 800 trees per hectare) into intensive one (above 1600 trees per hectare). The consequence of that change is more regular pruning activity as well as more unified size of the cut branches (thickness and length) which is propitious for mechanized harvesting of pruning residues. Moreover, the trees planted in rows facilitate all the technical processes connected with their cutting and harvesting. The harvesting machinery limits the amount of turns and works more effective increasing the total capacity and quality performance.

3 Apple Orchards Size Distribution and Their Energetic Potential in Europe—Assumptions and Analysis

Although the size of the orchard does not influence directly on the unit yield of the pruning residues itself, it has a significant role in terms of mechanized harvesting of the biomass. It arises from the fact that for larger orchards it is necessary to buy a sophisticated harvesting machinery to save time and labor costs. The cost of machinery able to pick-up cut branches and convert them into round bales or chips is in the range of 10,000–20,000 Euros [5–7]. In case of small orchards, such investment is not justified economically. Even the owners of the middle size orchards should consider the purchase of the machinery with care. Usually, the famers should cooperate with each other and share the machinery to make the business profitable. Only large orchard farmers are able to work independently using their own machineries. It should be marked that the exact estimation of the minimal size of the orchard for which the purchase of the harvesting machinery is reasonable is complex. Therefore, the case study supported by the economic analysis should be performed to limit the risk or to reach the expected revenues.

The pruning potential for energetic purposes of the cut branches in the apple orchards in Europe may be expressed as theoretical, technical or economic.

The annual theoretical energetic potential is determined as a total amount of biomass available in the apple tree orchards area in the considered European countries multiplied by the high heating value of the pruned biomass. The result is the amount of energy that could be obtained from apple orchards without recognition of the collection possibility, functionality of the orchards, technical constraints or operation's costs.

The technical potential is lower than the theoretical one because it takes into account the best available technology (BAT) on the market, system performance, topographic limitations, environmental aspects etc. The technical potential excludes the economic constraints and risks related to the process or technology. In this issue, the harvesting losses of the existing technology are assumed as 15% (85% of the pruned biomass is harvested by the machinery and might be used for energetic

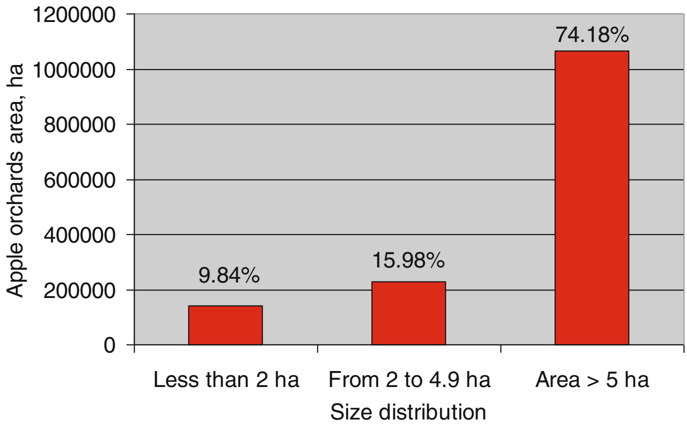


Fig. 5 The size distribution of fruit orchards in Europe

purposes). This index is influenced mainly by machinery imperfection but other factors may also play a role in the process (i.e. slope of the terrain, weather conditions, human mistakes) [6, 8, 9]. The technical potential is additionally lowered by the share of the small orchards (up to 2 ha) as they are usually not cultivated properly or pruned regularly at all. The average percentage share of this area in Europe for fruits orchards is 9.84% (see Fig. 5).

However, the share of these orchards in particular countries is very differentiated. It varies from 0.00% in Luxembourg to 58.74% in Cyprus (Table 1). As the differences are too large, in calculation of technical potential the values for a given country are used, respectively. Consequently, the summarized area considered for technical calculation is smaller, and the amount of the pruned biomass will be lower than in the theoretical potential.

In turn, the economic potential includes the realization of the task in economically justified way. In terms of mechanized harvesting of the pruned biomass in the apple orchards a dedicated machinery, causing investment, is required.

It should be marked that under economic restriction only farmers possessing bigger orchards or groups of farmers with small-middle size orchards are potentially able to purchase this machinery. The costs depend largely on the area of the orchard and the number of cut branches [10]. Thus, it is assumed that for determination of the economic potential of mechanized pruned biomass harvesting only orchards with an area larger than 5 ha are considered. Similar limitation is proposed also by other researchers [11].

The average percentage share of orchards with the area below 5 ha in Europe is 25.82% (see Fig. 5). Because of the share of these orchards in particular countries is also not even (from 1.59% in Ireland to 85.96% in Cyprus) in calculation of technical potential the values for a given country are used (see Table 1), respectively. In effect, the accessible orchards area for determination of economic potential are the lowest one (in relation to the theoretical and technical potential). It

Table 1 The total area and share of apple orchards in Europe

	Total apple orchards area (ha)	The share of apple orchards area[a]		
		Less than 2.0 ha (%)	From 2.0 to 4.9 ha (%)	Above 5.0 ha (%)
EU 28	449,628			
Belgium	6398	0.79	2.26	96.94
Bulgaria	5239	23.91	15.91	60.17
Czech Republic	10,487	1.35	2.54	96.12
Denmark	1347	0.98	6.37	92.65
Germany	31,738	3.79	6.02	90.19
Estonia	600	4.13	8.26	87.60
Ireland	615	0.00	1.59	98.41
Greece	8703	15.79	35.54	48.67
Spain	26,753	7.64	12.06	80.31
France	36,741	2.13	4.51	93.35
Croatia	4798	22.82	27.94	49.24
Italy	52,251	8.83	19.07	72.10
Cyprus	527	58.74	27.22	14.04
Latvia	2390	0.62	7.31	92.07
Lithuania	1401	8.80	26.02	65.17
Luxembourg	39	0.00	15.38	84.62
Hungary	25,265	15.48	8.92	75.60
Malta	0	43.24	29.73	27.03
Netherlands	7948	1.47	4.52	94.01
Austria	7907	4.33	10.69	84.98
Poland	143,113	5.98	19.15	74.87
Portugal	10,095	11.62	17.57	70.81
Romania	51,225	25.70	26.39	47.91
Slovenia	2701	12.43	19.05	68.52
Slovakia	3781	1.22	2.60	96.18
Finland	666	3.95	9.21	86.84
Sweden	1494	1.05	6.81	92.15
United Kingdom	5396	0.54	2.47	96.99

[a]Share of the given size of the apple orchards based on the size distribution of the fruit orchards in Europe in year 2010 (www.eurostat.eu)

this case, the mechanized pruned biomass harvesting losses (15%) must be taken into account, as well.

Finally, assuming that the average high heating value of the pruned biomass from apple orchards is HHV = 18.5 MJ/kg [3], the theoretical, technical and economic potential in Europe by country is defined (see Table 2).

The total energetic theoretical potential of pruned biomass from apple orchards in 28 EU countries is 29.11 PJ/year (see Table 2). However, this energetic potential

Table 2 The pruned biomass potential from apple orchards in Europe

	Theoretical potential (TJ/year)	Technical potential (TJ/year)	Economic potential (TJ/year)
EU 28	29,113	22,503	18,631
Belgium	414	349	341
Bulgaria	339	219	174
Czech Republic	679	569	555
Denmark	87	73	69
Germany	2055	1681	1575
Estonia	39	32	29
Ireland	40	34	33
Greece	564	403	233
Spain	1732	1360	1182
France	2379	1979	1888
Croatia	311	204	130
Italy	3383	2622	2073
Cyprus	34	12	4
Latvia	155	131	121
Lithuania	91	70	50
Luxembourg	3	2	2
Hungary	1636	1175	1051
Malta	0	0	0
Netherlands	515	431	411
Austria	512	416	370
Poland	9267	7405	5897
Portugal	654	491	393
Romania	3317	2095	1351
Slovenia	175	130	102
Slovakia	245	206	200
Finland	43	35	32
Sweden	97	81	76
United Kingdom	349	295	288

is not distributed equally across the Europe. On the one hand, there are countries with significant potential. The highest potential is in Poland (9.27 PJ/year) which is almost 32% of the overall value. Next countries are Italy, Romania, France and Germany characterized by values 3.38, 3.32, 2.38 and 2.05 PJ/year, respectively. On the other hand, the lowest potentials are located in Malta, Luxembourg, Cyprus and Estonia. In these four countries the summarized potential is below 0.08 PJ/year.

Considering the total energetic technical potential of pruning residues received from apple orchards in 28 EU countries is 22.50 PJ/year (see Table 2), which is ca. 23% lower than the theoretical potential. In this case, the highest potential is still located in Poland (7.40 PJ/year) which is almost 33% of the overall value. After

Poland are Italy (2.62 PJ/year), Romania (2.09 PJ year^{-1}), France (1.98 PJ/year) and Germany (1.68 PJ/year). The countries with the lowest potentials are without changes Malta, Luxembourg, Cyprus and Estonia.

From practical point of view the most important is economic potential as it presents the feasible value which might be reached if the pruning to energy strategy would be applied by the owners of the apple orchards. In the investigated EU countries, using mechanized harvesting of pruning residues, this potential reaches 18.63 PJ/year and represents 64% of the theoretical potential (see Table 2). Although it is a remarkable decrease of the value in terms of theoretical potential, the amount of energy that could be used for heat production on the market is still worth of attention. As a result, the economic potential in Poland counts nearly 5.90 PJ/year followed by Italy (2.07 PJ/year), France (1.89 PJ/year), Germany (1.57 PJ/year) and Romania (1.35 PJ/year). It might be observed that economic potential in France and Germany turned out to be higher than in Romania which is in opposite to the theoretical and technical potentials. It might be explained by the difference in the share of the orchards with the area above 5 ha. In case of Romania only ca. 50% of the orchards have the area larger than 5 ha (see Table 1), whereas in France and Germany this factor is much higher: 93.35 and 90.19% respectively.

4 Conclusions

The energetic potential of pruning residues from apple orchards in 28 EU countries is very scattered in Europe. The total theoretical, technical and economic potential is 29.11, 22.50 and 18.63 PJ/year, accordingly. The economic potential which corresponds to the mechanized harvesting of pruned biomass is still significant. Especially in Poland, where it is located ca. one third of this value (5.90 PJ/year).

It should be underlined, that on the value of the economic potential influences many factors including the share of the large size area orchards, tree density, harvesting losses etc. Therefore, the application of the mechanized harvesting technology should be analysed carefully prior the economic investments. In case of good circumstances the farmer may have additional financial profits thanks to the introduction of a new local fuel for energetic purposes.

Additionally, the are also other benefits related to environmental and social aspects, like: decrease of CO_2 emission, increase of energy production from renewable fuels or employment.

References

1. Garcia-Galindo, D., Gomez-Palmero, M., Germer, S., Pari, L., Afano, V., Dyjakon, A., Sagarna, J., Rivera, S., Poutrin, C.: Agricultural pruning as biomass resource: generation, potentials and current fates. An approach to its state in Europe. In: Proceedings of the 24th

European Biomass Conference and Exhibition (EUBCE), 6–9 June, Amsterdam, The Netherlands (2016)
2. Eurostat database. http://www.eurostat.eu. Last accessed 21 Mar 2017
3. Dyjakon, A., Den Boer, J., Bukowski, P., Adamczyk, F., Frąckowiak, P.: Wooden biomass potential from apple orchards in Poland. Wood **59**(198) (2016)
4. Frąckowiak, P., Adamczyk, F., Wąchalski, G., Szaroleta, M., Dyjakon, A., Pari, L., Suardi, A.: A prototype machine for harvesting and baling of pruning residues in orchards: first test on apple orchard (MALUS MILL.) in Poland. J. Res. Appl. Agric. Eng. **61**(3), 88–93 (2016)
5. Spinelli, R., Magagnotti, N., Nati, C.: Harvesting vineyard pruning residues for energy use. Biosys. Eng. **105**, 316–322 (2010)
6. Magagnotti, N., Pari, L., Picchi, G., Spinelli, R.: Technology alternatives for tapping the pruning residue resource. Biores. Technol. **128**, 697–702 (2013)
7. Dyjakon, A., den Boer, J., Gebresenbet, G., Bosona, T., Adamczyk, F.: Technological and economic analysis of the pruned biomass harvesting in apple fruit orchard for energetic purposes: a case study. In: Proceedings of the 2nd Renewable Energy Sources—Research and Business Conference (RESRB 2017), 19–21 June, Wroclaw, Poland (2017)
8. Spinelli, R., Lombardini, C., Pari, L., Sadauskiene, L.: An alternative to field of pruning residues in mountains. Ecol. Eng. **70**, 212–216 (2014)
9. Grella, M., Manzone, M., Gioelli, F., Balsari, P.: Harvesting orchard pruning residues in southern Piedmont: a first evaluation of biomass production and harvest loss. J. Agric. Eng. **44**(3), 97–102 (2013)
10. Spinelli, R., Picchi, G.: Industrial harvesting of olive tree pruning residue for energy biomass. Biores. Technol. **101**, 730–735 (2010)
11. Kallestad, J.C., Mexal, J.G., Sammis, T.W.: Mesilla Valley Pecan Orchard Pruning Residues: biomass estimates and value-added opportunities. Research Report 764, New Mexico State University Agricultural Research Station: Las Cruces, NM, USA (2008)

Using Photovoltaic Cells for the Large-Panel Urban Fabric Revitalization, Based on Select Neighborhoods

Jarosław Zawadzki

Abstract The aim of this paper is to present possible ways in which the process of large-panel urban fabric revitalization can be combined with renewable energy technologies. The social studies conducted in recent years confirm that the residents are interested in the above solutions. Alternative energy sources may help create a new brand of prefabricated apartment blocks. The geometry of modular apartment block buildings allows for uninhibited distribution of the cells on roofs and side walls of specific structures. Additionally, thanks to their South-Western position, the performance of the cells should be perfectly satisfying. The energy surplus would mainly be used to illuminate the intersections, such as hallways and entrances. This would help save money, which would benefit the entire community. Another benefit of the solution is aesthetics. The cells on the side walls can help add an interesting layer to the large-panel buildings that have become so infamous over the years, while also averting the overabundance of mismatched pastel colors. The studies conducted confirmed the assumptions and the implemented solutions will help not only add to the innovative aspect of post-modern buildings, but also protect the natural environment.

Keywords Revitalization · Photovoltaic · Large-panel

1 The Process of Revitalization in the Context of Currently Available Technology

1.1 Problematic Aspects

The remnants of the post-modern design philosophy has made its mark on the landscape of many Polish metropolitan areas and smaller urban areas. The concrete

J. Zawadzki (✉)
Faculty of Civil and Environmental Engineering, Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland
e-mail: studiobryly@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_59

legacy, dominating many areas for over fifty years, is the source of much controversy. In the past, the buildings were the object of desire for many Poles. By now, they have lost their luster. One of the causes of this state is a lack of clearly defined modernizing processes, as well as the isolation of ideas for solving the problems stemming from the new expectations that the dwellers have. In recent years, we've seen an escalation of this problem. The massively applied process of thermal modernization has been the cause of unexpected results, such as the buildings being painted in a number of mismatched pastel colors. This has become the topic of a nation-wide discussion. Many designers and public administration institutions stress the need for a reparations program that will help fix the deteriorated urban structures. Many specialists studying the effect emphasize the benefits of a comprehensive revitalization program. Countries like Germany and France, where the rehabilitation of module structures has been implemented to great effect, are a prime example of the satisfying effect of this solution. It should be remembered, however, that the modernization program should only be based on technology that is currently available. The power-saving construction policy demands that investors meet ever steeper power norms. Incorporating power-saving solutions should be one of the main points of a post-modern residential building revitalization program. This solution not only takes into account current power demands, but also prioritizes the quality improvement of the module large-panel spaces.

1.2 Implemented Assumptions

Currently, modernization processes utilizing alternative energy sources are being considered. As a result of the analyzed solutions, we can not only get hot water through the use of solar panels, but also the surplus electric energy gained through photovoltaic panels. For a long time both consumers and manufacturers have praised the benefits that these solutions bring. The dwellers of large-panel buildings with twin systems express a similar opinion. The benefits of this solution are undeniable. At first, the costs are incommensurate to the results, Another benefit to these assumptions is the fact that most costs are covered by highly developed environmental programs. One example of such a venture is the implementation of a hybrid heating installation in a Szczytno apartment building. Previously, the building was heated using the city's heating network. Thanks to the technology implemented, the building is now self-sustainable and the combined cost of the heating is only a couple of zloty per square meter, compared to the previous costs. A number of innovative solutions have been utilized for the heating installation modernization, including connecting the NIBE F1345-60 kW (2×60 cascade) heat pump with a compatible "on-grid" 40 kWP photovoltaic system, providing a combined power of 120 kW [1]. Another example of a hybrid heating system is the building managed by the Zielonka Housing Community. The building saw the implementation of a NIBE 60 kW heat pump and a compatible "on-grid" 10 kWp micro-photovoltaic installation [1]. Analogous projects utilizing the compilation of photovoltaic installation or solar panels can be found in many other Polish cities. According to tustolica.pl, the "Praga" Worker Housing Community plans to install solar panels on the roof of their building, as part of the EnSure program. This way, the administrator plans to implement the eco-friendly program and join the power saving policy that has the goal of not only obtaining energy from alternative sources, but also protecting the environment (Figs. 1 and 2).

Fig. 1 PV system located on the roof of an apartment building in Szczytno. *Source* Addur

Fig. 2 View of the system engine room located in Szczytno. *Source* Addur

1.3 Economic and Modern Technology Balance

When it comes to the construction projects, both planned and successfully implemented, it's hard to underplay the importance of the economic factor. The market for modern technologies has always been connected with disproportionate monetary expenditure. Nevertheless, the benefits of solutions like the commonly used solar panel and photovoltaic cell systems have convinced administrative bodies to co-finance the undertakings through countless programs and EU financing. One example of this type of solution are the many cases of thermal modernization of public utility buildings whose modernization is tightly connected with the installation of the aforementioned solar panels. Thanks to this, it is not only possible to improve the thermal comfort of the building, but also to gain warm water by using the solar energy. The notoriously brought up financing system for those ideas is not adequate to the initial costs. The economic balance is soulless, while the cost is very high. When it comes to the undertaking in Szczytno, the project cost almost PLN 625,000. Aside from the additional financing, the housing community received a loan from the Reconal Environment Protection Fund (Wojewódzki Fundusz Ochrony Środowiska), the payment of which is to be concluded in 6 years. The undeniable benefits lead to similar assumption. This is also supported by the sample economic balance, presented below [7] (Fig. 3):

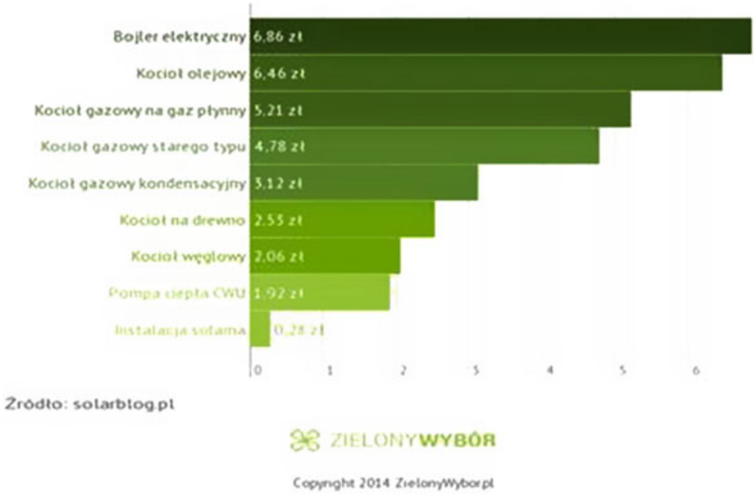


Fig. 3 Comparison of water heating costs. *Source* solarblog.pl

2 Photovoltaic Cells—The Future of Concrete Residential Structures

2.1 *The Construction of Large-Panel Buildings and Photovoltaic Cell Installation*

Large-panel construction, thanks to the simple construction patterns and serial repetition, opens up great opportunities for designers when it comes to the implementation of photovoltaic cells. The abovementioned elements can be installed on the roof, but also on side elevations. The shape of the windows allows for a comprehensive approach when it comes to arranging PV cells. Another benefit of the solution is the material used for the floor. The insulated concrete structure of the side walls, as well as the horizontal surface of the roof does not create a lot of problems for qualified installation teams, from a theoretic point of view. In both cases, classic solutions such as flat surface construction and systemic rail solutions for vertical surfaces can be used. Another piece of evidence for the high installation capabilities is the structure of the rooms in modular constructions that allows for the implementation of the rest of the installation equipment. The internal layout of specific buildings allows for a PV engine room in common areas located in the basement or attic. The architectural layout found in large-panel buildings does not prevent combining specific elements into a cohesive whole. The configuration of staircases and technological lines allows for the installation of cable systems, as well as free access to various warranty examinations.

2.2 *Benefits and Drawbacks of the Proposed Solutions*

There are three aspects that should be considered when talking about the benefits: aesthetic, environmental, and marketing. Analyzing the first case, it is important to remember that there are currently no real ideas for a solution to the concrete heritage. The inconsistent coloration present on many buildings did little to improve the external aesthetics of the buildings. In this case, there is the option of utilizing tested solutions that are commonly used in other countries. Namely, this involves connecting PV cells with plastic elements [4] (Fig. 4).

In the end, the assumptions made create interesting modules that can be molded at will. However, there are other acceptable composition, for example those utilizing glass surfaces and a whole range of composite materials. A result of this operation would be the combination of architecture with modern technology, which will bring benefits in terms of looks and from an economical perspective. The second aspect is also indisputable. The gains related with the use of PV panels will help save energy, first and foremost, the conventional production of which would be crucial to illuminating common areas within buildings. The surplus could be used to illuminate the stairwells or hallway systems. Such a solution would help

Fig. 4 Elevation created using PV cells. *Source* ONYX SOLAR BLOG

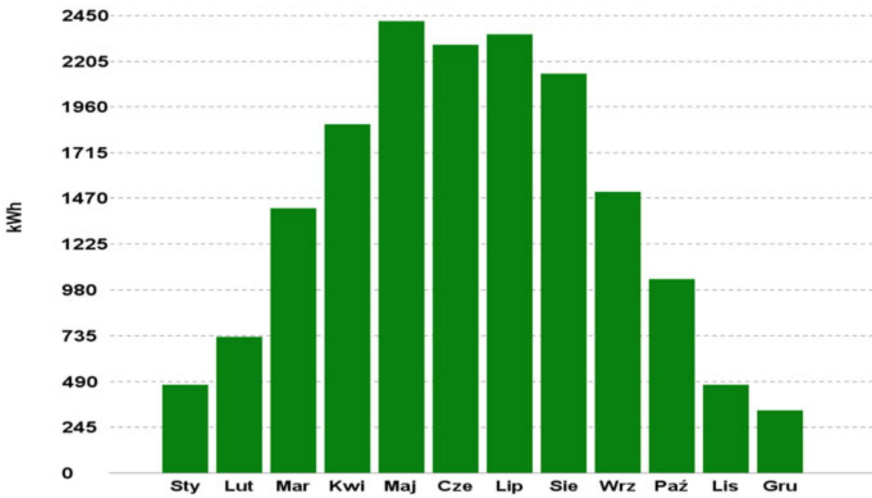


Fig. 5 Example of PV installation efficiency. *Source* OPEUS Energia

limit dweller expenses and direct resources to other, more important investments. Below is a chart presenting a hypothetical efficiency of PV cells that clearly shows that the results are very much in line with the notions of environmental protection [2] (Fig. 5).

Such eco-friendly solutions make us realize just how much the environment can be protected from gases and other particles that deepen the greenhouse effect.

It's also important to remember the element of urban marketing as an important factor speaking for the implementation of these assumptions. In many cases, the revitalization of devolved large-panel structures requires another stimulus that will lead to the inevitable modernization of the concrete structures. Implementing modern technological solutions will help speed up the process, and at a later stage increase the image and financial value of many buildings. The concrete legacy, expanded with the newest heating solutions, will be seen as lenders and buyers as a living space that can compete with newly created apartment buildings. Taking into account the benefits of PV cells in a prefabricated building, it's important to mention the drawbacks. While conducting social consultations dealing with planning the use and future of prefabricated buildings, the issue of alternative energy installations was brought up. The PV cell system is a source of many fears among a large number of residents. People associate the technology with the increase of initial payment. Nevertheless, this type of undertaking and the benefits of the eco-friendly and power-saving policy remain relatively misunderstood by many. Therefore, it is crucial that social campaigns be conducted with the aim of raising awareness about the proposed solutions in a clear way.

2.3 Currently Implemented Plans

Modern residential and service buildings are tightly connected with the technological developments market. PV cells have found a versatile use in many designed buildings. The main aim of most of them is the production of energy through the use of solar rays, but the avant garde PV system described in many cases also plays another role—improving the building's looks. In isolated cases, the PV system has been integrated with the building structure. An example of this solution is the Exhibition and Congress Center in Rzeszów concept. In this building, the cells and glass form a dome over the building as a filling in-between the steel elements [5] (Figs. 6 and 7).

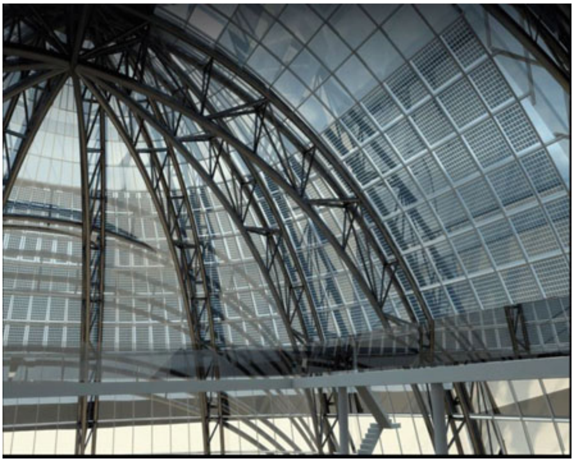
This bold approach helps the general public view PV cells not only as a power-generation installation, but also an important aesthetic architectural detail.

3 Conclusion

The problem discussed in the paper emphasizes the benefits of combining PV cell technology with architecture [6]. The PV cell implementation may help solve problems regarding contentious energy issues, as well as revitalize the large-panel urban fabric. Abandoning the grayscale of days gone by and replacing it with clashing pastel colors through the process of thermal modernization only escalated the problem of module structure degradation. A modernization involving PV technologies could be a way to solve this problem [3]. As a result of such a project,

Fig. 6 View of the PV cells forming the roof dome. *Source* Reconal

Fig. 7 View of the PV cells forming the roof dome. *Source* Reconal



we could create a system that would allow the installation of cells not only on roofs, as is the case now, but also on walls. This will help create a modern residential structure.

References

1. AddurPompy Ciepła. http://addur.pl/realizacje/. Last accessed 2016
2. Biznes Alert. http://biznesalert.pl/dluzszy-dzien-zwieksza-efektywnosc-paneli-fotowoltaicznych. Last accessed 2016

3. Jastrzębska, G.: Ogniwa słoneczne. Budowa, technologia i zastosowanie. WKŁ, Warszawa (2014)
4. Onyx Solar Blob. https://onyxgreenbuilding.wordpress.com/tag/solar-decathlon. Last accessed 2010
5. RECONAL. http://www.reconal.pl/typ_realizacji/wszystkie-realizacje/. Last accessed 2017
6. Tytko, F.: Urządzenia i systemy energetyki odnawialnej. Towarzystwo Słowaków, Kraków (2016), pp. 128–136
7. Zielonywybór. http://www.zielonywybor.pl/energia-sloneczna/kolektory-sloneczne. Last accessed 2014

Physical and Chemical Properties of Pellets Produced from the Stabilized Fraction of Municipal Sewage Sludge

Beata Brzychczyk, Tomasz Hebda and Jan Giełżecki

Abstract The physico-mechanical properties of compact biomass formed from biomass from the giant biomass power plant and the stabilized fraction of municipal waste have been studied. The strength properties study was carried out on pellets formed from mixtures containing 5, 10, 15, 20 and 25% stabilizer and moisture content of 12, 15 and 18%. Modified biofuel has been tested for energy properties. The heat of combustion, calorific value and ash content were determined according to the proportion of pelletized stabilizate.

Keywords Stabilizer · Biofuel · Underburden fraction · Physico-mechanical properties · Fuel properties · *Miscanthus* x *giganteus*

1 Introduction

Pursuant to Directive 2009/28/EC of the European Parliament and of the Council, Poland was required to achieve a minimum of 15% share of renewable energy in gross final energy consumption. In Poland, energy from renewable sources is the most often obtained the from solid biofuels. In 2013, its share of renewable energy sources was around 80% and mainly generated through combustion processes including the incineration of biofuels from waste biomass. By contrast, in the

B. Brzychczyk (✉) · T. Hebda · J. Giełżecki
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka nr 120, 30-149 Krakow, Poland
e-mail: Beata.Brzychczyk@ur.krakow.pl

T. Hebda
e-mail: Tomasz.Hebda@ur.krakow.pl

J. Giełżecki
e-mail: gielzeck@o2.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_60

European Union the share of renewable biofuels in renewable energy sources in 2012 was 47% [1, 2].

Biofuels are used in the process of burning or co-burning with coal to produce heat that can be later converted to other forms of energy. This is mainly done in power plants and power [3].

The premise for attempting to create a compact biofuel with the addition of a stabilized fraction of municipal waste sludge was the hierarchy of ways dealing with waste and the Regulation of the Minister of Economy introducing a ban on the storage of waste heat exceeding 6 MJ kg^{-1} of dry matter (d.m.), an organic carbon content of more than 5% dry weight and loss of ignition of more than 8% d.m. The regulation forces the waste to be processed before it reaches the storage site at a later stage. Generally, this fraction goes to the biological part of the MBT (mechanical-biological treatment) plant where after processing it is given the code 19 05 99 (other not listed waste from the oxygen distribution of solid waste). Physical-chemical characteristics of this waste suggests that it can be used in terms of energy.

Recent waste disposal practices, as recommended by the KPGO (National Waste Management Plan), have to be reduced. Because of this, stabilizers can be developed after the stabilization process to create alternative fuels (KPGO, 2022). Alternative fuel from waste classified in the waste catalog code 19 12 10—combustible waste is produced from non-hazardous waste and produced for energy recovery in combustion or co-firing plants.

Alternative fuels made from waste are mainly used in cement plants. It can also be used in co-combustion processes in heat plants, combined heat and power plants. In recent years, the growth of investments in Poland related to the thermal treatment of municipal waste has created the possibility of using alternative fuels in the TWTP (Thermal Waste Treatment Plant). The net calorific value of the stabilized urban waste underfill fraction of about 5–6 MJ kg^{-1} prevents its incineration without added calorific value. Such a calorific value will also not provide the minimum economic temperature required by the Ministerial Regulation of 1123 K which can be achieved with a calorific value of more than 7.5 MJ kg^{-1} [4].

Considering the above information, an attempt was made to model biomass-based biofuel from a power plant—a giant miscanthus and the addition of a stabilized fraction of municipal waste (stabilizate) to recover contained there energy. It presents the possibility of utilizing a stabilized fraction of municipal waste through a process other than storage.

Required Parameters of Molded Fuels

Polish biofuel standards in detail and restrictively classify fuels from the origin of the biomass source to the specific raw material. For businesses, incineration plants, cement plants, power plants and small private customers it is important for their fuel to have repetitive, well-known features. Technological processes require proper efficiency and operating conditions. Fuels for potential buyers should be characterized by:

- suitable for their installation calorific value,
- the lowest possible grams of aggressive elements (chlorine, fluorine, bromine, sulfur, etc.) and heavy metals (chromium, lead, mercury, zinc, chromium, manganese, nickel, arsenic, etc.)
- the least amount of ash with the correct chemical composition (which affects the so-called melting point and thus the difficulty of slagging the furnace).
- low content of hygroscopic moisture reducing,
- as much bulk density as possible,
- low emission of toxic gas products,
- high calorific value [5].

The parameters categorizing among others are: calorific value, chlorine content and mercury content. Thus, fuels used e.g. in the cement-lime industry when firing clinker should have:

- calorific value of not less than 12 MJ kg^{-1}
- humidity up to 30%
- chlorine content max. 0.3%
- sulfur content max. 2.5%
- ash content max. 15%
- content of polychlorinated biphenyl PCB max. 50 mg kg^{-1}
- Heavy metal content max. 2500 mg kg^{-1}
- mercury content up to 10 mg kg^{-1} [6–9].

Physical properties that affect transport and storage are also important [3].

In the case of thermal processing of waste conversion and incineration of alternative fuels into ZTPO (Thermal Treatment Plant), the legislator has defined the following requirements to be fulfilled in the above process:

- The minimum temperature in the combustion chamber depending on the chlorine content can not be less than 1373 or 1123 K,
- The organic carbon content in slags and ash should not exceed 3% or the proportion of flammable components in slags and furnace ash may not exceed 5% [4, 10].

1.1 Materials and Methods

The giant miscanthus (*Miscanthus* x *giganteus*) was acquired in the autumn 2015 from an experimental plantation of energy crops of the Faculty of Production Engineering and Energetics of the University of Agriculture in Cracow. The test material was seeded for a period of four months and then finely divided into a 6 mm fraction using a MF-4 Protechnika Cutter Mill.

The stabilized fraction of municipal waste was collected from MIKI Mieczysław Jakubowski’s Multinational Enterprise. The test material was isolated in the mechanical and biological treatment of municipal waste. The stabilization was legal:

- residue after ignition $\leq 35\%$ d.m.,
- TOC $\leq$ 20% g.m.,
- organic matter loss in relation to organic matter in waste, measured by a roasting loss or TOC of $\geq 40\%$,
- AT4 value is less than 20 mg O_2 g—dry matter,
- The stabilizer did not contain a biodegradable fraction with a gas-generating potential.

Thirty samples of material were taken. The collected material was averaged by quartering by taking a sample of 1.5 kg for laboratory testing. The stabilizer sample was then dried to constant weight. Drying was carried out using a Memmert type UF 55 dryer. The drying process was carried out, as was the case with the biomass of the miscanthus, at 105 °C for 24 h. Dried material was crushed using a MF-4 Protechnika Shredder Mill using a 6 mm sieve.

From the premixed giant miscanthus and stabilizer to fractions below 6 mm mixtures were prepared in the following proportions of stabilizate to miscanthus: 5:95, 10:90, 15:85, 20:80, 25:75. Prepared 15 samples of different types of biofuel pellets have been tested for mechanical strength. In addition, the specific density of compacted biofuels and fuel properties (combustion heat, calorific value and ash content) were determined.

The resulting mixture was ground to a fraction below 4 mm. The MF-4 Protechnika Cutter mill was used for final shredding. Fragmentation has had a positive effect on the homogenisation of the mixtures. These mixtures were subjected to an agglomeration process humidifying the humidity levels of 12, 15 and 18% for each of the mixtures [11, 12]. For the agglomeration the EDZ-20 strength machine was used, using a 12 mm spindle and a 2kN force. The agglomeration pressure was 166.66 MPa. Upon reaching the desired pressure force the specimen was left under its influence for a period of 10 s to obtain the appropriate density and stability of the pellet.

Subsequently, the samples were subjected to strength tests. Their density and fuel properties such as heat of combustion, calorific value and ash content were also determined.

A strength test (the so-called diameter test or Brazilian test) was performed by squeezing the pellets along the diameter of the MTS Insight 2 machine connected to a computer with Test Works software installed. The machine consists of a crushing head that compresses the test sample by sending to the computer data from the pressure sensors registered by the manufacturer software and written to the output file. The algorithm involved carrying out measurements of mass and geometry of the pellets (height and diameter), inserting data into the endurance program and placing the sample under the crushing head by moving it from 10 mm min^{-1} until the maximum force causing the sample destroyed. Based on the data entered the computer program determined the maximum force (destructive force). Calculations were made on the basis of formula (1) for mechanical resistance in radial compression:

$$\sigma_m = \frac{2 \cdot F_n}{\pi \cdot d \cdot h} \tag{1}$$

where:

σ_m mechanical resistance, MPa,
F_n compressive force (destructive) sample, N,
d sample diameter, m,
h height of the sample, m [13].

For each of the pellets 50 strength endurance repetitions were performed. The average value of mechanical resistance was calculated according to the humidity and the share of the stabilized fraction of municipal waste. The results are shown in Fig. 1. In addition, the specific biofuel density was calculated based on mass, measured diameter and height using formula (2):

$$\rho = \frac{m}{\pi \cdot \left(\frac{d}{2}\right)^2 \cdot h} \tag{2}$$

where:

ρ specific density, kg m^{-3},
m mass of sample, kg,
d diameter, m,
h height, m.

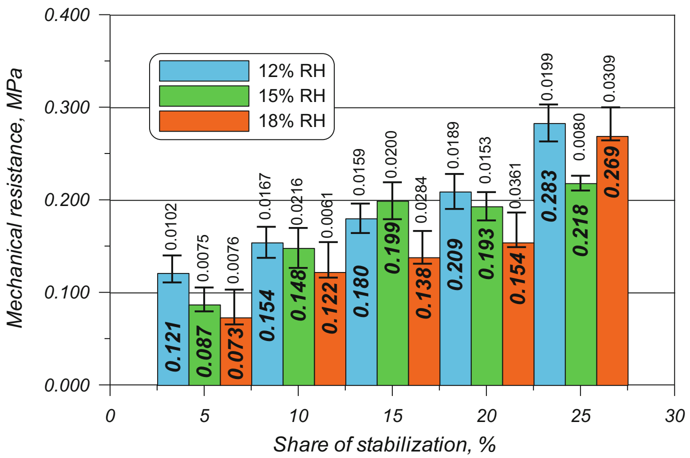


Fig. 1 Effect of moisture and stabilizer share on mechanical strength of pellet in Brazilian test

In the last stage basic analyzes of fuel properties of modeled compacted biofuels were performed. The ash content and the heat of combustion were tested for each percent stabilizer additive. The calorific value was converted to working condition for assumed humidity.

The ash content determination was performed according to PN-EN 14775 standart. Five specimens weighing 1 g were weighed and placed in heat-resistant vessels. Dishes were placed in a muffle furnace. The oven was heated to 250 °C for 30 min and the samples were heated for 60 min. The temperature was then increased to 550 °C over 30 min and the sample was heated for 120 min. Samples were removed and placed in a desiccator until ambient temperature was reached. Then the samples were weighed. The study was conducted for each stake of the stabilization. The mean ash content for each percentage of stabilizer additive was calculated.

Determination of combustion heat and calculation of calorific values for 15 mixtures were carried out in accordance with PN-EN 14918 standart. A sample weighing 1 g was weighed and placed in a crucible. Then the crucible was put in the IKA C 5000 Control calorimeter. The sample was burned in an atmosphere of pure oxygen. The value of the combustion heat that was measured by the calorimeter was read. Five measurements were taken for each percentage of stabilization. The calorific value in working condition for assumed humidity based on combustion heat and hydrogen content was calculated.

1.2 Result and Discussion

The results of mechanical strength analysis based on percentage of stabilized fraction of municipal waste and moisture content are presented in Fig. 1. The lowest average mechanical resistance was obtained by pellets with a moisture content of 18%. The highest average mechanical strength was obtained by test samples of fuel with a moisture content of 12%. The basic statistics showed that the mechanical strength of the formed pellets ranged from 5 to 23% of the average but it can be observed that as the moisture content increases the standard deviation increases, too. Variability coefficients did not show in each group of high volatility. The highest variability coefficient of 23% was obtained for the pellet obtained from a mixture containing 18% moisture and 20% stabilizer blend. Thus, the increase in moisture content caused a decrease in the mechanical resistance of the biofuel tested and had a significant effect on its strength.

The highest mechanical resistance was obtained by samples of a stabilized fraction of municipal waste at the level of 25%. The smallest average mechanical resistance was obtained by pellet samples with a stabilized fraction of municipal waste at the level of 5%. The increase in the percentage of stabilized fraction of municipal waste has increased the mechanical resistance of the modeled compacted fuel.

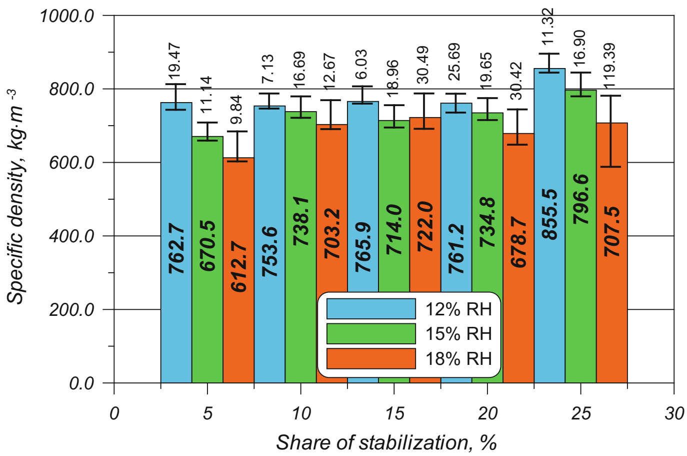


Fig. 2 Specific density of pellets depending on the content of stabilizer and moisture content of the material

The average specific density of biofuels depending on the moisture content and the contribution of the stabilized fraction of municipal waste is shown in Fig. 2. The highest average specific density was obtained by pellet samples with a moisture content of 12%, the smallest sample with a moisture content of 18%. The increase in moisture content caused a decrease in the density of the pellet. There was a correlation between the change in average density and the percentage of stabilized fraction of municipal waste. Samples with the lowest stabilization content obtained the lowest average density. On the other hand, the addition of 25% stabilization resulted in an increase in the average density of the modeled compacted fuel. After basic statistics it was found that in most cases the results did not differ by more than 2–4%. Only in the case of pellets formed from the mixture with the highest moisture content and the largest stabilizer additive resulted in a large dispersion of results with an average of up to 16%. In this group the largest differences in the obtained density values were observed which can be attributed to the heterogeneity of the stabilization composition. Variability coefficients showed small differences in particular groups. In general, the increase in the share of the stabilized fraction of municipal waste increased the average density of the pellets.

Results of the Study of Fuel Properties

The combustion heat and the ash content depending on the percentage of stabilizer in the dry fuel state are shown in Figs. 3 and 4. Its value decreases with the increase of the stabilized fraction of municipal waste. The highest value of 16,460 kJ kg^{-1} was obtained with a fuel containing 5% stabilizer. The smallest value of 14,859 kJ kg^{-1} was obtained with a 25% stabilization fuel. The addition of fractionated stabilized municipal waste resulted in a reduction in combustion heat. This is due to the high proportion of non-combustible fractions in stabilization.

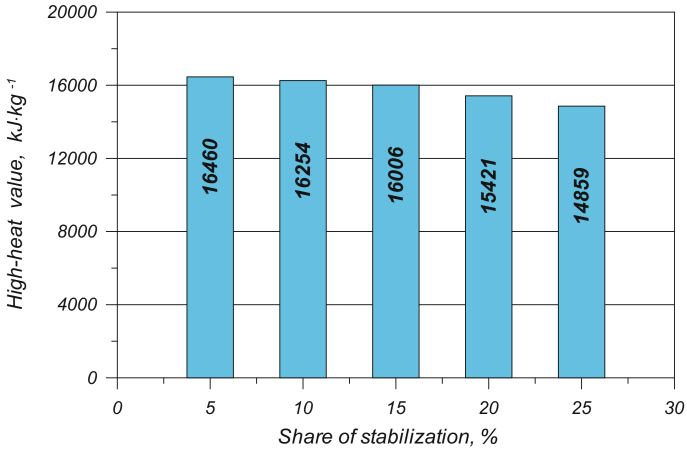


Fig. 3 The value of combustion heat from the contribution of stabilizate in pellets

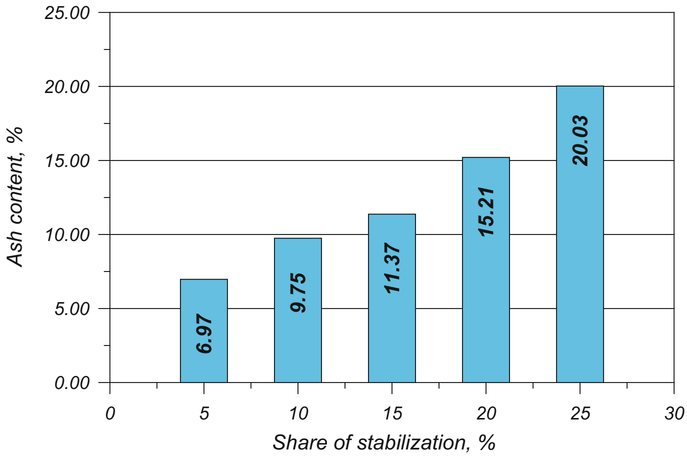


Fig. 4 Ash content depending on the proportion of pellets stabilized

This overlaps with a significant increase in the ash content with an increase in the proportion of stabilizer added. The smallest ash content was blended with a 5% addition of stabilized fraction of municipal waste, on average it was 6.97%. The highest content of ash had fuel samples with the addition of 25% of the stabilized fraction of municipal waste, on average it was 20.03%. The significant increase in the amount of ash along with the increase in the fraction of waste is due to the high proportion of the mineral fraction in the stabilized fraction of municipal waste.

The highest calorific value was achieved by pelletized fuel with 5% stabilizer (Fig. 5), and a moisture content of 12%, amounting to 14,777 kJ kg^{-1}. The smallest

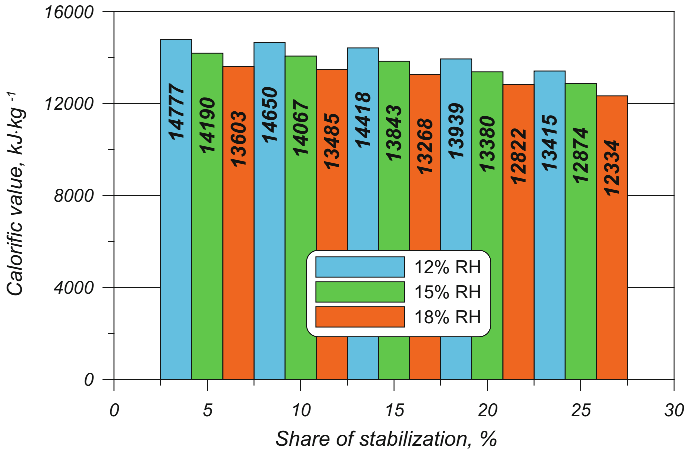


Fig. 5 Calorific value of biofuels for various stabilizers and moisture content in pellets

net calorific value was obtained with 25% stabilization pellets, amounting to 13,415 kJ kg^{-1}. Pellet with a moisture content of 15% achieved the highest calorific value at 5% stabilizer additive (14,190 kJ kg^{-1}). The smallest calorific value for this moisture content was obtained by pellets of 25% stabilization additive which amounted to 12,874 kJ kg^{-1}. Results of calorific values for 18% moisture contents in the material oscillate between 12,334 and 13,603 kJ kg^{-1}. In each of the examined cases the increase in the percentage of the stabilized fraction of urban precipitation in pellets resulted in lower calorific value.

For all tested models of pelletized model, with three moisture contents, in all cases the decrease in calorific value coincides with a significant increase in the ash content while increasing the proportion of stabilization.

2 Conclusions

The studies showed a decrease in the specific density and mechanical resistance of the pelletized fuel as moisture content increased. The increase in the share of the stabilized fraction of municipal waste in the model compact fuel has increased its density. Mechanical strength analysis showed an increase in mechanical resistance along with an increase in the percentage of stabilizate additive in the tested pellet samples. Analysis of ash content showed a significant increase in the amount of fuel residue with an increase in the share of stabilized fraction of municipal waste in compacted fuel. Studies have shown that the increase in the percentage of the stabilized fraction of urban precipitation in pellets has reduced its caloric value. Generated alternative fuel produced with a stabilized fraction of municipal waste up to 15% meets minimum fuel requirements (calorific value, moisture content, ash content) for clinker production facilities. Stabilizate fuel can be used in cement plants.. When analyzing the fuel used in power generation and heating all blends had the required minimum calorific value for fluidized bed and coal-fired boilers. For the lignite dust boiler only the 5, 10, 15% for each tested moisture content and the 20% moisture content of 12% were required for the minimum calorific value. In addition, there is a possibility of using alternative stabilized fraction of municipal waste in cement plants or the power industry.

Acknowledgements This Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Gużda, A., Szmolke, N.: Efektywność małej elektrowni wodnej na wybranym przykładzie, Współczesne Problemy Energetyki Iii, aut. książki Moniki Praca zbiorowa pod redakcją Krzysztofa Pikonia, Archiwum Gospodarki Odpadami i Ochrony Środowiska, Gliwice (2015)
2. Schnell, Ch.: Wykonanie celu OZE 2020. Analiza stanu obecnego i prognoza. Solivan, Warszawa 2016 [on-line], dostęp 13 July 2017
3. Van Tubergen, J., Milieu, E., Glorius, T., Waeyenbergh, E.: Classification of Solid Recovery Fuels. European Recovered Fuel Organization (2005)
4. Czajka, K., Mokrzycki, E., i Uliasz-Bocheńczyk, A.: Zasoby energetyczne odpadów, Energia z odpadów. Sopot (2000)
5. Poskrobko, S., Łach, J., Król, D.: Badanie podstawowych właściwości paliwowych, Energetyka (2009)
6. Malinowski, M., Sikora, J.: Wpływ zawartości odpadów ulegających biodegradacji na właściwości paliwa alternatywnego z odpadów. In: Proceedings of EC Opole (2008), strony 223–230
7. Trezza, M.A., i Scian, A.N.: Waste fuels: their effect on Portland cement clinker. Cem. Concr. Res. **35**, 438–444 (2005)
8. Wandrasz, J.W., Wandrasz, A.J.: Fueled Biofuels and Fuel From Waste in Thermal Processes. Seidel - Przywecki Sp. zoo Warszawa (2006). ISBN 978-83-919449-7-2
9. Duda, J.: Piec cementowy jako agregat do współspalania paliw alternatywnych. Spalanie paliw alternatywnych w energetyce i przemyśle cementowy. Opole (2003)
10. Rozporządzenie Ministra Rozwoju z dnia 21 stycznia 2016 r. w sprawie wymagań dotyczących prowadzenia procesu termicznego przekształcania odpadów oraz sposobów postępowania z odpadami powstałymi w wyniku tego procesu, Warszawa dnia 22 stycznia 2016 r. poz. 108
11. Skonecki, S.: Modelowanie ciśnieniowego zagęszczania materiałów roślinnych, Lublin, Wydawnictwo Akademii Rolniczej w Lublinie (2004)
12. Hejft, R.: Ciśnieniowa aglomeracja materiałów roślinnych, Białystok, Wydawnictwo i zakład poligrafi instytutu technologii eksploatacji (2002)
13. Borowski, G.: Porównanie dwóch sposobów określenia wytrzymałości brykietów z materiałów drobnoziarnistych. Postęp Nauki i Techniki nr **12**, 115–120 (2012)

The Research into Determination of the Particle-Size Distribution of Granular Materials by Digital Image Analysis

Artur Wójcik, Wioletta Przybyła, Sławomir Francik and Adrian Knapczyk

Abstract The granular materials, in particular fragmented biomass and cereal grains, are widely used in the power industry, the food industry, and agriculture. These materials are subjected to various processing methods and automated transport processes, which encourages implementation of fast tools (methods) for evaluation of the basic physical properties of these materials. The particle-size distribution is one of the basic characteristics of granular materials. The classic measurement methods are very time-consuming. Digital Image Analysis (DIA) provides new possibilities for quick, real-time measurements. The paper presents the study of the possibility of using DIA to determine the particle-size distribution of granular materials. The results obtained with DIA showed correlations with the actual particle-size composition at the values ranging from 0.63 to 0.89 R^2.

Keywords Particle-size distribution · Granular materials · Digital image analysis

A. Wójcik (✉) · W. Przybyła · S. Francik · A. Knapczyk
Faculty of Production and Power Engineering, Department of Mechanical Engineering and Agrophysics, University of Agriculture in Cracow University, Balicka 120, 30-149 Cracow, Poland
e-mail: artur.wojcik@urk.edu.pl

W. Przybyła
e-mail: wioletta1992@gmail.com

S. Francik
e-mail: slawomir.francik@urk.edu.pl

A. Knapczyk
e-mail: adrian.knapczyk91@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_61

1 Introduction

Granular materials are commonly found in almost all areas of economy (agriculture, food, energy, construction), and their processing involves large quantities of energy. Therefore, the determination of the physical properties of granular materials, which influence the behavior of these materials in unit operations, assumes so much importance (Fig. 1).

The basic physical properties which describe granular materials include the following: shape factor; bulk density; porosity; static and kinetic friction; and the angle of repose. A significant indicator of the physical properties of granular materials is also the particle-size distribution which is often considered in the context of the quality of various mixture types.

The particle-size distribution is defined as the distribution of particles of varying sizes, constituting the granular material. It is given as a percentage of different fractions relative to the total weight of the test sample, whereas the fraction is a group of particles of close size. At present, the particle-size distribution is most commonly assessed with a sieve analysis and the gravitational method, which are used for splitting up a test sample into size fractions. A sieve analysis involves a set of sieves with decreasing mesh openings. The fractions of particles within a certain size range are retained on sieves of a given mesh size. The mass fraction on each sieve divided by the total weight of the test sample and the sieve size may be used to construct a histogram illustrating the gradation of fractions within a given sample [1–4] (Fig. 2).

The major disadvantage of typical methods for determining the particle-size distribution is that they take relatively long time; moreover, some materials are susceptible to damage, which effectively prevents these methods from being used. The search for quick and non-invasive processes, therefore, seems to be fully justified. A fairly common method for object recognition is a computer-based image analysis [5–8].

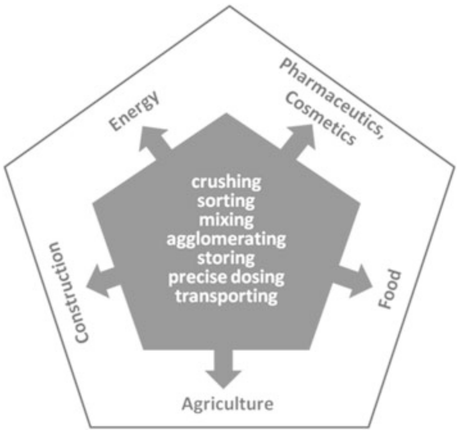


Fig. 1 Granular materials, areas of application, unit operations

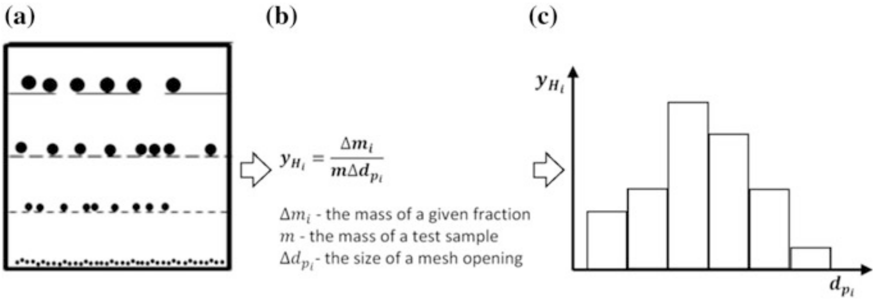


Fig. 2 Granular materials, areas of application, unit operations

The paper aims to assess the usefulness of computer image analysis for predicting the particle-size distribution of granular materials; in other words, it examines the relation between the actual particle-size composition and the information contained in the images showing the surface layer of an investigated material.

2 Material and Method

Two mixtures of two components, i.e., one consisting of balls having a diameter of 6 and 8 [mm] (mixture I—6 mm balls with added 8 mm balls and the other one made up of wheat and peas (mixture II—wheat with added peas), were used as test samples. For both samples, the same procedure was followed:

- For each main material, a suitable mass of an additive was added to make up 0, 10, 20, 30, 40, 50 [%] of the whole mixture, respectively. For both mixtures, the mass of the main material was the same (Tables 1 and 2).
- Each mixture was poured into a transparent container. Then, the top and side images of the mixtures were taken. Subsequently, the test samples were agitated and photographed again. For each particle-size composition, the procedure was repeated 20 times, which provided 240 images of the mixture I and 240 shots of the mixture II for analysis (Fig. 3).

Table 1 The characteristics of the mixtures made up of 6 and 8 mm granules (mixture I)

	Unit	Composition					
		1 (0%)	2 (10%)	3 (20%)	4 (30%)	5 (40%)	6 (50%)
The mass of the mixture	kg	0.75	0.825	0.9	0.975	1.05	1.125
The mass of the added material (8 mm balls)	kg	–	0.075	0.15	0.225	0.3	0.375
Material volume	dm^3	0.54	0.61	0.69	0.78	0.84	0.9

Table 2 The characteristics of the mixtures made up of wheat and peas (mixture II)

	Unit	Composition					
		1 (0%)	2 (10%)	3 (20%)	4 (30%)	5 (40%)	6 (50%)
The mass of the mixture	kg	0.75	0.825	0.9	0.975	1.05	1.125
The mass of the added material (peas)	kg	–	0.075	0.15	0.225	0.3	0.375
Material volume	dm^3	1.07	1.15	1.21	1.29	1.38	1.5

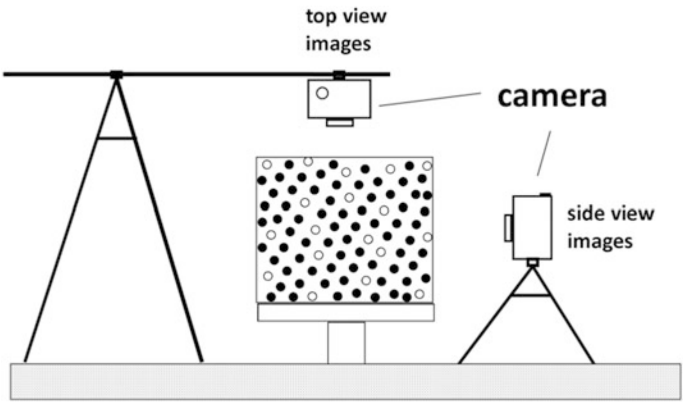


Fig. 3 The scheme of the test facility

- For each calibrated image, the entire mixture was divided into multiple segments through the process of image segmentation. This allowed for determination of the surface areas and the Feret diameter [5]. The automatic granular segregation of a given fraction was performed on the basis of the surface area of a given object; for the partially covered granules the Feret diameter was also used to determine the particle size (Fig. 4).

3 Analysis of Results

The described measurement procedure was repeated for each image taken from the top and the side view. The obtained results were plotted in graphs (Fig. 5). Figure 5a, c, e, and g show the percentage of the surface areas occupied by the analyzed fraction in relation to the area of the whole image for the mixture I and mixture II, respectively.

In the following step, correlation analysis was conducted to explore the relationship between the actual particle-size distribution and the results obtained from

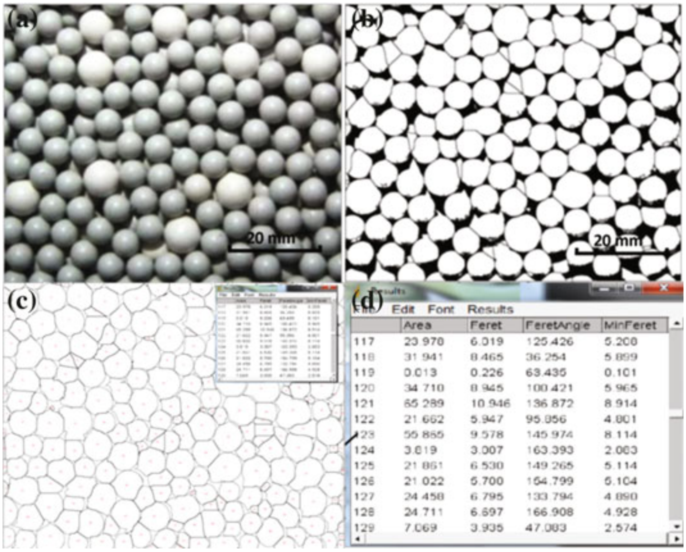


Fig. 4 The selected stages of image processing; **a** image output, **b** binary image, **c** image segmentation, **d** the values of surface areas and the Feret diameter of individual particles

computer image analysis. These studies were supposed to show whether or not there was a relationship between the actual percentage share and the percentage share of the surface areas occupied by the added fraction, which are visible in the images, compared to the entire image. The correlation analysis was performed by the least squares method at a 0.95 confidence level and at the assumed significance level $p < 0.05$. Figure 5b, d, f, h and Table 3 shows correlation for individual variants.

In Fig. 5 f, for example, one may observe large discrepancies in the obtained results. Some results for adjacent values of compositions overlap (the gray box on the graph). This, at small amount of repetitions, may lead to misinterpretation of the results and contribute to an inaccurate prediction of the particle-size distribution (Fig. 6).

4 Conclusions

It has been found that there is a statistically significant relationship between the obtained results and the actual particle-size distribution. There was a strong positive correlation showing that with the growing actual percentage share, the percentage of the surface areas of the added fraction, visible in the pictures, in relation to the entire image also increases. These results provide the basis for the finding that computer image analysis can become a tool for predicting particle-size distribution.

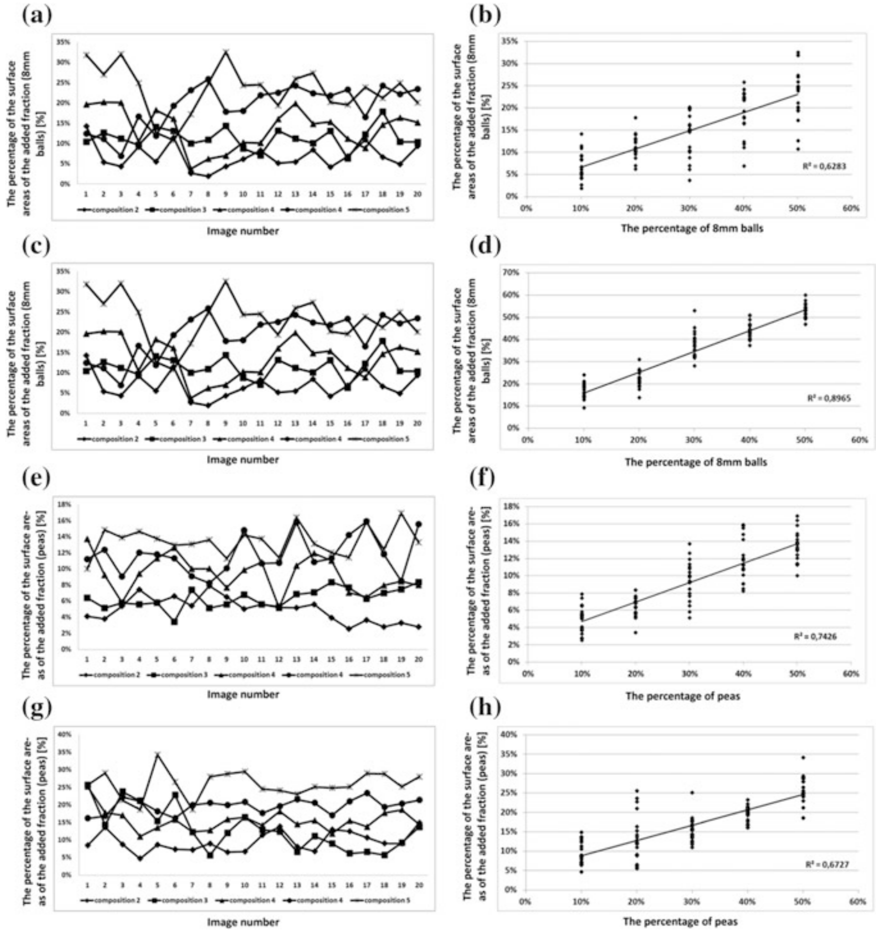


Fig. 5 The percentage of a given fraction (surface areas) in the upper and the side layers. **a** Mixture I—side view images (balls 6 and 8 mm), **b** correlation diagram for results (**a**), **c** Mixture I—top view images (6 and 8 mm balls), **d** correlation diagram for results (**c**), **e** Mixture II—side view pictures (wheat, peas), **f** correlation diagram for results (**e**), **g** Mixture II—top view pictures (wheat, peas), **h** correlation diagram for results (**g**)

Table 3 The results of the correlation

Mixture	Correlation coefficient R	Determination coefficient R^2
Mixture I (side view)	0.7926	0.6283
Mixture I (top view)	0.9468	0.8965
Mixture II (side view)	0.8618	0.7426
Mixture II (top view)	0.8202	0.6727

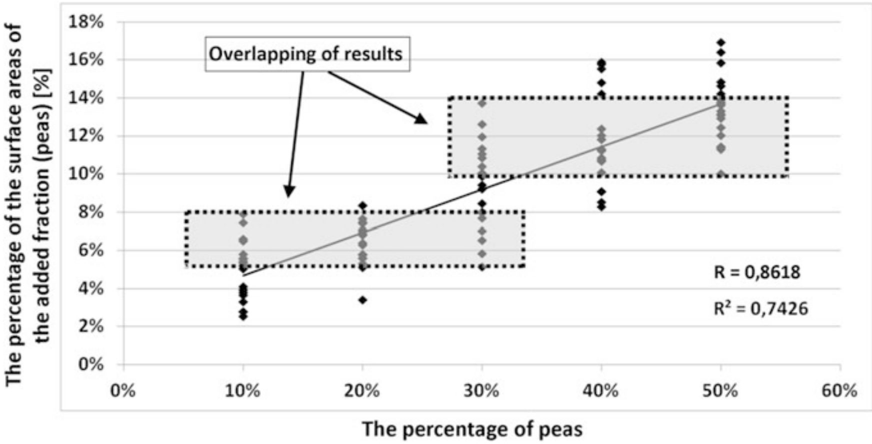


Fig. 6 Problems with predicting the particle-size distribution

The performed investigations were preliminary in nature. In order to obtain a higher correlation coefficient, the image area needs to be increased, while the number of pictures for each particle-size composition has to be multiplied (50 or even 100 images). A uniform and standardized mixing method also requires consideration.

Acknowledgements This Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Chen, H., Tang, H.-W., Liu, Y., Wang, H., Liu, G.-P.: Measurement of particle size based on digital imaging technique. J. Hydrodyn. **25**(2), 242–248 (2013)
2. Barbosa-Cánovas, B.V., Harte, F., Yan, H.H.: Particle size distribution in food powders. In: Encyclopedia of Life Support Systems (EOLSS), Food Eng. (2012)
3. Peszko, B., Niedoba, T., Szymańska-Czaja, M.: Składanie rozkładów wielkości ziaren otrzymanych z różnych metod pomiarowych. Górnictwo i Geoinżynieria, Zeszyt 3/1, (2006)
4. Grochowicz, J.: Machines for Claaning and Sorting of Seeds. Warsaw, Poland: Published for the U.S. Dept. of Agriculture and the National Science Foundation by the Foreign Scientific Publications Dept. of the National Center for Scientific, Technical and Economic Information; Springfield, Va.: Available from the National Technical Information Service (1980)

5. Wojnar, L., Kurzydłowski, K.J., Szala, J.: Practice of image analysis. Polskie Towarzystwo Stereologiczne, Kraków (2002). (in Polish)
6. Hartmann, H., Böhm, T., Jensenb, P.D., Temmerman, M., Rabierc, F., Golserd, M.: Methods for size classication of wood chips. Biomass Bioenergy **30**, 944–953 (2006)
7. Shouche, S.P., Rastogi, R., Bhagwat, S.G., Sainis, J.K.: Shape analysis of grains of Indian wheat varieties. Comput. Electron. Agric. **33**, 55–76 (2001)
8. Baptista, P., Cunha, T.R., Gama, C., Bernardes, C.: A new and practical method to obtain grain size measurements in sandy shores based on digital image acquisition and processing. Sed. Geol. **282**, 294–306 (2012)

The Dynamic Model of Willow Biomass Production

Artur Wójcik, Krzysztof Krupa, Bogusława Łapczyńska-Kondon, Sławomir Francik and Dariusz Kwaśniewski

Abstract The paper presents methods and tools for building computer simulation models for supporting decision-making activities. The cultivation of energy crops for biomass production is a continuous process in which delays are very important along with other factors the values of which may denote a function of many parameters. The harvest of energy plants is a discrete process, so the simulation must combine both of these processes. The paper presents the method of constructing a model for growing energy crops and interprets conclusions resulting from the operation of the model, for changing values of the decision parameters.

Keywords Willow · Biomass production · Computer simulation model

A. Wójcik (✉) · B. Łapczyńska-Kondon
Faculty of Production and Power Engineering, Department of Mechanical Engineering and Agrophysics, University of Agriculture in Cracow University, Balicka 120, 30-149 Cracow, Poland
e-mail: artur.wojcik@urk.edu.pl

B. Łapczyńska-Kondon
e-mail: boguslawa.lapczynska-kordon@urk.edu.pl

K. Krupa
Faculty of Mechanical Engineering, Institute of Production Engineering, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Kraków, Poland
e-mail: 100krup@gmail.com

S. Francik
Faculty of Production and Power Engineering, Department of Mechanical Engineering and Agrophysics, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Kraków, Poland
e-mail: slawomir.francik@urk.edu.pl

D. Kwaśniewski
Faculty of Production and Power Engineering, Institute of Agricultural Engineering and Informatics, University of Agriculture in Krakow, Krakow Ul. Balicka 116B, 30-149 Kraków, Poland
e-mail: Dariusz.Kwasniewski@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_62

1 Introduction

Energy from renewable sources is one of the priorities of the European Union. According to the Directive of the European Parliament on the promotion of energy from renewable sources (2009/28/EC OJEU 5.6.2009), in 2020 20% of energy should come from renewable sources (10% in the transport sector). Achieving such participation is associated with the intensification of the implementation of the various methods of producing such energy. According to Central Statistical Office data, in Poland, in 2014, most of the energy was derived from solid biomass (76.62%); the remaining contributors to the renewable energy were liquid biofuels (9.23%), hydropower (2.33%), biogas (2.57%), wind power (8.18%), heat pumps (0.15%), geothermal energy sources (0 25%), municipal waste (0.46%), and solar radiation (0.21%) [1].

It is clear that the share of biomass is dominant as compared to other renewable energy sources. It is possible to use various instruments (e.g. subsidies, adequate credits, etc.) to change the percentage distribution of the renewable energy mix, but biomass will account for an essential part of the total due to its availability and lower investment costs [2, 3].

Biomass is defined as the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste [4]. It is used for energy purposes as a source of energy released to exhaust gases in the form of heat. As a result, the chemical energy of biomass is converted into the internal energy of combustion products, including exhaust gases, and subsequently kinetic energy of the exhaust gases may be transformed into electrical energy through energy transfer taking the form of work performed by exhaust gases. The conversion of chemical energy accumulated in the biomass into other forms of energy takes place through thermal conversion processes (pyrolysis, gasification) and combustion or co-combustion with coal [5, 6]. In order to obtain permanent sources of biomass, energy crops are purposefully grown (e.g. grasses, especially willow), for more efficient production of biomass [7, 8]. The profitability of these crops depends on many factors, such as climatic conditions, soil environment, species, variety, as well as financial support for growers [9, 10].

The question arises whether it is profitable to cultivate energy crops. With no special financial instruments based on market mechanisms, is it possible to profit economically from such crops? What impact will natural factors such as temperature, sunlight, rain, etc. have on crops? More similar questions may be posed, but in order to enable variant analysis of the answers a proper computer model should be build with the view of investigating how the system would respond to a change of input parameter values.

2 System Model

The system model of willow biomass production for a specific area describes the demand for biomass against its economic aspects such as costs and profits. The model is based on the balance between the mass harvested, mass required and the costs in order to secure economic efficiency. The decision-making variables in the model are as follows: the size of a crop area; the density of seedlings; and the harvesting season. The main criteria in the decision-making model are plantation efficiency and profits. Table 1 shows the structure of the operating model of the analyzed system.

The model system of energetic willow plantation can be considered in two categories: agricultural and economic. The agricultural part seems to be relatively simple, because it is characterized by periodicity, and it might seem that the system will quickly reach a steady state. But it does not necessarily have to. When unexpected natural factors occur such as a drought period, a yield can be significantly impacted. Even more factors affecting the model can coincide, and their simultaneous occurrence may produce unpredictable results [11, 12]. Figure 1 shows a part of the energy willow plantation model, just in terms of agriculture.

The initial parameters were as follows:

- the size of the area—10 ha
- the density of seedlings—20,000 units/ha
- the period set—1 year
- average yield of dry matter—13 t/ha

Table 1 The structure of the operating model

Variable information	Equation	Unit
FINAL TIME	300	month
Harvest time	4	month
The average number of plants per ha	20,000	unit/ha
Balance	$\int_{t_0}^{t}(\text{Subsides} + \text{Income} - \text{Costs})\text{dt}$	PLN
Costs	Plantation establishment costs + Taxes * Area + Costs of harvesting + Costs of crop * Area	PLN/ month
Finance	Balance—the cost of preparing the plantation * Area	PLN
Harvest	IF THEN ELSE (Plants during the growing season > 0:AND : Seasonality of harvest > 0, Labor productivity, 0)	unit/ month
Mass harvested	$\int_{t_0}^{t}(\text{Harvest} \cdot \text{Plant productivity} - \text{Sale})\text{dt}$	Kg
Mass required	$\int_{t_o}^{t}\text{Pace of deficiencies}\,\text{d}t$	Kg
Plantation establishment costs	Planting * Cost of seedlings + IF THEN ELSE(Planting > 0, ZIDZ (Cost of planting * Area, Time), 0)	PLN/ month
Plants during the growing season	$\int_{t_0}^{t}(\text{Propagation} + \text{Planting} - \text{Harvest})dt$	unit

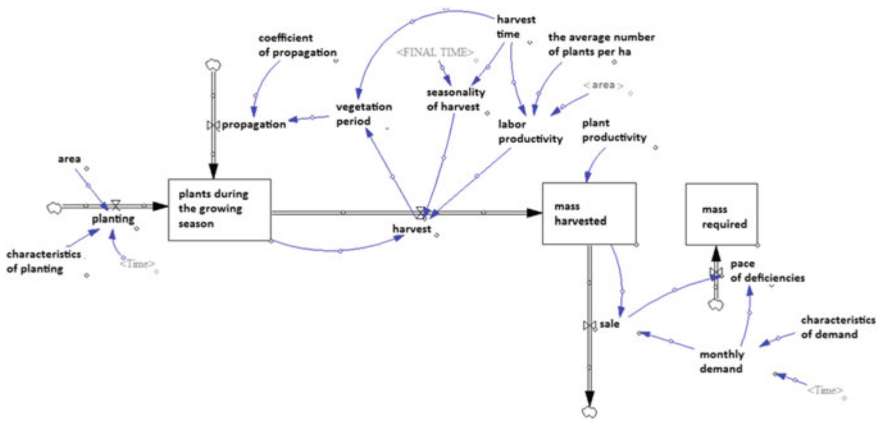


Fig. 1 Model of energetic willow plantations—agricultural aspect

In this model self-regulation mechanism is used, with the parameter "Productivity" adjusted in such a way that the crop was harvested in its entirety. Already at this stage, the model becomes useful, because it allows you to calculate the demand for labor resources. Two input streams were defined: planting and propagation. The former one will have a significant impact on the cost of plantation establishment, while the latter is a part of feedback loop involving the coefficient of proportionality. The coefficient of propagation can act as a factor strengthening or weakening the plantations in the next year. Figure 2 shows the process of growing and harvesting willow. The process is periodic, with a period consisting of 12 months. The graph also shows a line indicating the planting process.

It can be assumed that a plantation that is to be set up has to cover a certain area. What provides a direct stimulus in such a system, however, is the demand for a finished product. It would be perfect if the demand could exceed the supply. Then, the whole output would be consumed and increased production could be considered. In the case of willow, however, there exists a safety buffer, because the crop

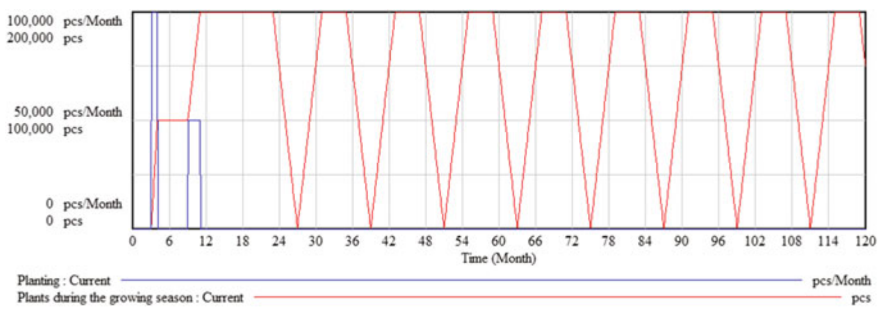


Fig. 2 Planting and plant vegetation

can be harvested in a one-, two-, or three-year system. This means that the cost of storage would not be incurred. Posing a problem in such a way, especially when each part of the plantation would be grown using a different method, would cause additional difficulty. But of course, it is possible to simulate it. Figure 3 shows the system response to a stimulus understood as assumed sales resulting from demand.

It is seen that for the sales parameters, as shown above, each year there is surplus harvested biomass. This means that the crop area should be reduced or increase in demand should be ensured by applying various instruments. Already at this stage of the model construction, feedback mechanisms can be taken into account, which give rise to a self-regulation system. In this particular case, it may happen by changing the coefficient of propagation (although the validity is questionable), by changing the area of plantations, or by changing the density of plants (Fig. 4).

Figure 4 presents a proposal for feedback loop that can automatically adjust the system. The adjustment can be additionally dependent on economic aspects.

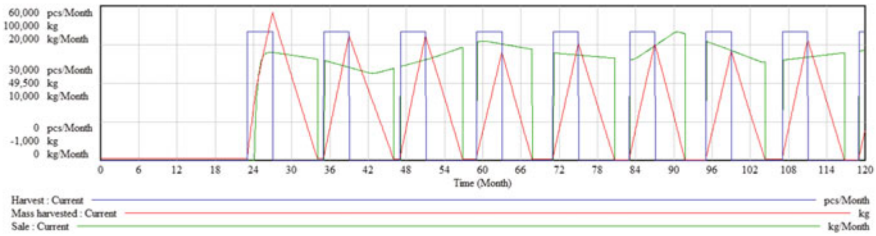


Fig. 3 Sales in the context of harvest time and sourced mass

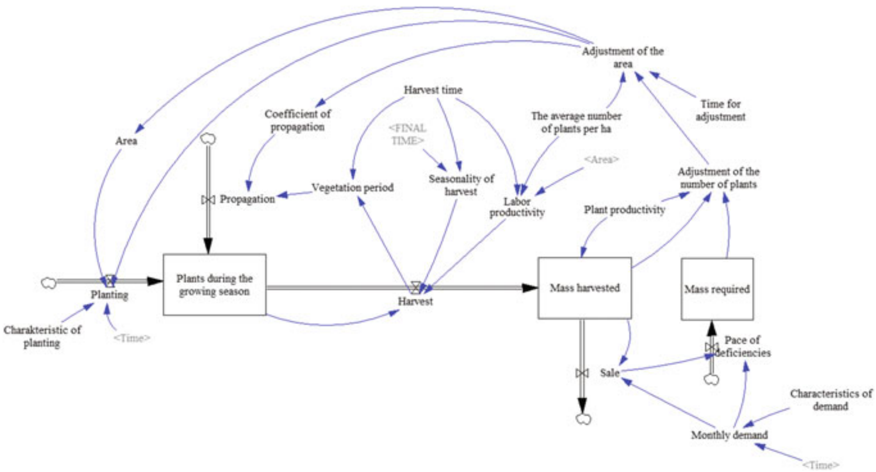


Fig. 4 Sales in the context of harvest time and sourced mass

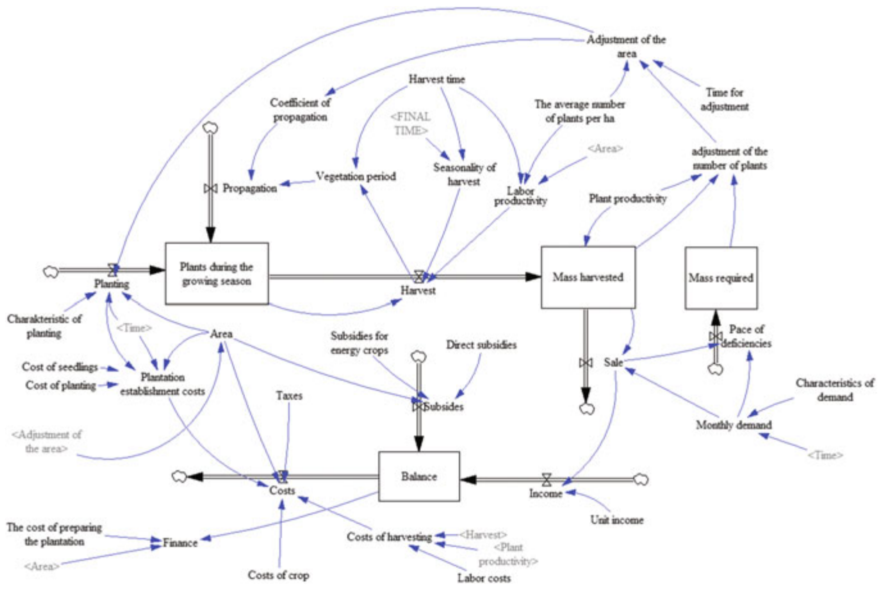


Fig. 5 System model developed by the economic aspect

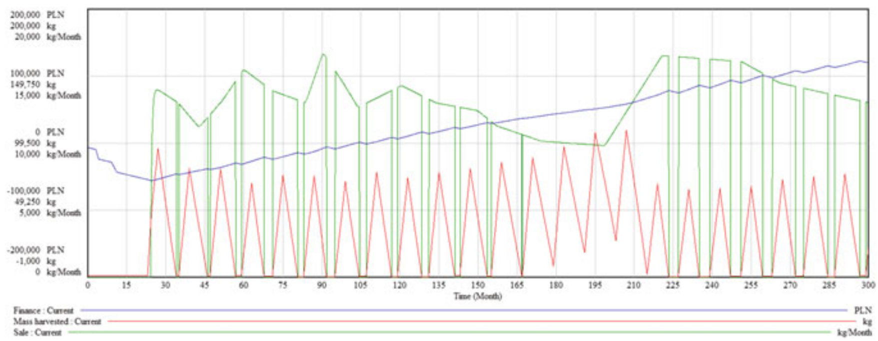


Fig. 6 The system response to the established value of sales

Figure 5 presents the extended model which takes into account the costs and revenues of the considered plantation.

In the presented model, input parameters based on data from D. Kwasniewski's study [10, 13] were adopted. Each of these parameters can in a continuous or discrete way change its value, thereby resulting in the ability to simulate the system and based on its results, making strategic decisions. Sample simulation results are shown in Fig. 6.

The chosen initial parameters were as follows:

- Cost of seedlings—0.12 PLN/pcs
- Cost of planting—490.00 PLN/ha
- Taxes—85/12 PLN/(ha * Month)
- Subsidies for energy crops—120/12 PLN/(ha * Month)
- Direct subsidies—301/12 PLN/(ha * Month)
- Labor costs—68/13000 PLN/kg
- Unit income—150/1000 PLN/kg

For the adopted model (Fig. 5) showing the relationships between different variables, the system response was elicited. Figure 6 displays relationships for three selected variables over the period considered. The simulation calculations were performed, assuming that the plantation would be harvested up to 25 years (300 months) at the assumed sales values. The graph shows the change in the possible volume of mass harvested, mass sales, and sales profits (finances). Willow harvesting and the corresponding sales over the time periods are recorded. Interestingly, it can be seen that after approximately 105 months, the cumulative revenue is higher than the invested funds and current costs. So, for the assumed parameters of the system a return on investment can be earned.

3 Summary

This paper presents the preliminary draft of the problem addressing building of a simulation model for energy willow plantation. Some light was shed on the relationship between the parameters, with particular attention paid to feedback loops which make one of the main causes of system dynamics. It also presents an extended version of the model, taking into account the economic aspect. The model itself is a good base for analysis of the effects of decisions that have been made. It also gives an opportunity to observe the system in response to various types of interference. These may contribute to improving risk optimization when running such plantations; i.e., making such decisions which—to the greatest possible extent—will help make the system resistant to market factors (e.g., demand) as well as unpredictable natural disasters (e.g., drought).

Acknowledgements This Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. GUS 2015—http://www.paiz.gov.pl/prawo/odnawialne_zrodla_energii
2. Gospodarki, M.: Polityka energetyczna Polski do 2030 roku. Załącznik do uchwały nr 202/2009 Rady Ministrów z dnia 10 listopada 2009 r (2009)
3. Turkenburg, W. C., Beurskens, J., Faaij, A., Fraenkel, P., Fridleifsson, I., Lysen, E., Sinke, W. C.: Renewable energy technologies. In: World Energy Assessment: Energy and the Challenge of Sustainability, pp. 219–272, (2000)
4. Dyrektywa 2001/77/WE Parlamentu Europejskiego i Rady z dnia 2001-09-27;w sprawie wspierania produkcji na rynku wewnętrznym energii elektrycznej wytwarzanej ze źródeł odnawialnych
5. Mc Kendry, P.: Energy production from biomass (part 1): overview of biomass. Biores. Technol. **83**(1), 37–46 (2002)
6. Dzikuć, M., Piwowar, A.: Ecological and economic aspects of electric energy production using the biomass co-firing method. The case of Poland. Renew. Sustain. Energy Rev. **55**, 856–862 (2016)
7. Dubas, J. W., Tomczyk, A.: Zakładanie, pielęgnacja i ochrona plantacji wierzb energetycznych. Wydawnictwo SGGW Warszawa. ISBN 83-7244-617-2 (2005)
8. Oliveira, Sixto H., Canellas, I., Rodriguez-Soalleiro, R., Perez-Cruzado, C.: Productivity model and reference diagram for short rotation biomass crops of poplar grown in Mediterranean environments. Biomass Bioenergy **72**, 309–320 (2015)
9. Ericsson, K., Rosenqvist, H., Nilsson, L.J.: Energy crop production costs in the EU. Biomass Bioenergy **33**(11), 1577–1586 (2009)
10. Kwaśniewski, D.: Koszty i opłacalność produkcji biomasy z trzyletniej wierzby energetycznej. Inżynieria Rolnicza **1**(126), 145–154 (2011) (Kraków)
11. Krupa, K.: Modelowanie, symulacja i prognozowanie. Systemy ciągłe, WNT, Warszawa (2008)
12. Frączek, J.: i inni: Produkcja biomasy na cele energetyczne. Polskie Towarzystwo Inżynierii Rolniczej, Kraków (2010)
13. www.vensim.com

Possibility to Utilize Fish Processing By-Products in the Context of Management of Non-renewable Resources

Marcin Niemiec, Krzysztof Mudryk, Jakub Sikora, Anna Szeląg-Sikora and Monika Komorowska

Abstract Fish processing generates considerable amounts of waste which constitutes a potential threat to the environment. The aim of this paper was to assess the possibility to use processing waste for anaerobic digestion and to use the generated digestate for fertilization purposes. This research involved evaluation of chemical composition of waste from a carp processing plant and of the digestate after methane fermentation. The content of dry matter, organic carbon, nitrogen, and other macroelements was determined in the samples. Moreover, the content of trace elements was determined. Dry matter content in the studied waste was 40%. Nitrogen content was approximately 5.56%, phosphorus—1.758%, calcium—0.4%, whereas mean potassium content was 0.502 g kg^{-1}. As a result of conducting methane fermentation, a reduction in nitrogen content by about 50% and a considerable increase in quantity of almost all elements were observed. A high zinc content was recorded in the digestate, whereas concentration of other microelements was at a level close to the one in natural fertilizers. Concentrations of heavy metals did not exceed permissible values for organic fertilizers. The studied material can be a component for fertilizer production, and its fertilizing value depends mostly on nitrogen and phosphorus content.

Keywords Fish processing waste · Anaerobic digestion · Digestate Organic fertilizers

M. Niemiec (✉)
Department of Agricultural and Environmental Chemistry, Faculty of Agriculture and Economics, University of Agriculture in Krakow, Al. Mickiewicza 21, 31-120 Krakow, Poland
e-mail: marcin1niemiec@gmail.com

K. Mudryk · J. Sikora · A. Szeląg-Sikora
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 b, 30-149 Krakow, Poland

M. Komorowska
Department of Vegetable and Medicinal Plants, Faculty of Biotechnology and Horticulture, University of Agriculture in Krakow, Al. 29 Listopada 54, 31-425 Krakow, Poland

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_63

1 Introduction

Industrial waste management is strategic for rational economy of the present-day world. The purpose of actions to limit generation of excessive amounts of waste is to search for technologies that use it as a substrate in a new process. Such solutions are usually used in chemical industry, where generated waste is characterized by repeatability of chemical composition and physical nature [1]. Agri-food industry waste, which is problematic when it comes to managing it, is a special type of industrial waste. The problem is its high moisture content and low microbiological stability as well as varied chemical and physical properties which are determined by the type of processing. The common feature of agri-food processing waste is a high content of organic matter and macro- and microelements, which creates a potential for using it for energy purposes or as fertilizers or agents improving soil properties [2–4]. Despite the high content of plant nutrients, the use of organic waste from agri-food industry is very low and the fundamental method of its management is to treat it at a sewage-treatment plant. In highly developed countries, conversion of organic waste to obtain energy is gaining on importance. It is a part of the policy of limiting the emission of greenhouse gases and diversifying energy resources [5–7]. The most commonly used method of harvesting energy from biomass is its anaerobic conversion through methane fermentation [8, 9]. Current biogas plants are based on mixtures of manure and plants cultivated specially for that purpose, mainly maize in the form of silage. More and more attention is paid to the possibility of using vegetable waste from agri-food processing and organic fraction of municipal sewage in biogas plants. They are an inexpensive and valuable feedstock in the process of anaerobic digestion. Due to a dominant share of the vegetable fraction in it, there is no need to modify the process [10]. Management of fish processing waste is a difficult challenge for the technology of waste treatment. Fish processing involves generation of considerable amounts of waste such as heads, skins, fins, bones and entrails. Amounts of generated waste, depending on fish species and on the type of final product, can reach from 30 to even 60% of raw material mass. Fish processing waste is a potentially valuable material for the production of protein, amino acids, oil, collagen and gelatine [11, 12]. A problem associated with obtaining these products from fish waste is to maintain proper hygienic conditions at each stage of processing as well as the necessity to store waste under microbiologically stable conditions. Currently, the number of processing plants that are based on fish processing waste in Poland is insufficient, and conventional methods of managing this type of waste are energy-consuming, which significantly raises production costs. Therefore, fish processing plants, particularly the low production ones, are looking for methods of waste management that would allow to manage it without incurring additional costs. Management of waste in the place of its origin would reduce the costs connected with transport, which constitutes an important part of the costs of this process. Subjecting fish processing waste to methane fermentation appears to be an effective method of its management. Methanogenesis produces a gas that may be used as an energy source in a farm.

Harvesting energy from waste is a strategic part of sustainable waste management. Owing to its ecological and social role, production of aquaculture animals should be carried out using processes that minimize its negative effect on the environment. One of the more important acts which constitute the basis for development of an organic waste treatment technology is the Directive on waste disposal (1999/31/EC) which requires reduction of biodegradable waste going to landfills, as well as the Framework Directive on waste [13]. Despite the lower energy potential and technological difficulties, using agri-food processing waste for methane fermentation is important in terms of its management and reducing the emission of greenhouse gases. Digestate is the by-product of methane fermentation; it is a post-process waste, but it has a potential to be used for fertilization or as a component that improves soil properties. Along with the applied digestate, considerable amounts of plant nutrients as well as organic matter (whose amount is gradually reduced in soils) are supplied to soil. Usability of digestates from biogas plants that use plant substrates for fertilization purposes has been pointed out by numerous authors [14–17]. There is little information in scientific literature on the possibility of using the digestate generated after fermentation of animal waste for fertilization purposes. From the point of view of chemical composition of fish processing waste, special attention should be paid to phosphorus as its global resources will have been exhausted by the end of the 21st century. The possibility of using the digestate generated after methane fermentation for fertilization may be an important link in the cycling of elements in agroecosystems, within the scope of implementing rational methods of agricultural production. According to Polish legislation, digestate does not meet the organic fertilizer criterion, but it can be used on farmers' own fields as an agent to improve soil properties. Fish farms which produce calm-prey fish often have agricultural lands on which cereals intended for fish feeding are produced. Digestate that is used for crops fertilization may be an additional source of nutrients, thanks to which fertilization level could be reduced.

The aim of this paper was to assess the chemical composition of carp processing waste as well as the chemical composition of the digestate from methane fermentation of this waste. Suitability of this waste as means to improve soil properties was assumed as the assessment criterion.

2 Materials and Methods

For the achievement of the objective pursued, carp processing waste was subjected to analysis. The waste was composed of heads, entrails, gills, fins and skins. The material was obtained from a fish farm Zarząd Dóbr Smolin, located in Lubaczów in the Podkarpackie province, in which construction of a fish processing plant is being planned within the framework of diversification of income from aquaculture production. The technological process is based on fish stunning, decapitation, gutting, cutting out gill arches and fins, and skinning. In June 2016, a laboratory sample was collected from a batch of mixed waste (approximately 200 kg) for chemical analyses. The bulk sample (20 kg) consisted of 20 increments. The bulk sample was subjected to homogenization. From the material prepared this way, a laboratory sample of approximately 500 g was isolated. The remaining part was sent to a laboratory where it was subjected to methane fermentation. After methane fermentation, an approximately 5000 g sample of digestate was collected. The digestate was mechanically dehydrated. The solid fraction of the digestate as well as untreated waste were dried at 65 °C, then sent to the laboratory.

The laboratory samples were homogenized and subjected to wet mineralization in a closed system. The samples were mineralized using microwave energy, using ANTON PAAR Microwave 3000. Mineralization was carried out using a mixture of nitric acid and hydrogen peroxide in a quantitative ratio of 3:1 v/v. The analytical sample was approximately 0.5 g dry matter. Concentration of the studied elements in the obtained solutions was determined by atomic emission spectrometry, on an Optima 7600 spectrometer manufactured by PerkinElmer. Wavelengths that were used to determine the concentration of the studied elements as well as the detection limit for the methods are provided in Table 1. Nitrogen and carbon content was determined by elemental analysis method, using Elementar vario MAX cube. The correctness of analyses of the studied elements was verified using a certified reference material (IAEA-407). Table 1 shows results of analyses of the reference material and an estimated value of recovery based on analyses conducted in 4 replications.

Table 1 Paremeters of analysis method

Parameters	Wavelengths [nm]	Limit detection [mg dm^{-3}]	Content in certificated material [mg kg^{-1}]	Measured [mg kg^{-1}]	Recovery [%]
Mg	285.208	0.0016	2.72	2.904	104
P	213.617	0.076	–	–	–
Ca	317.933	0.01	27	28.33	104
Na	589.592	0.069	13.1	12.88	98.3
K	766.490	–	13.1	12.91	89.6
Cd	228.802	0.0027	0.189	0.179	94.7
Cr	267.707	0.0071	0.73	0.71	97.3
Cu	327.393	0.0097	3.28	3.38	103.0
Fe	238.204	0.0046	146	154	105.5
Mn	257.608	0.0014	3.54	3.37	95.2
Ni	231.604	0.015	0.6	0.567	94.5
Pb	220.353	0.042	0.12	0.126	105.0
Zn	206.200	0.0059	67.1	68.68	102.4
Ba	233.527	0.004	2.46	2.386	97.0
B	249.677	0.0057	55.67	53.86	96.7
Sr	407.777	0.0004	130	135.7	104.4
Co	238.616	0.007	0.1	0.104	103.6
Al	308.215	0.0045	13.8	14.62	105.9

3 Result and Discussion

According to Polish legislation, biomass after methane fermentation is regarded as waste. Regulation of the Minister of Environment on waste catalogue [18] specifies that the waste is coded as 19 06 06—digestate from anaerobic treatment of animal and vegetable waste. According to the Regulation of the Minister of Environment [19], recovery of the digestate using the R10 method is possible by distributing it over land in order to assist cultivation. If the digestate meets the qualitative requirements for organic fertilizers or plant growing enhancers, it may be regarded as such. Criteria for organic fertilizers and for plant growing enhancers have been set forth in the Regulation the Minister of Agriculture and Rural Development of 18 June 2008 on implementation of certain provisions of the act on fertilizers and fertilization (Table 2). In organic fertilizers, permissible concentrations of pollutants as well as the minimum concentrations of fertilizer components are reduced, whereas in plant growing enhancers only pollutant concentrations are reduced. These criteria apply to all organic fertilizers, composts or fermentats after aerobic stabilization, and also to stabilized composts intended to be distributed over land to fertilize or improve the soil.

The purpose of methane fermentation is to convert organic carbon into methane. The process of methanogenesis is also accompanied by transformations which lead to formation of gases such as ammonia and hydrogen sulfide. In order for the process of methanogenesis to run efficiently and effectively, the material subjected to fermentation must have adequate properties, the most important of which is the ratio of carbon to nitrogen (which should be 40:1). The value of this parameter in the material subjected to fermentation in this experiment was at a level of 10.9. Nitrogen content in untreated fish processing waste amounted to 5.08% in dry matter, whereas the amount of his element in the digestate was at a level of 2.17% DM (Table 3). A reduction in nitrogen content as a result of methane fermentation of pig slurry was also observed by Vaneeckhautea et al. [20]. Similarly to our research, these authors observed nitrogen loss at a level of about 50%. A part of nitrogen, both in organic form and in mineral form, remained in the liquid fraction

Table 2 Quality requirements for organic fertilizers and plant conditioners (Reg. 2008)

Parameter	Organic fertilizers	Plant conditioners
	mg kg^{-1} d.m.	
Ni	≤ 60	≤ 60
Cr	≤ 100	≤ 100
Pb	≤ 140	≤ 140
Cd	≤ 5	≤ 5
	g kg^{-1} f.m.	
K	≥ 1.78*	–
P	≥ 0.684*	–
N	≥ 3*	–

*Concerns if declared their content in organic fertilizer formed after dewatering the digestate. Nitrogen concentrations determined in the studied digestate are high and comparable to the ones found in natural fertilizers (Table 3). The content of this element in the digestate was 0.25% fresh matter, and this amount is slightly lower than generally observed in slurry [21]. However, application of the said waste to soil should be always preceded by application of the fertilization plan, so as not to exceed the allowable amount of this element that can be introduced to soil, which amounts to 170 kg N ha^{-1} $year^{-1}$ [22]. Nitrogen content in digestates is a subject of numerous studies as it is this element that builds the fertilization potential of this waste. Bustamante et al. [23] give concentrations of nitrogen in waste after methane fermentation of grape pomace at a level of 2.3%, whereas in the case of grape shoots—0.55% in terms of dry matter. Nitrogen content in digestates is a derivative of the type of material subjected to fermentation and of the effectiveness of the process itself.

From the point of view of nitrogen fertilization and restricting dissipation of this element in the environment. The use of this digestate would be substantiated. Nitrogen present in fermented organic matter is more easily available for plants compared with organic fertilizers, whereas losses of this element are significantly lower than in the case of using mineral fertilizers [30]. In addition, soil application

Table 3 Elements content in the digestate untreated waste

Element	Unit	Untreated waste	Digestate	Manure data from literature*
Sodium	g kg^{-1}	0.320	0.155	1–4
Magnesium		0.102	0.155	4–12
Potassium		0.502	0.236	12–20
Calcium		4.015	7.831	10–30
Phosphorus		17.58	48.37	6–15
Nitrogen	%	5.56	2.17	2–3
Organic carbon		60.21	58.3	–
Dry matter		60	11.63	–
Chromium	mg kg^{-1}	4.358	8.524	2–8
Manganese		17.09	57.07	20–180
Iron		118.5	442.5	400–2000
Nickel		0.558	1.916	2.8–9.2
Copper		2.398	2.966	15–185
Zinc		150.4	383.3	54–194
Cadmium		0.533	1.168	0.09–0.52
Lead		3.425	7.505	11.1–35
Strontium		61.56	137.81	14–115
Barium		0.075	0.125	4.4–25.2
Cobalt		0.75	0.844	0.3–0.89
Lithium		0.275	0.436	3.3–28

*Data from literature [24–29]

of materials subjected to fermentation has a positive effect on soil microflora [31]. Carbon content in the studied material was approximately 60% and no changes in the content of this element as a result of fermentation were detected (Table 3). Carbon content in the digestate was slightly lower compared with untreated waste. The perspective of using digestate from methane fermentation of fish waste is extremely advantageous from the point of view of improving phosphorus management. Phosphorus is a strategic element whose global reserves are quickly depleting; it is also the most important element that intensifies eutrophication of waters. Therefore, it is important to support all actions to limit dissipation of this element in the environment. Due to the nature of the material subjected to fermentation, phosphorus content in it was very high. The amount of this element in untreated waste was 17.58 g kg^{-1}. After fermentation, the content of this element increased almost three-fold and was 48.37 g kg^{-1}. The determined phosphorus content is several times higher than what can be found in natural fertilizers. Therefore, the studied material can be regarded as a potential source of this element. Garfí et al. [32] observed a reverse relationship—a reduced amount of phosphorus in manure as a result of methane fermentation.

The studied material had a low potassium content, and as a result of methane fermentation of fish processing waste there was a considerable reduction of the content of this element in the solid fraction of the digestate (Table 3). The content of this element in untreated waste was 0.502 g kg^{-1} DM, whereas the amount of this element in the digestate was 0.236 g kg^{-1} DM. Owing to good solubility of potassium compounds, a part of this element remained in the liquid fraction of the digestate. From the point of view of potassium and nitrogen use, a better alternative would be to use a digestate that has not been dewatered. However, it would be problematic due to substantial costs associated with the long-distance transport of this product, the problem with its application, odors and lack of microbiological stability. Potassium content in the studied material was many times lower than generally observed in natural fertilizers (Table 3). Results of the conducted research indicate that in the case of most elements their content in digestate is significantly higher than in untreated waste. Calcium content increased almost two-fold, from 4.015 g Ca kg^{-1} DM in untreated waste to 7.831 g Ca kg^{-1} DM in the digestate. Calcium content determined in the studied digestate was slightly lower than in natural fertilizers. Magnesium and sodium content in the studied materials was much lower than generally observed in natural fertilizers or in different types of waste after fermentation of plant origin materials [14, 23]. No great differences in the content of these elements were detected in the untreated waste or digestate (Table 3). In the case of methane fermentation of food industry waste there may be a problem of inadequate physical structure of the raw material or its chemical composition. The waste that was the subject of this research had a high content of nitrogen, phosphorus and sodium. From the point of view of the methanogenesis process this may be problematic due to the high sodium content. Sodium content in the material subjected to fermentation, in the amount of 0.05 g kg^{-1} may reduce the effectiveness of this process [14, 33]. Evaluation of the suitability of substances for use as fertilizers or as agents improving soil properties should also cover the content of microelements and heavy metals. Currently, an increasing problem in agricultural production are deficiencies of microelements, particularly zinc, copper, manganese and iron. Organic and natural fertilizers are believed to be a valuable source of micronutrients which are readily available for plants [24, 25]. The use of natural and organic fertilizers in Poland has been gradually decreasing due to the reduction of the number of animals and regionalization of livestock production. This is one of the causes of a decreasing amount of organic matter and microelements in soils. One of the possible problems associated with using methane fermentation waste is the risk posed by heavy metals [34]. Heavy metals are bioaccumulated in plants, and because of that they are incorporated into the human food chain. That is why their permissible amount in organic fertilizers is legally regulated (Table 2). The studied samples were found to have a very high zinc content. Concentration of this element in the untreated waste was 150.4 mg Zn kg^{-1} DM, whereas the amount of this element in the digestate was at a level of 383.3 mg Zn kg^{-1} DM. Zinc concentrations determined in the studied digestate were comparable to the amount of this element in digestates from gardening waste and from energy crops [35, 36]. Concentrations of barium and lithium determined in the studied digestate were several times lower than average concentrations of these elements in natural fertilizers. whereas the amounts of cobalt and strontium were comparable with natural fertilizers from different parts of the world (Table 3). In no case did we observe that the permissible heavy metals content in organic fertilizers was exceeded. Concentrations of cadmium, lead, chromium and nickel were in each case several times lower than generally found in natural fertilizers of various origin (Table 3). Using the studied waste for improvement of soil properties will not bring about an increase in its quantity in agroecosystems. The content of macroelements and trace elements in fish processing waste is determined by the quality of raw material. Many authors draw attention to substantial differences in the content of elements in fish depending on species, age, type of food, sex and even to differences between individual specimens of the same population [37–39]. Methane fermentation of animal waste is the good way to manage it. The effects of this process include generation of energy in the form of methane as well as the possibility of microbiological stabilization of waste [40]. Processes of decomposition of organic compounds present in waste increase nutrient absorption by plants and transformations of carbon compounds lead to formation of compounds which more readily undergo humification, thus increasing the amount of soil organic matter. Many authors draw attention to the substantial availability of elements present in digestates. Even if concentrations of fertilizer elements are low, using digestates always brings positive effects due to the complexity of fertilization as well as introduction of a considerable amount of organic matter. Garfí et al. [32] found a statistically significant increase in potato yielding after application of digestate in the amount corresponding to 17 kg of nitrogen. The evaluation of the chemical composition of the studied digestate showed that it can be a useful material used for fertilization or as an agent improving soil properties, owing to the presence of nitrogen and phosphorus in it. At a dose of 1 Mg dry matter of the studied digestate, more than 25 kg N and more than 110 P_2O_5 will be introduced to soil. However, digestates can be a source of microbiological contamination, that is why their use should depend on the results of analyzing their quality. Walker et al. [41] also draw attention to the problems with odors during application of this type of material. Moreover, they usually contain a large amount of fatty acids which can have a phytotoxic effect. The physical nature of these materials may cause problems associated with fertilizer application.

4 Conclusions

4.1 The studied digestate was found to have high concentrations of nitrogen and phosphorus. These are the main elements which decide on the fertilizing value of the studied material. Nitrogen content was approximately 2.5% N, whereas phosphorus content—10.8% P_2O_5.

4.2 The content of potassium and magnesium was much lower than it is specified in scientific literature for different natural fertilizers.

4.3 As a result of methane fermentation of the studied fish processing waste a reduction in nitrogen and potassium content was observed. In the case of most of the elements, considerably higher concentrations were observed in the digestate than in the untreated waste.

4.4 The permissible heavy metals content in natural fertilizers was not exceeded in the obtained material.

4.5 From the point of view of chemical composition. The studied digestate from methane fermentation of fish processing waste can be a valuable source of plant nutrients and its use in agriculture can be a part of rational management of non-renewable environmental resources.

References

1. Pivnenko, K., Eriksen, M.K., Martín-Fernández, J.A., Eriksson, E., Astrup, T.F.: Recycling of plastic waste: presence of phthalates in plastics from households and industry. Waste Manage. **54**, 44–52 (2016)
2. Frąc, M., Ziemiński, K.: Methane fermentation process for utilization of organic waste. Int. Agrophys. **26**(3), 317–330 (2012)
3. Sikora, J., Szeląg-Sikora, A., Cupiał, M., Niemiec, M., Klimas, A.: Biogas production potential for energy purposes in ecological farms. (Pl) Proc. ECOpole **8**(1), 279–287 (2014)
4. Tampio, E., Marttinen, S., Rintala, J.: Liquid fertilizer products from anaerobic digestion of food waste: mass, nutrient and energy balance of four digestate liquid treatment systems. J. Clean. Prod. **125**, 22–32 (2016)
5. Velis, C.A., Longhurst, P.J., Drew, G.H., Smith, R., Pollard, S.J.T.: Biodrying for mechanical–biological treatment of wastes: a review of process science and engineering. Bioresour. Technol. **100**, 2747–2761 (2009)

6. Bustamante, M.A., Alburquerque, J.A., Restrepo, A.P., de la Fuente, C., Paredes, C., Moral, R., Bernal, M.P.: Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. Biomass Bioenerg. **43**, 26–35 (2012)
7. Lalak, J., Kasprzycka, A., Paprota, E., Tys, J., Murat, A.: Development of optimum substrate compositions in the methane fermentation process. Int. Agrophys. **29**(3), 313–321 (2015)
8. Arthur, R., Baidoo, M.F., Antwi, E.: Biogas as a potential renewable energy source: a Ghanaian case study. Renew. Energy **36**, 1510–1516 (2011)
9. De Souza, S.N.M., Wernacke, I., Marques, C.A., Bariccatti, R.A., Santos, R.F.S., Nogueira, C.E.C., Bassegio, D.: Electric energy micro-production in a rural property using biogas as primary source. Renew. Sustain. Energy Rev. **28**, 385–391 (2013)
10. Karellas, S., Boukis, I., Kontopoulos, G.: Development of an investment decision tool for biogas production from agricultural waste. Renew. Sustain. Energy Rev. **14**(4), 1273–1282 (2010)
11. Bhagwat, P.K., Dandge, P.B.: Isolation, characterization and valorizable applications of fish scale collagen in food and agriculture industries. Biocatal. Agric. Biotechnol. **7**, 234–240 (2016)
12. Ghaly, A.E., Ramakrishnan, V.V., Brooks, M.S., Budge, S.M., Dave, D.: Fish processing wastes as a potential source of proteins, amino acids and oils: a critical review. J. Microb. Biochem. Technol. **5**(4), 107–129 (2013)
13. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)
14. Alkanok, G., Demirel, B., Onay, T.T.: Determination of biogas generation potential as a renewable energy source from supermarket wastes. Waste Manage. **34**(1), 134–140 (2014)
15. Kasprzycka, A., Lalak, J., Tys, J.: Impact of fragmentation on biogas production from plant biomass. Acta Agrophys. **22**(2), 139–149 (2015)
16. Koszel, M., Lorencowicz, E.: Agricultural use of biogas digestate as a replacement fertilizers. Agric. Agric. Sci. Proc. **7**, 119–124 (2015)
17. Tampio, E., Ervasti, S., Rintal, J.: Characteristics and agronomic usability of digestates from laboratory digesters treating food waste and autoclaved food waste. J. Clean. Prod. **94**, 86–92 (2015)
18. Regulation of the Minister of the environment of 9 December 2014 on waste catalogue (Journal of Laws from 2014 item 1923)
19. Regulation of the Minister of Environment on R10 recovery operation of April 5 2011 (Journal of Laws from 2011 item 476)
20. Vaneeckhaute, C., Meers, E., Michels, E, Buysse, EJ., Tack, F.M.G.: Ecological and economic benefits of the application of bio-based mineral fertilizers in modern agriculture. Biomass Bioenerg. **49**, 239–248 (2013)
21. Fangueiro, D., Surgy, S., Fraga, I., Monteiro, F.G., Cabral, F., Coutinho, J.: Acidification of animal slurry affects the nitrogen dynamics after soil application. Geoderma **281**, 30–38 (2016)
22. Act of 10 July 2007 on Fertilizer and Fertilizing item 1033
23. Bustamante, M.A., Restrepo, A.P., Alburquerque, J.A., Pérez-Murcia, M.D., Paredes, C., Moral, R., Bernal, M.P.: Recycling of anaerobic digestates by composting: effect of the bulking agent used. J. Clean. Prod. **47**, 61–69 (2013)
24. Akbarian, M.M., Sharif Abad, H.H., Modafebehzadi, N., Bagheripour, M.A.: The effects of chemical fertilizers and cow manure on quantity and quality saffron characteristics in Dehbakri Bam Region. Ann. Biol. Res. **4**(6), 361–365 (2013)
25. Xiu, S., Shahbazi, A., Shirley, V.B., Wang, L.: Swine manure/Crude glycerol co-liquefaction: physical properties and chemical analysis of bio-oil product. Bioresour. Technol. **102**, 1928–1932 (2011)
26. Huang, G., Han, L., Yang, Z., Wang, X.: Evaluation of the nutrient metal content in Chinese animal manure compost using near infrared spectroscopy (NIRS). Bioresour. Technol. **99**, 8164–8169 (2008)

27. Ko, H.J., Ki, K.Y., Kim, H.T., Kim, C.N., Umeda, M.: Evaluation of maturity parameters and heavy metal contents in composts made from animal manure. Waste Manage. **28**, 813–820 (2008)
28. Nicholson, F.A., Chambers, B.J., Williams, J.R., Unwin, R.J.: Heavy metal contents of livestock feeds and animal manures in England and Wales. Bioresour. Technol. **99**, 8164–8169 (1999)
29. Ihnat, M., Fernandes, L.: Trace elemental characterization of composed poultry manure. Bioresour. Technol. **57**, 143–156 (1996)
30. Weiland, P.: Biomass digestion in agriculture: a successful pathway for the energy production and waste treatment in Germany. Eng. Life Sci. **6**, 302–309 (2006)
31. Sapp, M., Harrison, M., Hany, U., Charlton, A., Thwaites, R.: Comparing the effect of digestate and chemical fertiliser on soil bacteria. Appl. Soil. Ecol. **86**, 1–9 (2015)
32. Garfí, M., Gelman, P., Comas, J., Carrasco, W., Ferrer, I.: Agricultural reuse of the digestate from low-cost tubular digesters in rural Andean communities. Waste Manage. **31**, 2584–2589 (2011)
33. Voelkner, A., Holthusen, D., Ellerbrock, R., Horn, R.: Quantity of hydrophobic functional CH-groups—decisive for soil water repellency caused by digestate amendment. Int. Agrophys. **29**(2), 247–255 (2015)
34. Baker, L.R., White, P.M., Pierzynski, G.M.: Changes in microbial properties after manure, lime, and bentonite application to a heavy metal-contaminated mine waste. Appl. Soil. Ecol. **48**, 1–10 (2011)
35. Govasmark, E., Stäb, J., Holen, B., Hoornstra, D., Nesbakk, T., Salkinoja-Salonen, M.: Chemical and microbiological hazards associated with recycling of anaerobic digested residue intended for agricultural use. Waste Manage. **31**(12), 2577–2583 (2011)
36. Lehtomaki, A., Bjornsson, L.: Two-stage anaerobic digestion of energy crops: methane production, nitrogen mineralisation and heavy metal mobilization. Environ. Technol. **27**, 209–218 (2006)
37. Boalt, E., Miller, A., Dahlgren, H.: Distribution of cadmium, mercury, and lead in different body parts of *Baltic herring* (*Clupea harengus*) and perch (*Perca fluviatilis*): implications for environmental status assessments. Marine Pollut. Bull. **78**(1–2), 130–136 (2014)
38. Dhaneesh, K.V., Gopi, M., Ganeshamurthy, R., Kumar, T.T.A., Balasubramanian, T.: Bio-accumulation of metals on reef associated organisms of Lakshadweep Archipelago. Food Chem. **131**(3), 985–991 (2012)
39. Niemiec, M.: Accumulation of zinc in water, sediments and bleak fish (*Alburnus alburnus* L.) in the ecosystem of the Dunajec River. J. Elementol. **21**(1), 173–184 (2016)
40. Martínez, E.J., Fierro, J., Sánchez, M.E., Gómez, X.: Anaerobic co-digestion of FOG and sewage sludge: study of the process by Fourier transform infrared spectroscopy. Int. Biodeterior. Biodegradation **75**, 1–6 (2012)
41. Walker, L., Charles, W., Cord-Ruwisch, R.: Comparison of static, in-vessel composting of MSW with thermophilic anaerobic digestion and combinations of the two processes. Bioresour. Technol. **100**(16), 3799–3807 (2009)

Influence of Storing *Miscanthus* x *gigantheus* on Its Mechanical and Energetic Properties

Adrian Knapczyk, Sławomir Francik, Artur Wójcik and Grzegorz Bednarz

Abstract The purpose of the study was to analyze the effect of storage of a Giant miscanthus on its mechanical and energy properties. The research material came from an experimental plantation of the Faculty of Production Engineering and Energetics of the University of Agriculture in Cracow. It was compared to plant material stored under cover where it was protected from atmospheric agents such as rain, snow and wind. The studies compared energy properties such as calorific value, moisture content and ash content. The second part of the research was used to determine selected mechanical properties—unit destructive force. Measured calorific value in two groups was: storage = Yes: 16,568 [kJ/kg], storage = No: 15,897 [kJ/kg]. Mean values of Pj (unitary destructive force) for stored and not-stored miscanthus were different. For X1—storage = Yes Pj = 48.27 [N] and for storage = No Pj = 40.73 [N].

Keywords Giant miscanthus · Mechanical strength · Energy properties Calorific value · Biomass

A. Knapczyk · S. Francik (✉) · A. Wójcik
Department of Mechanical Engineering and Agrophysics,
Faculty of Production and Power Engineering, University of Agriculture in Krakow,
Krakow Ul. Balicka 120, 30-149 Kraków, Poland
e-mail: slawomir.francik@urk.edu.pl

A. Knapczyk
e-mail: adrian.knapczyk91@gmail.com

A. Wójcik
e-mail: artur.wojcik@urk.edu.pl

G. Bednarz
Department of Forest Pathology, Mycology and Tree Physiology,
Faculty of Forestry, Institute of Forest Ecosystem Protection,
University of Agriculture in Krakow, Al. 29-Listopada 46, 31-425 Kraków, Poland
e-mail: grzegorz.bednarz@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_64

1 Introduction

Intensive climate change occurring in the recent years can sharply increase bioenergy importance in global energetics. This tendency stimulates growth of bioenergy sector, including organic waste and energy crops. The latter can make up from 20 to 60% of biomass [1].

Giant miscanthus (*Miscanthus* × *giganteus* Greef et Deu.) is in the area of interest of many researchers [2–8]. Giant miscanthus is an energy crop of Pocaceae family. Stem, consisting of nodes and internodes, can reach 2–3.5 m length. Root system can reach up to 2.5 m below the Surface. Miscanthus is harvested outside of vegetation period, most optimally at the turn of February and March [9, 10]. Miscanthus is a C4 photosynthesis type plant, naturally occurring mainly in East Asia. However, it easily adapts to different climates, and for this reason it is successfully cultivated in Europe and North America. Miscanthus plantation lifespan usually varies from 3 to 5 years, with the highest yield (20–30 t ha^{-1}) occurring after third year of cultivation. After the harvest yield should be dried to reach humidity below 15%. Miscanthus incineration leaves good quality ash with low minerals content (0.2–0.6% N; 0.5–1.3% K; 0.1–0.5% Cl and 1.6–4.0%) and heavy metals concentration lower than in wood ash [11]. Miscanthus is one of the most promising energy crops, able to become key energy crop in Europe thanks to high yield and every year harvest [12].

Taking that into account, the need of storing miscanthus should be further investigated.

2 Aim of the Study

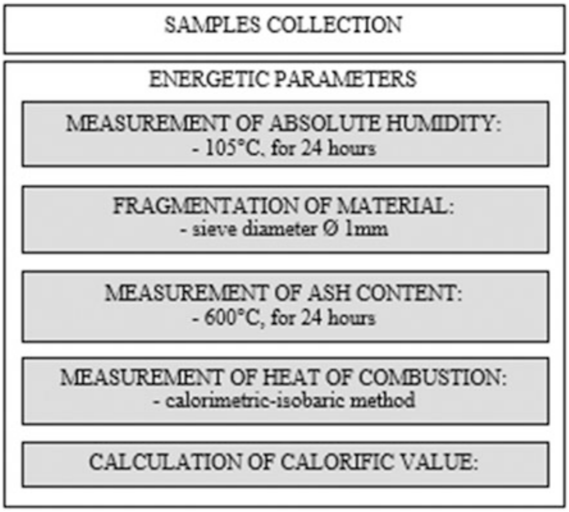
The aim of this study was to determine the influence of storing *Miscanthus* × *giganteus* on its physico-mechanical and energetic properties. The research consist of two research tasks:

I analysis of impact on energetic properties
II analysis of impact on physico-mechanical properties

3 Materials and Methods

The samples were collected in the experimental plantation belonging to Agricultural University in Cracow, located at the Balicka street. The harvest was performed twice—in the last week of March 2015 (stored material) and in the first week of May 2017 (fresh material). The stored yield was stockpiled horizontally on the hard surface under the roof.

Fig. 1 Outline of performed energetic parameters survey



The first research task was to compare energetic parameters of fresh and stored miscanthus biomass. Figure 1 shows actions performed to achieve that goal.

The next step was to define the absolute humidity, which was measured using a dehumidifier. That method consist of measuring the weight of water vaporized from sample (leaves and stems) in standardized conditions—105 °C, for 24 h.

The absolute humidity was calculated from the formula [13]:

$$X = \frac{m_1 - m_2}{m_1} \cdot 100\,[\%]$$

where:

X absolute humidity [%]
m_1 fresh sample weight [g]
m_2 dried sample weight [g]

After drying, sample was crushed and saved for further research.

To measure analytical moisture, 1 g samples were dried in 105 °C for 30 min. Calculations were made with the following formula [14]:

$$W^a = \frac{m_2 - m_3}{m_2 - m_1} \cdot 100\%, [\%_{mas}]$$

where:

W^a analytical moisture [%]
m_1 empty bowl weight [g]
m_2 bowl weight with fresh sample [g]
m_3 bowl weight with dried sample [g]

Heat of combustion was measured with calorimetric method, using IKA automatic isoperibol calorimeter.

Based on those measurements, calorific value was calculated using formula [15]:

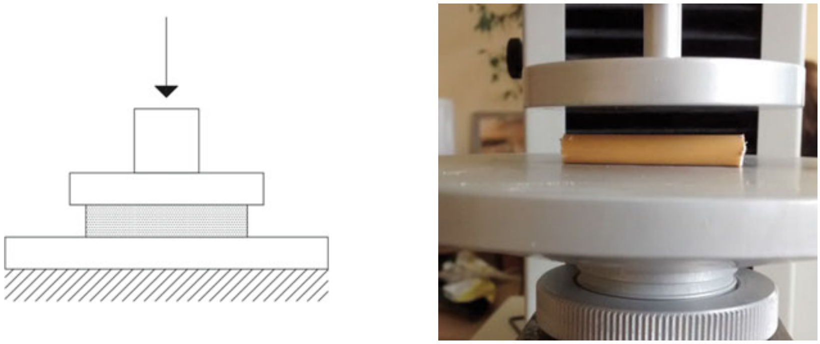
$$Q_w = Q_s - \frac{r}{100}(8.94H^a - W^a)$$

where:

Q_w calorific value [kJ/kg]
Q_S heat of combustion [kJ/kg]
W^a analytical moisture [%],
H^a hydrogen content in the sample [%]
r enthalpy of vaporization of water, r = 2454 kJ/kg

Because there was no possibility to measure hydrogen content in the sample, reference value H^a = 6.09 was assumed [16]. Calculated Q_w was compared with reference value of 16,490 kJ/kg dry weight [17].

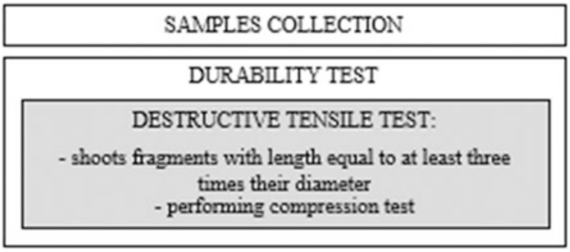
To complete second research task (analysis of physico-mechanical properties of stored and fresh samples), destructive tensile test (Fig. 2) was performed on fresh and stored samples. Received value is important regarding further processing of yield, e.g. bricketing and pelletizing. Test was performed on universal testing machine MTS Insight 2, capable to run both tensile and stretching tests. Results were processed and archived in TestWork software (Fig. 3).



(a) outline **(b)** actual photography

Fig. 2 Outline and actual photography of tension test

Fig. 3 Outline of performed durability tests



The value measured during the test was destructive tension. For further calculations, the P_j factor was introduced:

$$P_j = \frac{P}{l} \cdot 10$$

where:

P_j unitary destructive force [N/m]
P destructive force value indicated by the machine [N]
l lenght of tested interstem fragment [m]

All plant samples tested for durability were taken from interstems 1–5. Shoots/stalks fragments with length equal to at least three times their diameter was tested—in order to limit the impact of possible damage stalks in the cutting plane.

4 Statistical Calculations

To verify research hypotheses on the impact of storing miscanthus on its energetic parameters (calorific value) and mechanical properties (destructive tension), data were tested statistically.

If the distribution was normal, hypotheses were tested with t-Student test. Otherwise, Mann-Whitney U test was performed. Those tests were used to verify null hypotheses (H0 for t-Student test—there is no statistically significant difference between means in two analyzed populations; H0 for Mann-Whitney U test—there is no statistically significant difference between medians in two analyzed populations).

The t-Student test requires fulfilling three assumptions:

(1) the observations are independent,
(2) the sample data have a normal distribution within factor levels and
(3) the dependent variable's variances within each factor level are homogeneous.

For the Mann-Whitney U test, distribution doesn't have to be normal and variance doesn't need to be homogeneous, but there are two assumptions that have to be fulfilled:

(1) all repeats for both populations have to be statistically independent,
(2) dependent variable is measured in ordinal or interval scale.

In both mentioned tests, test statistic is calculated and on its basis probability (p) is determined. That p value is then compared with assumed level of significance α. If $p \leq \alpha$, the null hypothesis (H0: samples were taken from the same population) is rejected and alternative hypothesis (H1: samples were taken from different populations) is confirmed. If $p > \alpha$, there is no reason to reject null hypothesis.

Assumption that dependent variables (calorific value and P_j) in each pile zone have normal distribution was verified using Shapiro-Wilk test. Assumption that variances in each group don't differ was verified using Levene test.

All statistical calculations were performed using STATISTICA StatSoft, Inc., assuming level of significance $\alpha = 0.05$.

5 Results

5.1 Energetic Properties Research Results

Table 1 contains results of Shapiro-Wilk W test for dependent variable 'calorific value'.

For group 'X1—storage = No' $p > \alpha$ ($\alpha = 0.05$), then null hypothesis (H0: distribution is normal) has to be rejected. Therefore, the Mann-Whitney U test has to be used for calorific value.

The results of Mann-Whitney U test are shown in Table 2. It was found that there is no statistically significant difference between analyzed groups and null hypothesis (H0: there is no statistically significant difference between medians in two analyzed populations) was confirmed. The correction for continuity was included.

Figure 4 shows basic statistics for calorific value (mean, standard error, confidence interval) in compared groups. Although Mann-Whitney U test didn't prove difference between groups statistically significant, mean value, that difference is noticeable. For fresh samples calorific value was 15,896 [kJ/kg] and for samples from stored material it was 16,594 [kJ/kg]. Dispersion of results in both groups were small (standard deviation was low) (Table 3).

Table 1 Results of Shapiro-Wilk W test for calorific value

X1—storage	Shapiro-Wilk test statistic W	*p*-value	Distribution
Yes	0.940723	0.530288	Normal
No	0.763632	0.030345	Not normal

Table 2 Results of Mann-Whitney U test (correction for continuity included) for calorific value

Variable	Ranks sum	Ranks sum	U	Z	*p*
Calorific value	15.00000	6.000000	0.00	1.745743	0.080857

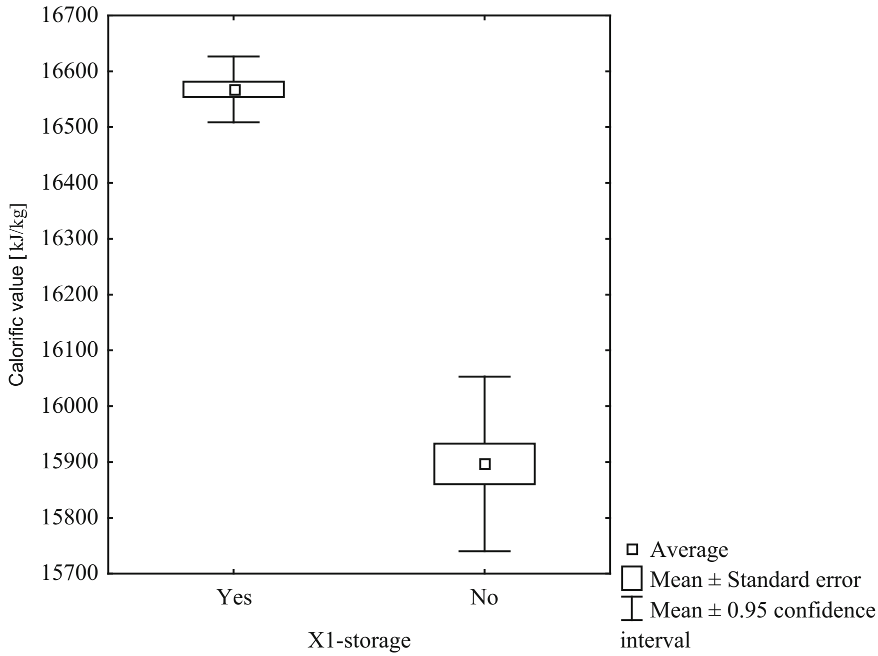


Fig. 4 Mean values ± 95% of confidence interval for calorific value

Table 3 Basic statistics of energetic parameters for stored and non-stored miscanthus

Storage	Heat of combustion	Ash content (%)	Absolute humidity (%)
Yes	17,861 ± 24	1.38 ± 0.0275	9.40
No	17,191 ± 63	1.88 ± 0.0760	22.51

Data are presented as means from independent measurements ± standard deviation (SD)

5.2 Mechanical Properties Research Results

Table 4 contains results of Shapiro-Wilk W test for dependent variable P_j. For both groups the probability (p) that null hypothesis is true (H0: distribution is normal) is greater that assumed level of significance ($\alpha = 0.05$). Therefore, there is no premise to reject null hypothesis and distribution is normal.

Table 4 Results of Shapiro-Wilk W test for P_j

X1—storage	Shapiro-Wilk test statistic W	*p*-value	Distribution
No	0.935784	0.538281	Normal
Yes	0.945808	0.644185	Normal

Table 5 Results of Levene test for P_j

Variable	F	*p*	Variance
P_j	0.116269	0.737554	Homogenous

Table 6 Results of t-student test for P_j

Variable	t	*p*	Standard deviation
P_j	−1.03022	0.318230	16.39243

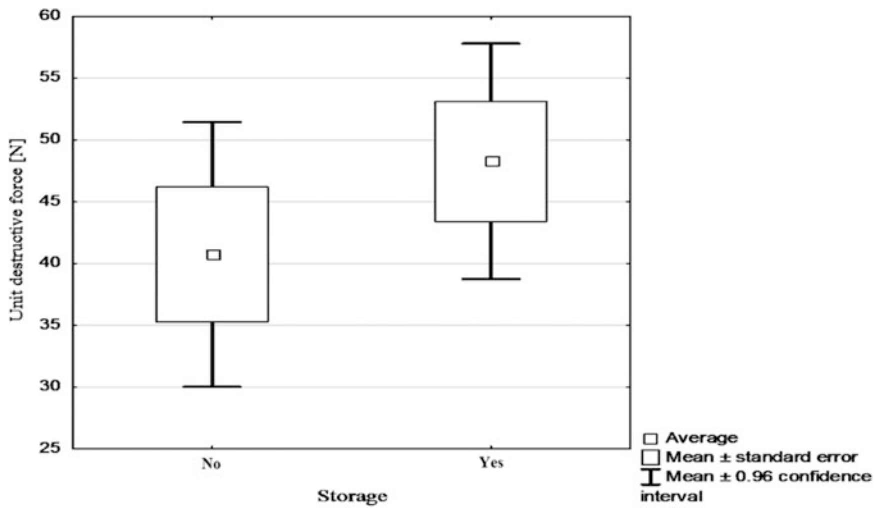


Fig. 5 Mean values ± 96% of confidence interval for P_j

Table 5 contains Levene test results for dependent variable P_j. Because probability (*p*) that null hypothesis is true (H0: variance is homogenous) is greater that assumed level of significance ($\alpha = 0.05$), there is no premise to reject null hypothesis and variance is homogenous.

Because all assumptions for t-Student test were fulfilled, the test was performed and results are shown in Table 6. It was found that there is no statistically significant difference between analyzed groups and null hypothesis (H0: there is no statistically significant difference between means in two analyzed populations) was confirmed.

For X1—storage = No mean value of Pj was 40.73 ± 16.39 [N], and for X1—storage = Yes it was 48.27 ± 14.59 [N]. It can be noted that values of Pj from two groups can overlay (Fig. 5).

6 Conclusions

Conducted research revealed that there is no statistically significant difference between analyzed groups regarding calorific value (Mann-Whitney U test) and P_j (t-Student test). Thus null hypothesis (H0: there is no statistically significant difference between two analyzed populations) was confirmed.

Measured calorific value in two groups was:

– storage = Yes: 16,568 [kJ/kg]
– storage = No: 15,897 [kJ/kg]

Therefore, difference between two groups is noticeable, although not statistically significant.

Other researched characteristics were also noticeably different in two groups. Absolute humidity varied by 10% between stored and non-stored miscanthus and ash content varied by 26% between these two groups.

Mean values of P_j for stored and not-stored miscanthus were different. For X1—storage = Yes $P_j = 48.27$ [N] and for storage = No $P_j = 40.73$ [N]. Standard deviation for both groups was similar, amounting 14.59 [N] for stored and 16.39 [N] for non-stored miscanthus.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Beringer, T., Lucht, W., Schaphoff, S.: Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy **3**, 299–312 (2011). https://doi.org/10.1111/j.1757-1707.2010.01088.x
2. Angelini, L.G., Ceccarini, L., Di Nassa, N.N.O., Bonari, E.: Comparison of *Arundo donax* L. and *Miscanthus* x *giganteus* in a long-term field experiment in Central Italy: analysis of productive characteristics and energy balance. Biomass Bioenergy **33**(4), 635–643 (2009). https://doi.org/10.1016/j.biombioe.2008.10.005
3. Barney, J.N., Mann, J.J., Kyser, G.B., DiTomaso, J.M.: Assessing habitat susceptibility and resistance to invasion by the bioenergy crops switchgrass and *Miscanthus* x *giganteus* in California. Biomass Bioenergy **40**, 143–154 (2012). https://doi.org/10.1016/j.biombioe.2012.02.013
4. Mann, J.J., Barney, J.N., Kyser, G.B., Di Tomaso, J.M.: *Miscanthus* x *giganteus* and *Arundo donax* shoot and rhizome tolerance of extreme moisture stress. Global Change Biol. Bioenergy **5**(6), 693–700 (2013a). https://doi.org/10.1111/gcbb.12039
5. Mann, J.J., Kyser, G.B., Barney, J.N., DiTomaso, J.M.: Assessment of aboveground and belowground vegetative fragments as propagules in the bioenergy crops *Arundo donax* and *Miscanthus* x *giganteus*. Bioenergy Res. **6**(2), 688–698 (2013b). https://doi.org/10.1007/s12155-012-9286-z

6. Smith, R., Slater, F.M.: The effects of organic and inorganic fertilizer applications to *Miscanthus* x *giganteus*, *Arundo donax* and *Phalaris arundinacea*, when grown as energy crops in Wales, UK. Global Change Biol. Bioenergy **2**(4), 169–179 (2010). https://doi.org/10.1111/j.1757-1707.2010.01051.x
7. Smith, R., Slater, F.M.: Mobilization of minerals and moisture loss during senescence of the energy crops *Miscanthus* x *giganteus*, *Arundo donax* and *Phalaris arundinacea* in Wales, UK. Global Change Biol. Bioenergy **3**(2), 148–157 (2011). https://doi.org/10.1111/j.1757-1707.2010.01069.x
8. Triana, F., Di Nasso, N.N.O., Ragaglini, G., Roncucci, N., Bonari, E.: Evapotranspiration, crop coefficient and water use efficiency of giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus* x *giganteus* Greef et Deu.) in a Mediterranean environment. Global Change Biol. Bioenergy **7**(4), 811–819 (2015). https://doi.org/10.1111/gcbb.12172
9. Kolowca, J., Wróbel, M., Baran, B.: Mechanical model of *Miscanthus giganteus* grass blades/ Model mechaniczny źdźbła trawy *Miscanthus giganteus* (in Polish). Inżynieria Rolnicza **6** (115), s. 149–154 (2009)
10. Kolowca, J., Wróbel, M.: Mechanical strength of the grass blade of *Miscanthus giganteus*/ Wytrzymałość mechaniczna źdźbła trawy *Miscanthus giganteus* (in Polish). Inżynieria Rolnicza **4**(122), s. 121–126 (2010)
11. Lewandowski, I., Clifton-Brown, J.C., Scurlock, J.M.O., Huisman, W.: Miscanthus: European experience with a novel energy crop. Biomass Bioenergy **19**, 209–227 (2000)
12. Hastings, A., Clifton-Brown, J., Wattenbach, M., Mitchell, C.P., Stampfl, P., Smith, P.: Future energy potential of Miscanthus in Europe. GCB Bioenergy **1**, 180–196 (2009). https://doi.org/10.1111/j.1757-1707.2009.01012.x
13. PN-EN ISO 18134-1:2017-03
14. PN-EN ISO 18134-3:2017-03
15. Cieślikowski, B., Juliszewski, T., Łapczyńska-Kordon, B.: Utilisation of bio-fuel technology by-products for power production purposes/Utylizacja na cele energetyczne produktów ubocznych technologii biopaliwowej (in Polish). Inżynieria Rolnicza **12** (2006)
16. Komorowicz, M., Wróblewska, H., Pawłowski, J.: Skład chemiczny i właściwości energetyczne biomasy z wybranych surowców odnawialnych (in Polish). Ochrona Środowiska i Zasobów Naturalnych, nr **40**, s.402–410 (2009)
17. Król, D., Łach, J., Poskrobko, S.: O niektórych problemach związanych z wykorzystaniem biomasy nieleśnej w energetyce (in Polish). Energetyka, Nr **1**, (2010)

Analysis of MSW Potential in Terms of Processing into Granulated Fuels for Power Generation

Marcin Jewiarz, Jarosław Frączek, Krzysztof Mudryk, Marek Wróbel and Krzysztof Dziedzic

Abstract Due to its morphological composition which includes mostly combustible material (plastics, paper, textiles, etc.), municipal solid waste is potentially a valuable raw material for use in power generation. On the other hand, content of incombustible fraction (glass, metal, rocks, etc.) reduces its value, particularly when solid municipal waste must be processed into the form of granulate as in case of co-combustion with coal in pulverized-fuel or fluidized-bed boilers. The process of granulation reduces also the costs of logistics processes such as transport, storage and handling. That is why the research carried out in the framework of "EkoRDF—an innovative manufacturing technology of alternative fuel from municipal waste for power and heating plants—a key component of the Polish waste management system" financed by Polish Centre for Research and Development (GEKON Programme) aimed at determining the MSW potential not only in terms of use in power generation, but mainly from the point of view of technologies of converting the waste into granulated fuels for power generation units. The test material comprised oversize and undersize fractions of municipal solid waste obtained from four sources (sorting plants). The morphological and grain-size analyses were carried out, and the parameters important from the point of view of power generation were determined (moisture content, calorific value, volatile matter content, ash content). The impact of those parameters on key stages of RDF production from waste (drying, comminution and granulation) were analysed. The analysis led to determination of acceptable raw material parameters for use in production of fuel granulates dedicated to burning in power generation units.

Keywords Municipal solid waste · Refuse derived fuel · Proximate analysis

M. Jewiarz (✉) · J. Frączek · K. Mudryk · M. Wróbel · K. Dziedzic
Department of Mechanical Engineering and Agrophisics, Faculty of Production and Power Engineering, University of Agriculture in Krakow,
Balicka 120, 31-149 Krakow, Poland
e-mail: marcin.jewiarz@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_65

1 Introduction

The waste management has been undergoing significant changes in recent years. Current trends propagated in the EU recommend maximizing the raw material and energy potential of municipal solid waste [1]. These actions aim at minimizing the amount of landfilled waste. In addition, many developed countries, guided by the sustainable development principle, are passing, or are planning to pass, legislation which significantly limits the waste landfilling without energy recovery. This approach forces collection of curb-side segregated waste, which in turn affects a two-way development of waste processing technologies. The technologies allowing to recover recyclable raw materials from waste (glass, metals, plastics, paper) are developing particularly fast. This is accompanied by growth of technologies which aim at using the waste in energy generation which is particularly favourable in case of mixed waste where recovery of raw materials is a complicated process and often unprofitable in terms of energy. One of the most widely used methods of energy recovery from waste is thermal treatment as in case of incinerating plants. More advanced technologies include processing of waste into fuels with precisely defined quality parameters (RDF—Refuse-Derived Fuels or SRF—Solid Recovered Fuels) which can be used in typical industrial plants, Currently, most of such waste-derived fuels is sent to cement plants.

Growing interest in using municipal solid waste to generate power results directly from regulations according to which by 2020 the landfilling must be limited to 35% of biodegradable MSW by weight in comparison with the weight of such waste generated in 1995. According to the forecast prepared by Szpadt [2], in 2020 the amount of biodegradable waste which should be treated, will reach 3640 Gg/year.

The mechanical processing of municipal solid waste is particularly popular in Europe which relates to the EU policy [3, 4] on processing of mixed municipal waste and landfilling of biodegradable waste [5–8]. The two aforementioned directives indicate a correct hierarchy of waste handling with prevention/reduction on top, next reuse and recycling (i.e. mechanical), recovery in the form of energy, and finally landfilling as the least favored method of waste processing [9].

Taking into account the physical properties of waste, particularly variety of materials, low bulk density and also requirements of potential users, the key issue seems to be to develop a technology of agglomeration of waste into the form of technical pellets. It is very important to determine the detailed characteristics and parameters of feedstock so that the final product has appropriate quality features. In addition to significant energy benefit, the granulation process reduces also the costs of logistics operations such as transport, storage or handling.

In terms of energy recovery, municipal solid waste is a mixture of combustible and incombustible materials. The analysis of morphological composition indicates that combustible material is mainly plastics, paper, textiles, etc. which are potentially a valuable raw material for use in power generation. On the other hand, incombustibles such as glass, metal, rocks, etc. reduce the calorific value and are only a ballast. This is particularly important in case of densification processes and leads to faster wear of machinery and increased energy consumption during the process.

From the point of view of using waste in energy generation, the most important information is material composition along with basic division into combustibles (desirable) and incombustibles (ballast). While the ballast does not need to be further separated because its morphological composition does not affect its energy parameters, the composition of combustibles will have a significant impact on the energy potential of analysed waste. Hence, the methodology of determining the MSW composition assumes that the samples will be separated into: fines <10 mm, medium fraction 10–40 mm, coarse fraction 40–100 mm, and mesh fraction >100 mm.

2 Methodology

The analysis focused on parameters significant from the point of view of using the waste to produce technical pellets. The test material comprised samples taken during a 6 months period from four Mechanical Biological Treatment (MBT) plants in southern-east regions of Poland, presented on Fig. 1. The aim of sampling during a few periods was to determine average indicators for individual plants. As all plants had sieve separation systems, the taken material was divided into oversize and undersize fractions. All parameters were estimated in certified laboratory, according to up to date standards.

The first analysed parameter was grain-size distribution: Three sieves were used with mesh sizes of 10, 40 and 100 mm. The calculations were performed in accordance with the PN-EN 15415-1:2011 [10] and PN-EN 15415-2:2012 [11]. The contents of individual fractions were determined as weight share in the whole analysed sample.

The analysis of morphological composition was performed by dividing the sample into the following material types: paper, plastics, textiles, biomass, glass, metal, hazardous waste and other incombustibles. Then the separated materials were weighted. Similarly to the grain-size composition, the values reflect the weight content of individual materials in the analysed sample.

The next parameter was bulk density which was determined in accordance with the PN-EN ISO 17828:2016-02 [12] standard, with use of the container with volume of 25 dm^3. Next, the samples were dried in a convection drier (temperature 105 °C) in order to determine the moisture content. The calculations were performed in accordance with the CEN/TS 15414-1:2010 [13] standard.

Later, the whole material within a single test was averaged using the quartering technique in order to obtain representative samples for the qualitative analysis, according to the PN-EN 15413:2011 [14] standard. The material was shredded mechanically to obtain the grain size in the sample below 1 mm. Such prepared samples were then analysed to determine moisture content (PN-EN 15414-3:2011

Fig. 1 Locations of MBT plants taken into investigation; KR-Krakow, TW-Tarnow, WA-Włoszczowa, TG-Tarnobrzeg

[15]), ash content (PN-EN 15403:2011 [16]), volatiles content (PN-EN 15402:2011 [17]), and heat of combustion (PN-EN 15400:2011 [18]).

3 Results and Discussion

3.1 Morphological Analysis

Morphological composition of the wastes, could give important information on either quality of materials or how to prepare materials for further processing. The materials in this analysis were manually separated into eight groups presented in Table 1.

Table 1 Morphology factions with materials and abbreviations used in results presentation

Fraction	Abbreviation	Materials
Paper	PA	Papers, books, used packing papers
Plastic	TW	Plastic bottles, polymer packaging, foils, toys elements
Textile	TE	Cloths, natural and synthetic fibers
Biomass	BI	Wood, straw, biodegradable matter
Glass	SZ	Broken glass, glass bottles and containers etc.
Metal	ME	Metal elements, screws, rods, toys and machinery parts
Hazardous	NI	Baby napkins, pantyliners, syringes
Other	IN	Other, noncombustible materials

As it could be obviously noticed, oversieve fraction is mainly composed of light materials like plastics and paper. What is important for all MBT plants content of plastics were usually above 70% by mass (Fig. 2). In one case (WA), plastic content was above 95%, what could suggest that this plant is processing mainly, unpure polymer materials, that couldn't be recycled. This assumption seems to be confirmed by analysis of morphology of undersieve fraction (Fig. 3). In all analyzed samples higher content of other material groups than plastic (in comparison to oversive), what is expected trend, as plastics are quite flexible and remain during collection and transportation in ample pieces. What need to be noticed, in all undersize fractions, amount of other incombustible matter, was about 5% by mass, and in this case it was mainly soil and ash. In two location, TW and KR, higher share (about 20%) of glass was estimated. Agglomeration requires material free of glass, metal and other hard to mill materials, which in most cases could affect the quality of pellets, or even lead to equipment failure.

Analysis of grain size distribution, gives information about material, especially important in case of agglomeration processes. What need to be noticed, the MBT

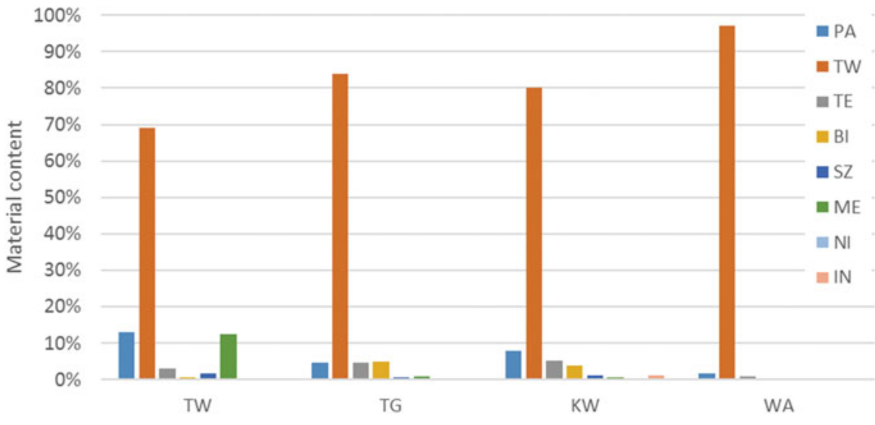


Fig. 2 Materials share in oversive faction in connection with MBT location

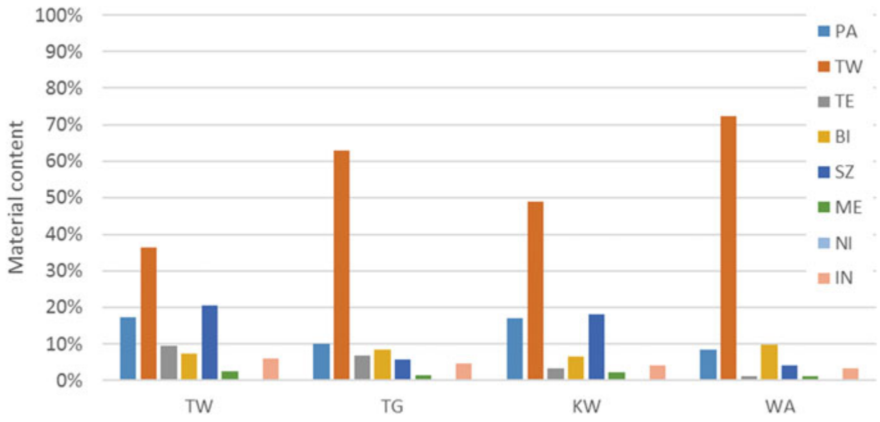


Fig. 3 Presentation of materials share in undersize faction in connection with MBT location

plant located in Krakow (KR), has shredding system at beginning of the line, so the material which was delivered, was initially fragmented, that's why results presented on Fig. 4 for oversize fraction are strongly in opposite to three other MBT locations. What could be expected, oversive fractions is dominated by large particles, above 40 mm. The small particles (below 40 mm), are impurities, which were not separated during separation in MBT plants. Generally, such grain size distribution of oversize fraction, indicates need of MSW complex fragmentation processes (shredding and milling) before agglomeration.

In case of undersize fraction, sieve analysis (Fig. 5) shows that these materials would need only milling process before agglomeration. The highest share in all cases was obtained for fraction from 40 to 100 mm.

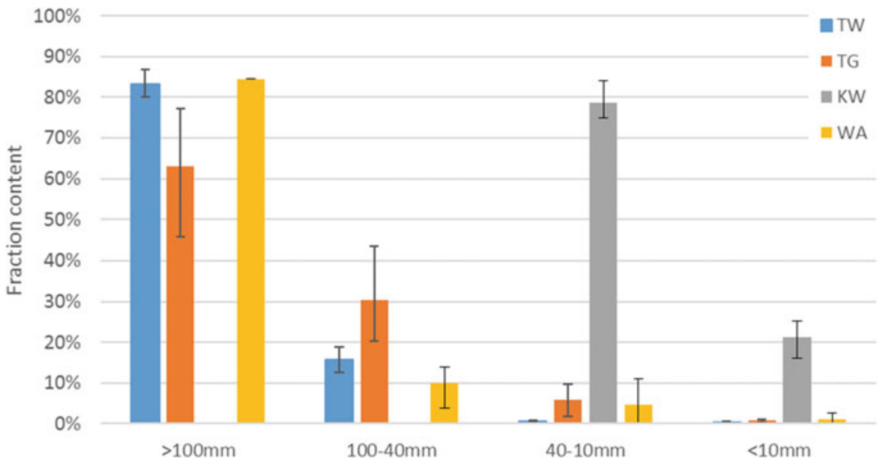


Fig. 4 Sieve analysis of oversize fraction of MSW in connection with MBT location

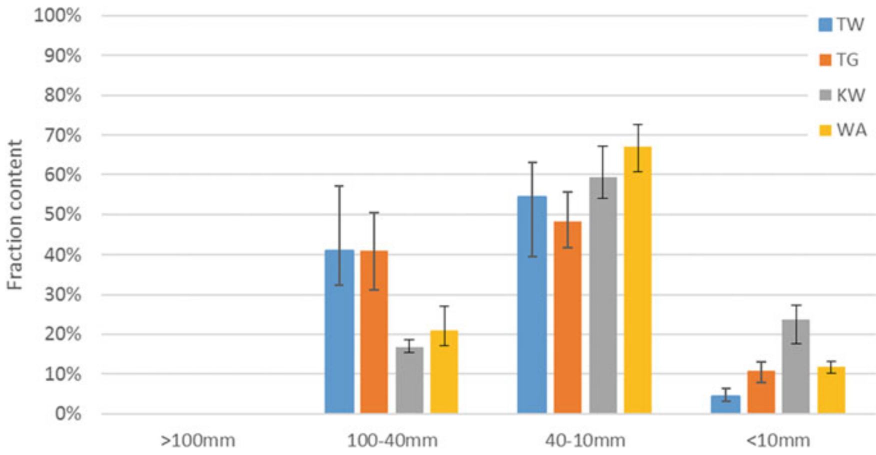


Fig. 5 Sieve analysis of undersize fraction of MSW in connection with MBT location

The bulk density, presented on Fig. 6, illustrates how light are oversize fractions of MSW. In all analysed MBT plants, the bulk density was more than twice higher for undersize fraction in comparison to the relevant oversize fraction. This could be due to higher share of mineral fraction in analysed undersize fractions. Usually the loose and airy structure of the undersize fraction, mainly due to high amount of plastics, textiles and paper, promotes such low bulk density. Presented results, shows that agglomeration process, could be cost effective, if we take into account long range transportation, but in this case, special calculations should be made, to confirm authenticity of this presumptions.

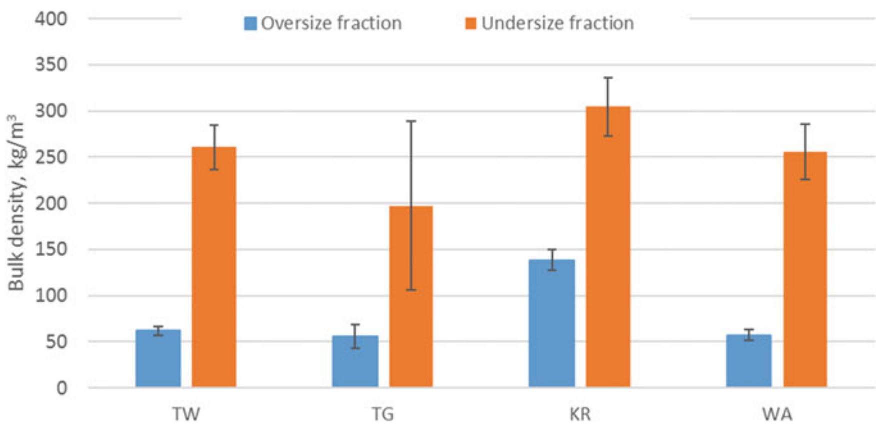


Fig. 6 Bulk densities of MSW in connection with MBT location

Table 2 Proximate analysis of RDF materials obtained from different locations

	Moisture (%)			Ash (%)			Volatile (%)			HHV (kJ/g)		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Oversize fraction												
TW	**26.0**	11.4	40.0	**19.8**	17.4	21.8	**75.2**	71.7	78.8	**24.9**	21.4	27.4
TG	**21.8**	11.9	41.8	**17.7**	13.2	20.8	**77.0**	72.5	80.4	**25.8**	19.6	34.4
KR	**30.3**	23.7	39.8	**27.2**	24.0	29.3	**63.1**	57.4	67.1	**19.9**	18.2	21.1
WA	**25.3**	9.7	42.7	**20.2**	17.0	24.7	**75.1**	69.2	80.0	**28.1**	22.2	31.9
Undersize fraction												
TW	**37.2**	33.4	42.0	**57.8**	50.7	63.2	**37.6**	35.3	39.4	**14.0**	9.2	20.1
TG	**45.1**	31.7	55.0	**48.2**	26.8	64.6	**47.7**	33.6	65.3	**16.9**	7.6	26.4
KR	**46.7**	39.5	50.4	**58.1**	52.8	66.7	**39.1**	30.8	45.8	**15.8**	9.9	20.1
WA	**54.1**	45.2	62.0	**66.1**	62.2	68.3	**29.7**	28.6	31.3	**10.6**	9.3	12.9

Moisture present as total moisture content, and all other results presented in dry state
Bold numbers are used to indicate the average values

3.2 Proximate Analysis of Raw Materials

During the research, over filthy samples were selected and analysed. Detailed results are presented in Table 2 in which are collated averages, maximum and minimum values for the appropriate MBT plant. This allows to compare differences between MSW form different location, and partially observe trends in divergence of quality parameters.

What could be notice at the beginning, the moisture content is higher in all undersive fractions. This could be due to higher share of biodegradable and paper fraction. Also there should be more soil and other mineral fractions, which would be more hydrophilic materials than plastics, which dominates in the oversize fraction. Higher amount of mineral fraction in undersize fraction is also reflected in ash content, which parameter for all MBT is above 50%. Such high amount would be normal, as material taken into analysis was not treated to separate high density materials. The significantly lower ash content in case of oversize fraction was observed. Higher ash content reflects in lower volatile matter content and higher heating value in case of undersize fraction.

What need to be mentioned, variability of measured values across investigated period of time, was on noticeable level. The spread of values was higher for undersize fraction.

4 Summary

Municipal solid waste (MSW), is very interesting material, which can be used in production of power and heat. It is important to use it in plants with strict emission control. Nevertheless presented results shows that quality of this raw material, can differ markedly not only for different Mechanical Biological Treatment plants, but also across year. Differences in morphology, as well as grain size distribution, lead to necessity of shredding and milling of the material before further processing. On the other, hand low bulk density affects profitability of transportation for longer distances. One of the method which will increase cost effective transport, would be agglomeration to form of briquettes and pellets. Proximate analysis shows, that such material can compete successfully with solid fuels like hard coal or lignite, but it must be noticed, that ashes formed in combustion, should undergo special treatment, to minimize influence of heavy metals contamination. In comparison with biomass fuels, higher ash content could be observed.

Acknowledgements This research are financed by Polish Centre for Research and Development and National Fund for Environmental Protection and Water Management under the GEKON Programme—project No: GEKON2/05/268002/17/2015. “EkoRDF—an innovative manufacturing technology of alternative fuel from municipal waste for power and heating plants—a key component of the Polish waste management system”.

References

1. Environment DG: European Commission, Refuse derived fuel, current practices and perspectives. Final Report, CO5087-4, July 2003
2. Szpadt, R.: Problemy gospodarki odpadami komunalnymi ulegajacymi biodegradacji. Politechnika Wroclawska, Instytut Inzynierii Ochrony Srodowiska (2012)
3. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives
4. Council Directive 99/31/EC of 26 April 1999 on the landfill of waste
5. Abeliotis, K., Kalogeropoulos, A., Lasaridi, K.: Life cycle assessment of the MBT plant in Ano Liossia, Athens, Greece. Waste Manag. **32**, 213–219 (2012)
6. Binner, E.: Mechanical biological pre-treatment of residual waste in Austria. In: Proceedings of the International Symposium on Sustainable Waste Management, University of Dundee, Scotland, UK, pp. 213–224 (2003)
7. Dębicka, M., Zygadło, M., Latosinska, J.: Investigations of bio-drying process of municipal solid waste. Ecol. Chem. Eng. A **20** (2013)
8. Dias, N., Belo, N., Máximo, A., Carvalho, M.T.: Recovery of glass contained in the heavy residual fraction of Portuguese mechanical biological treatment plants. J. Clean. Prod. **79**, 271–275 (2014)
9. Garg, A., Smith, R., Hill, D., Longhurst, P., Pollard, S., Simms, N.: An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. Waste Manag. **29**, 2289–2297 (2009)
10. PN-EN 15415-1:2011 Solid Recovered Fuels—Determination of Particle Size Distribution—Part 1: Screen Method for Small Dimension Particles. European Committee for Standardization
11. PN-EN 15415-2:2012 Solid Recovered Fuels—Determination of Particle Size Distribution—Part 2: Maximum Projected Length Method (manual) for Large Dimension Particles. European Committee for Standardization
12. PN-EN ISO 17828:2016-02 Solid Biofuels—Determination of Bulk Density. European Committee for Standardization

13. CEN/TS 15414-1:2010 Solid Recovered Fuels—Determination of Moisture Content Using the Oven Dry Method—Part 1: Determination of Total Moisture by a Reference Method. European Committee for Standardization
14. PN-EN 15413:2011 Solid Recovered Fuels—Methods for the Preparation of the Test Sample from the Laboratory Sample. European Committee for Standardization
15. PN-EN 15414-3:2011 Solid Recovered Fuels—Determination of Moisture Content Using the Oven Dry Method—Part 3: Moisture in General Analysis Sample. European Committee for Standardization
16. PN-EN 15403:2011 Solid Recovered Fuels—Determination of Ash Content. European Committee for Standardization
17. PN-EN 15402:2011 Solid Recovered Fuels—Determination of the Content of Volatile Matter. European Committee for Standardization
18. PN-EN 15400:2011 Solid Recovered Fuels—Determination of Calorific Value. European Committee for Standardization

Characterization of Selected Plant Species in Terms of Energetic Use

Marek Wróbel, Krzysztof Mudryk, Marcin Jewiarz, Szymon Głowacki and Weronika Tulej

Abstract The paper presents the characteristics and analysis of the usefulness of selected biomass, obtained from different plant spices (*Silphium perfoliatum* L., *Helianthus salicifolius* A. Dietr., *Sida hermaphrodita* Rusby). The botanical characteristics of the species surveyed from North America was presented. It has been shown that these species meet the requirements for plants intended for so called Energy crops, as they are characterized by high yield, disease and pest resistance and low habitat requirements. The basic physical properties of biomass were determined, like moisture content during harvesting, specific density, ash content, net calorific value. The paper also presents a comparison of the research results obtained by determining the fuel quality indicator. It has been shown that the best parameters are willowleaf sunflower biomass, and the worst is the biomass obtained from cup plant.

Keywords Biomass quality · Energy crops · Cup plant
Willowleaf sunflower · Virginia fanpetals

M. Wróbel (✉) · K. Mudryk · M. Jewiarz
Faculty of Production and Power Engineering, University of Agriculture in Krakow, Balicka 120, 30-149 Kraków, Poland
e-mail: marek.wrobel@urk.edu.pl

K. Mudryk
e-mail: krzysztof.mudryk@urk.edu.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

S. Głowacki · W. Tulej
Faculty of Production Engineering, Warsaw University of Life Sciences—SGGW, Warsaw, Poland
e-mail: szymon_glowacki@sggw.pl

W. Tulej
e-mail: weronikabazylak@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_66

1 Introduction

Over the last few years there has been observed an increase in the use of renewable energy sources either in individual households or in the energy sector. The most popular source remains biomass. The most important advantages of biomass are the lower sulfur dioxide emissions compared to fossil fuels, and the carbon dioxide produced during combustion can be treated as zero because the plants absorb it by photosynthesis [1]. It should be borne in mind that this balance does not take into account the carbon dioxide emitted during the collection, transport and processing of biomass. These processes are still based on traditional energy carriers produced from fossil fuels.

Due to the high interest in biomass, it is envisaged that the plantation of energy crops will be the main source of biomass for the production of solid biofuels [2]. This should ensure a certain amount of standardized biomass required for further processing. The classic energetic plant is willow (*Salix viminalis* L.), which, due to the water-soil requirements, can't be cultivated on all potentially attractive fields for energy crops. Because of the diversity of soil conditions used for energy crops cultivation, it is advisable for potential growers to have at their disposition a wide range of plant species, so that the crop can be adapted to area characteristic. Only in such case, the maximum yield of biomass will be obtained with minimum effort required to obtain it.

Many research institutions, both in Poland and abroad, conduct research to assess the suitability of new plant species for energy crops [3–7]. These plants should first of all be characterized by a high annual growth, disease and pest resistance, low habitat requirements and adaptation to climatic conditions.

Biomass obtained from the plantation usually in a fragmented form is characterized by low bulk density, which increases the costs of transport and storage. For this reason, the particulate material is subjected to a densification process (agglomeration). This process occurs as a result of pressure compaction during which, the contact surface of the particle rises so the forces of adhesion and cohesion leads to permanent link between these particles.

Due to species origin, biomass is characterized by a variety of parameters that determine its susceptibility to agglomeration processes. In addition, physical properties such as particle size composition, density, porosity significantly affects the granulation process. As shown by biomass studies, these properties, in addition to process parameters, significantly influences the quality of the resulting granules. The degree of fragmentation affects the process of the material feeding to the granulator and the density of the resulting granules [8]. Significant fraction of fine particles in the raw material is the improvement of the quality and durability of the granules [9, 10]. However, too high fragmentation results in a decrease in durability and an increase in the costs of granulation [11]. Often, the parameters of the raw material can differ from one manufacturer to another, hence there is a need to standardize some of quality parameters. However, for individual consumers, the most important parameters are energy parameters (ash content, combustion heat, fuel quality index), regardless of the degree of biomass conversion.

Based on this information the main aim of the study was to characterize selected botanical species in terms of botanical and their use for energy purposes.

2 Methodology

The research material was obtained from experimental fields conducted within the Energy Plant Collections kept in University of Agriculture in Krakow. Selected plants are perennial species (honey, fodder, ornamental plants), but exhibit the characteristics of potential energy crops (high yield, low habitat requirements, disease resistance). Characterized species include: cup plant (*Silphium perfoliatum* L.), willowleaf sunflower (*Helianthus salicifolius* A. Dietr), virginia fanpetals (*Sida hermaphrodita* Rusby)

The paper presents: botanical characteristics of plants, determination of energy-relevant properties: harvest moisture, dry matter yield, specific density, ash content, combustion heat, fuel quality indicator.

Measurements of most parameters were carried out in accordance with PN-EN ISO standards for the properties of solid biofuels (humidity, ash content, combustion heat) or according to methods determined by applied test apparatus (specific density). Determination of the analytical moisture content was carried out in accordance with PN-EN ISO 18134-3: 2015-11 [12]; moisture content in the material immediately after harvest (Mh) according to PN-EN ISO 18134-1: 2015-11 [13]. The ash content was determined according to PN-EN ISO 18122: 2016-01 [14] and the gross calorific value according to PN-EN 14918: 2010 [15].

Estimated yield from 1 ha was determined on the basis of the yield obtained from the experimental field of 50 m^2. The harvested material was weighed immediately after cutting. Knowing the area of the plot and the mass of harvested material, yield of fresh mass (p) was determined. After determining the moisture content of fresh weight (Mh), yield of dry matter ps.m was determined according to the formula (1):

$$p_{s.m.} = p\left(1 - \frac{M_h}{100}\right) \tag{1}$$

where:

$p_{s.m.}$ yield of dry mass (t/ha)
p yield of fresh biomass (t/ha),
M_h moisture content after harvesting (%)

The specific density of the examined plants shoots was determined using the Geopyc 1360 quasifluid pycnometer produced by Micromeritics. The device measures the volume of the sample placed in the measuring chamber, using so-called dry quasi-fluid (DryFlo) with a particle size of less than 250 μm which does not react with the sample and adapts to their shape. The use of this powder instead of liquid eliminates the wetting of the test material (soaking), which allows the testing of materials with high humidity.

The ideal energy plant should be characterized by high calorific value. A very important feature of plants used for energy purposes is also the smallest ash content and high specific density. The so-called FVI (fuel value index) coefficient describes the pro-energetic value of biomass, based on the above parameters according to formula (2) [16]:

$$FVI = \frac{qv_{gr,d} \cdot DE_d}{A_d \cdot M} \quad (2)$$

where

$qv_{gr,d}$ gross heating value (kJ/g),
DE_d specific density of the biomass in dry state (g/cm^3),
A_d ash content in dry state (%),
M total moisture content (%)

3 Plant Characterisation and Results

3.1 Cup Plant

Cup plant (*Silphium perfoliatum* L.) is a large, coniferous perennial flowering plant in the family Asteraceae. Similarly to common sunflower (*Helianthus annuus* L.) or Jerusalem artichoke (*Helianthus tuberosus* L.) native to eastern and central parts of the North America, where it is a component of prairie vegetation. It occurs in vast areas of Canada and the USA. In the 18th century it was brought to Europe due to its decorative and aesthetic value, and used in naturalistic garden and parks. In the former USSR was cultivated for fodder. A similar direction of application is currently promoted in Belarus and Ukraine [17], but the high content of phenolic acids limits the possibility of using it as forage [18, 19]. In contrast, the high content of saponin compounds in leaves, inflorescences and rhizomes is a valuable raw material for the pharmaceutical industry [20]. This plant is also a valuable melliferous species. Its honey yield is 550 kg/ha [21] and pollen productivity is 200–300 kg/ha [22].

Morphology of the specie is presented on Fig. 1. It is a plant with a naked, raised, four-stalk stem reaching 2.5–3 m height. In the first year of vegetation it produces only a rosette of leaves, and generative shoots grows in the following years. The number of shoots (up to 10–25) increases with age. Stems constructed from 8 to 12 internodes of 20–30 cm in length are filled with spongy core. Triangular or oval-shaped leaves (up to 40 cm in length) with serrated edges and covered with rough hair and arranged in pairs along the stem. Lower leaves with

Fig. 1 Cup plant *Silphium perfoliatum* L.: 1—generative sprout, 2—flower bud, 3—flower, 4—fructification, 5—seeds, 6—cross-section of a sprout. *Source* own materials

winged petioles, upper leaves are slightly shorter, sitting and covering the stem. Yellow flowers 5–7.5 cm in diameter collected in loose tops. It flowers from July to September. The seeds are gray-brown marbled. The advantage of the species is its high resistance to low temperatures (it lasts the temperatures below −25 °C).

Because of its low nutrient requirements, it can be used as a pioneer plant for the recultivation of the degraded areas. Because of its high yield—15–19 t/ha of dry matter [17], this plant is considered as an energy crop. The plantation should be established in autumn (X–XI), by sowing seeds in rows with spacing 100 cm [23].

Table 1 shows the values of the measured parameters obtained for biomass obtained from cup plant.

Table 1 Cup plant—values of the measured parameters

Quantity	Abbreviation	Unit	Value
Moisture content (raw material)	M_h	%	22.1
Dry matter yield	$p_{s.m.}$	Mg/ha	14.1
Specific density (dry material)	DE_d	g/cm^3	0.21
Ash content (dry state)	A_d	%	3.6
Gross calorific value (dry state)	$qv_{gr,d}$	J/g	17,324
Fuel value index (moisture content 12%)	FVI	–	0.08

3.2 Willowleaf Sunflower

According to the systematics, willowleaf sunflower *Helianthus salicifolius* A. Dietr, belongs to the genus sunflower, the Aster family [24], such as *Helianthus annuus* L. and *Helianthus tuberosus* L., which are also used as a source of solid biofuels. Sunflower is native to arid parts of North America, Plain of Texas and Nebraska. The natural habitat is most often found on the side of roads, wastelands, rocky hills, which is evidence of its small soil requirements.

In Poland this species is grown in gardens as an popular ornamental plant, can be found mainly at the discounts, as a soliter or in a group of 2–3 plants. Willowleaf sunflower requires positions in full sun and it is a plant that tolerates drought well. This plant has no particular requirement as to the type of soil. So far, does not provide any information about diseases and pests that attack the plant, which scale of impact would significantly affect the growth and yielding of the plantation. It is important that during the first year of cultivation is sensitive to low temperatures.

Morphology (Fig. 2): a perennial plant that produces large clumps of generous shoots reaching a height of 3–3.5 m, light green to purple red. Produces fine yellow flowers that are held in trusses of inflorescences which appears in late summer, and persist until the first frosts. Leaves of 15–40 cm in length are single, unaltered, light green, lanceolate, drooping, similar to the willow leaves, hence its species name. In a natural habitat, the plant produces seeds, while reproduction in our climatic zone is made by splitting the rhizomes because the seeds do not ripen. One rhizome is obtained from several rhizomes.

An important issue, prior to the foundation of the sunflower seedlings, is the proper preparation of post-harvest pods, based primarily on the performance of the postharvest covering of post-harvest residues and the treatments aimed at eliminating the occurrence of weed infestation. Planting should be done, like sowing corn, into warm soils. It is proposed that planting should be carried out mechanically by means of planter. Plant cover per 1 m^2 should be between 3 and 4 pieces in sunlight, but in areas with difficult access to light, the plant is susceptible to lodging, so it is recommended to increase the stock from 4 to 6 pieces. Table 2 shows the values of the measured parameters obtained for biomass obtained from cup plant.

3.3 Virginia Fanpetals

Virginia fanpetals *Sida hermaphrodita* Rusby., is a perennial, growing each year, increasing the number of stems in a compact clump from one in the first year to 20–30 in the following years. It belongs to the Malvaceae family which includes several hundred species of plants. It comes from North America where it occurs in the natural environment of several states, but mainly Virginia and Pennsylvania.

Fig. 2 Willowleaf sunflower *Helianthus salicifolius* A. Dietr.: 1—generative sprout, 2—flower bud, 3—flower, 4—snag, 5—rhizomes, 6—cross-section of a sprout. *Source* own materials

Table 2 Willowleaf sunflower—values of the measured parameters

Quantity	Abbreviation	Unit	Value
Moisture content (raw material)	M_h	%	38.3
Dry matter yield	$p_{s.m.}$	Mg/ha	18.1
Specific density (dry material)	DE_d	g/cm^3	0.53
Ash content (dry state)	A_d	%	2.3
Gross calorific value (dry state)	$qv_{gr,d}$	J/g	18,221
Fuel value index (moisture content 12%)	FVI	–	0.35

Other species of this type are found in the areas of Africa, Australia and Cape Verde. In Poland it appeared in the 50s.

Morphology (Fig. 3)—a plant with a compact clump with a strong root system that develops from few to several shoots with a height of over 3.5 m. Stems raised with a circular cross-section from 5 to 50 mm in diameter, with an opening in the

Fig. 3 Virginia fanpetals *Sida hermaphrodita* Rusby: 1—generative sprout, 2—flower bud, 3—flowers, 4—fructification, 5—leaf, 6—root seedling, 7—seeds. *Source* own materials

middle of the lower part, growing each year from the buds on roots in the bulbous zone. Number of shoots increases every year. Palm leaves, lobed, marginal, high indentation, moss and size. The colour of the leaves from intensely dark green through light green to celadon. An insect-friendly plant is attracted by bees and pollen-obfuscated pollen. Inflorescence is a corymbothyrsus consisting of small flowers with a diameter of about 20 mm with 5 white flakes of the crown, 5 plots of the cup and yellow anthers. Flowering period is from July to September. The fruit is stupefied with an average of 5–8 seeds, weighing a thousand seeds of 2.5–4 g. Seeds do not shed, so there is no natural sowing. Due to the so-called phenomenon of “hardness” of seeds their ability to germinate immediately after harvest is only 2%. After a year of storage, this ability increases to 50–60%. Fruit ripen gradually at the turn of August and September. The Virginia fanpetals generates generatively, that is, seed and vegetative—by root or herbaceous plants.

It is species with low climatic and soil requirements. Resistant to extreme temperatures, both low and high, withstands precipitation deficiency in summer and is not very demanding in terms to the soil. The plant is suitable for cultivation in all regions of the Poland on soils of all classes except VI and weak V classes, neutral, slightly acidic. However, to obtain high biomass yield, it requires nutrient-rich soils. Deep root system of the mulch enables it to survive drought periods, but with

Table 3 Virginia fanpetals—values of the measured parameters

Quantity	Abbreviation	Unit	Value
Moisture content (raw material)	M_h	%	26.5
Dry matter yield	$p_{s.m.}$	Mg/ha	13.3
Specific density (dry material)	DE_d	g/cm^3	0.29
Ash content (dry state)	A_d	%	2.7
Gross calorific value (dry state)	$qv_{gr,d}$	J/g	17,523
Fuel value index (moisture content 12%)	FVI	–	0.16

too little rainfall the crop yields are significantly lower. Plantation can be set from seed sowing or through rooting. The optimum harvesting date is the end of September to November—after frosts, the end of vegetation and the natural dryness of the stems. After the freezing of the surface the use of mulch harvesting machines is preferable. Table 3 shows the values of the measured parameters obtained for the biomass of the virginia fanpetals.

4 Summary

According to the biomass classification which can be found in PN-EN ISO 17225-1: 2014-07 [25], the basis for the classification of biomass in the EU quality system is its origin and source. The hierarchical classification system contains four types of biomass because of their origin:

- woody biomass—wood and bark of trees and bushes,
- herbaceous—annual plants and perennials with non-woody shoots, dying after vegetation,
- fruity—parts of plants containing seeds or they themselves,
- mixtures (deliberately mixed biomass and mixed by accident).

According to the above classification, all presented plants can be classified as herbaceous biomass from plants whose stems are not woody and whose above-ground part dies at the end of the growing season. The source of biomass is the deliberate cultivation of the so-called. "Flowers"—other plants not belonging to cereals, grasses, oily, root crops and legumes, collected every year as whole plants. The above information may therefore be encoded as: 2.1.6.1 with the species name given.

All analysed species are characterized by high yield of dry matter (cup plant—14.1; willowleaf sunflower—18.1; virginia fanpetals 13.3 Mg/ha), relatively low moisture content (except willowleaf sunflower). When analysing the parameters relevant from the energy utilization point, like specific density, ash content and gross calorific value, it can be seen that the highest density and calorific values were obtained for biomass form willowleaf sunflower (respectively 0.53 g/cm^3 and

18,221 J/g) in combination with the lowest ash content (2.3%). On the other hand the lowest density and calorific value were obtained cup plant (0.21 g/cm^3 and 17,324 J/g) with highest ash content (3.6%). The above relationships are fully confirmed by the calculated fuel quality index, which indicates that the best energy properties besides investigated spices has willowleaf sunflower (0.35) and the worst cup plant fanpetals (0.08). The mentioned index was determined for working moisture content 12% as a technological moisture level for the agglomeration process. In the case of determining the FVI for the biomass obtained after harvest, the obtained indicators (cup plant—0.04, willowleaf sunflower 0.11 and virginia fanpetals 0.07), despite the significantly higher moisture content of the sunflower, also promotes this type of biomass as having the best parameters among the tested species.

References

1. Lewandowski, W.: Proekologiczne odnawialne źródła energii. WNT, Warszawa (2007)
2. Robbinsa, M.P., Evansb, G., Valentinea, J., Donnisona, I.S., Allisona, G.G.: New opportunities for the exploitation of energy crops by thermochemical conversion in Northern Europe and the UK. Prog. Energy Combust. Sci. **38**, 138–155 (2012). https://doi.org/10.1016/j.pecs.2011.08.001
3. Gansberger, M., Montgomery, L.F.R., Liebhard, P.: Botanical characteristics, crop management and potential of *Silphium perfoliatum* L. as a renewable resource for biogas production. A review. Ind. Crops Prod. **63**, 362–372 (2015). https://doi.org/10.1016/j.indcrop.2014.09.047
4. Mayr, J., von Gehren, P., Gansberger, M., Hosch, H., Liebhard, P., Montgomery, L.F.R., Pachinger, B., Gautam, I.: The potential of the energy crop *Silphium perfoliatum* L. In: Proceedings of 23rd European Biomass Conference and Exhibition, Vienna, Austria, pp. 1831–1834, 1–4 June 2015
5. Nabel, M., Barbosa, D.B.P., Horsch, D., Jablonowski, N.D.: Energy crop (Sida hermaphrodita) fertilization using digestate under marginal soil conditions: a dose-response experiment. Energy Proc. **59**, 127–133 (2014). https://doi.org/10.1016/j.egypro.2014.10.358
6. Havrland, B., Ivanova, T., Lapczynska-Kordon, B., Kolarikova, M.: Comparative analysis of bio-raw materials and biofuels. In: Proceedings of 12th International Scientific Conference on Engineering for Rural Development, Jelgava, pp. 541–544 (2013)
7. Mudryk, K., Fraczek, J., Slipek, Z., Francik, S., Wrobel, M.: Chosen physico-mechanical properties of cutleaf coneflower (*Rudbeckia laciniata* L.) shoots. In: Proceedings of 12th International Scientific Conference on Engineering for Rural Development, Jelgava, pp. 658–662 (2013). http://tf.llu.lv/conference/proceedings2013/Papers/122_Mudryk_K.pdf
8. Maj, G., Kuranc, A.: Technologie produkcji oraz systemy certyfikacji jakości peletów z biomasy roślinnej. In: Piekarski, W. (ed.) Wybrane problemy z zakresu ekoenergii i środowiska, Monografia Naukowa "Towarzystwo Wydawnictw Naukowych LIBROPOLIS" Lublin. ISBN 978-83-63761-46-2 (2014)
9. Hejft, R.: Ciśnieniowa aglomeracja materiałów roślinnych. Wyd. i Zakład Poligrafii Instytutu Technologii Eksploatacji, Radom (2002)
10. Mani, S., Tabil, L., Sokhansanj, S.: Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenerg. **30**, 648–654 (2006)
11. Frączek, J., Mudryk, K., Wróbel, M.: Nakłady energetyczne w procesie brykietowania wierzby *Salix viminalis* L. Inżynieria Rolnicza **3**(121), 45–52 (2010)

12. PN-EN ISO 18134-3:2015-11. Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 3: Moisture in General Analysis Sample
13. PN-EN ISO 18134-1:2015-11. Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 1: Total Moisture—Reference Method
14. PN-EN ISO 18122:2016-01. Solid Biofuels—Determination of Ash Content
15. PN-EN 14918:2010. Solid Biofuels—Determination of Calorific Value
16. Klašnja, B., Orlović, S., Galić, Z.: Comparison of different wood species as raw materials for bioenergy. South-East Eur. For. **4**(2), 81–88 (2013)
17. Majtkowski, W.: Źródła biomasy do celów energetycznych. In: II Regionalne forum energetyki odnawialnej proceedings, Przysiek, pp. 49–55. ISBN 978-83-60164-08-2 (2006)
18. Kowalski, R., Wolski, T.: Evaluation of phenolic acid content in *Silphium perfoliatum* L. leaves, inflorescences and rhizomes. Electron. J. Pol. Agric. Univ. [online], Horticulture. **6**(1), #3 (2003). http://www.ejpau.media.pl/volume6/issue1/horticulture/art-03.html. Last accessed 12 Jun 2017
19. Piłat, J., Majtkowski, W., Majtkowska, G., Mikołajczak, J., Góralska, A.: Przydatność do zakiszania wybranych form gatunku roślin z rodzaju silphium. J. Cent. Eur. Agric. **8**(3), 363–368 (2007)
20. Kowalski, R.: Ocena zawartości oleanozydów w organach nadziemnych i podziemnych rożnika przerośniętego *Silphium perfoliatum* L. Acta Sci. Pol. Hortorum Cultus **1**(2), 5–15 (2002)
21. Jabłoński, B., Kołtowski, Z.: Nectar secretion and honey potential of honey-plants growing under Poland's conditions—part XV. J. Apic. Sci. **49**(1), 59–63 (2005)
22. Kołtowski, Z.: Wielki atlas roślin miododajnych. Przedsiębiorstwo Wydawnicze Rzeczpospolita S.A. ISBN 8360192138 (2006)
23. Majtkowski, W.: Potencjalny gatunek energetyczny. Sylfia z prerii. Agroenergetyka. **3**(17), 8–9 (2006)
24. Heiser, C.B., Smith, D.M., Clevenger, S., Martin, W.C.: The North American sunflowers (Helianthus). Mem. Torrey Bot. Club **22**(3) (1969)
25. PN-EN ISO 17225-1:2014-07. Solid Biofuels—Fuel Specifications and Classes—Part 1: General Requirements

Influence of Plant Biomass Added to Sewage Sludge on the Product Energy Potential

Krzysztof Gondek, Monika Mierzwa-Hersztek, Krzysztof Dziedzic, Marcin Jewiarz, Krzysztof Mudryk and Marek Wróbel

Abstract The authors of this study aimed at evaluating the influence of plant biomass added to sewage sludge on the product energy potential. In order to improve its physical properties, sewage sludge was mixed with wheat straw, sawdust, and bark of conifers. Materials with a natural water content were mixed at 1:1 weight ratio on a dry matter basis. The scheme of the experiment was as follows: sewage sludge without any additions (SS), sewage sludge + wheat straw (SS + WS), sewage sludge + sawdust (SS + S), sewage sludge + bark (SS + B). The moisture of materials, the contents of volatile matter, combined carbon, heat of combustion and calorific value were determined in the study. The addition of plant biomass to sewage sludge reduced the moisture content and increased the volatile matter content compared to sewage sludge without such addition, in which case the variation was relatively low. For the studied mixtures, larger variations were observed in relation to the ash and combined carbon contents. The highest contents of ash and combined carbon were found in the mixture of sewage sludge and bark. The highest value of heat of combustion was determined in the mixture of sewage sludge and sawdust (14,000 J g^{-1}). Calorific values of the mixture of sewage sludge and wheat straw and sewage sludge and bark were 13,640 J g^{-1} and

K. Gondek · M. Mierzwa-Hersztek
Department of Agricultural and Environmental Chemistry, University of Agriculture in Krakow, Al. Mickiewicza 21, 31-120 Krakow, Poland
e-mail: krzysztof.gondek@urk.edu.pl

M. Mierzwa-Hersztek
e-mail: m.mierzwa@ur.krakow.pl

K. Dziedzic · M. Jewiarz (✉) · K. Mudryk · M. Wróbel
Department of Mechanical Engineering and Agrophysics, University of Agriculture in Krakow, Balicka 120, 30-149 Krakow, Poland
e-mail: marcin.jewiarz@urk.edu.pl

K. Mudryk
e-mail: krzysztof.mudryk@urk.edu.pl

M. Wróbel
e-mail: marek.wrobel@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_67

11,540 J g^{-1}, respectively, and were higher by more than 40% on the average compared to the calorific value of sewage sludge without any additions.

Keywords Sewage sludge · Calorific value · Heat of combustion

1 Introduction

Increased efficiency of municipal waste water treatment systems results in the generation of greater amounts of sewage sludge. Sewage sludge management is an important issue in any modern municipal waste water treatment plant. Based on demographic forecasts, it is estimated that the amount of sewage sludge that will be produced in Poland in 2018 will increase from 612,800 to 706,600 Mg of dry matter in 2010 [1]. On-site storage and temporary warehousing of sewage sludge in treatment plants and its use for land reclamation, including for agricultural purposes, are less and less popular, while alternative methods of its transformation are sought. Methods of thermal transformation of sewage sludge starts to dominate both in Poland and in the world [2–4].

The type of sewage delivered to waste water treatment plants and the method of its treatment determine the physical and chemical properties of sewage sludge. The chemical composition of sewage sludge depends on the chemical composition of sewage sludge can contain a large variety of elements and compounds, including contaminants, such as heavy metals and dioxins, furans, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, as well as halogen derivative compounds. Energy properties of sewage sludge also depend on the type of sewage delivered to the treatment plant and on the process of sludge treatment [5]. The most important properties determining the energy potential of sewage sludge are: the content of dry matter, volatile matter, mineral substances, heat of combustion and calorific value; the elemental and chemical compositions of ashes are also of great importance.

The dry matter content or—in other words—hydration of sewage sludge appears to be a key parameter of sewage sludge hindering the energy use of this type of materials. That is why, in western European countries, such as Belgium, the Netherlands and Austria, sewage sludge is co-combusted with hard coal [6]. Mixing sewage sludge with plant waste is another approach and can also significantly reduce the hydration of these materials and improve the physical characteristics in the combustion process, which will encourage better energy efficiency [7]. Mixing sewage sludge with plant materials may also bring significant changes in leaching of, among others, heavy metals which, when released from organic compounds and accumulated in ashes, may pose a potential threat to individual links of the food chain [8]. According to Hong et al. [9] sewage sludge combustion can have a significant impact on the global warming potential (GWP).

The aim of this study was to evaluate the influence of plant biomass added to sewage sludge on the product energy potential.

2 Experimental Section

2.1 Material Sampling, Characterization, and Pretreatments

Sewage sludge used in the study came from municipal waste water treatment plant located in Krakow (southern Poland). The sewage sludge was stabilized before sampling. After initial concentration, the sludge was subjected to mechanical disintegration (cavitation at a sudden reduction of pressure), then it was redirected to biological reactors or to an intermediate tank. At this point, the sludge was put into separate fermentation chambers in which it was mixed with a stirrer and heated on heat exchangers. The sludge was fermented in separate chambers for 19 days. After fermentation, it was de-watered on a belt press.

Materials used as components for the preparation of sewage sludge mixtures were selected taking into account the ease of access as well as the efficiency of improving the physical properties of sewage sludge. Wheat straw used in the study came from a farmstead. Sawdust and bark of conifers were obtained as sawmill waste. Elemental composition of sewage sludge and waste plant materials is presented in Table 1.

In order to improve its physical properties, sewage sludge was mixed with plant materials. Before mixing with sewage sludge, wheat straw (WS) and bark of conifers (B) were shredded and 5 mm sieved. Sawdust of conifers (S) was used in a form in which it was obtained. Materials with a natural water content were mixed at 1:1 weight ratio on a dry matter basis. The scheme of the experiment was as follows: sewage sludge without any additions (SS), sewage sludge + wheat straw (SS + WS), sewage sludge + sawdust (SS + S), sewage sludge + bark (SS + B).

The characteristics of the chemical composition of plant feedstocks, sewage sludge and mixtures used in the study were presented in the article of Gondek et al. [10].

The materials were analyzed in order to evaluate the influence of plant biomass added to sewage sludge on the product energy potential. The energy potential of feedstocks and mixtures was studied after determining their elemental composition, moisture, the contents of volatile matter and combined carbon, heat of combustion

Table 1 The content of dry matter and N, C, H, S, O in plant materials and sewage sludge used in the experiment

Material	Dry matter	N	C	H	S	O
	$g\ kg^{-1}$	$g\ kg^{-1}$ DM				
WS	917	3.70	461	63.9	0.56	410
B	912	4.33	342	40.9	0.34	197
S	898	0.87	475	67.1	0.05	448
SS	260	30.2	185	40.3	22.9	209
SS + WS	471	27.6	441	34.7	13.0	483
SS + S	454	25.6	529	39.5	10.7	395
SS + B	582	21.9	316	24.6	8.93	629

and calorific value. Dry matter content in the materials was determined at 105 °C for 12 h [11]. Elemental composition (C, H, N, S) was determined in the samples using a CHNS Vario EL Cube analyzer manufactured by Elementar. Total O was derived by subtraction according to DIN 51733 method as follows:

$$\begin{aligned} \mathrm{O}\ (\%\mathrm{w/w}) = {} & 100 - \mathrm{ash}\ (\%\mathrm{w/w}) \\ & - \mathrm{C}\ (\%\mathrm{w/w}) - \mathrm{N}\ (\%\mathrm{w/w}) - \mathrm{H}\ (\%\mathrm{w/w}) - \mathrm{S}\ (\%\mathrm{w/w}) \end{aligned}$$

The ash content was determined according to PN-EN 14775:2010 method by calculation from the mass of the residue remaining after the sample was heated in air under rigidly controlled conditions of time, sample weight and equipment specifications to a controlled temperature of (550 ± 10) °C.

The volatile content was determined according to PN-EN 15148:2010 method. A test portion of the general analysis sample is heated out of contact with ambient air at (900 ± 10) °C for 7 min. The percentage of volatile matter is calculated from the loss in mass of the test portion after deducting the loss in mass due to moisture.

The calorific value was determined according to PN-EN 14918:2010 method. The above determination was performed on a sample with a mass of 1 ± 0.1 g placed in a bomb calorimeter in the form of a compressed pellet. Ignition of the sample was made using a cotton thread with a diameter of 0.1 mm embedded into the pellet. The calorific value was calculated by a computer program controlling the operation of the calorimeter.

3 Results and Discussion

3.1 Chemical Composition of Materials

Sewage sludge used in the study had a relatively low dry matter content compared to wheat straw, sawdust, and bark of conifers from which the mixtures were prepared. The addition of plant materials to sewage sludge was an important factor influencing the reduction of water content in sewage sludge [12] (Table 1).

Elemental composition of materials used in the study differed significantly (Table 1). The highest nitrogen and sulfur contents were found in sewage sludge. The addition of plant materials diluted both components in the mixtures. Different results were obtained for carbon in which case the addition of plant materials led to a significant increase in the C content in the mixtures compared to the content of this element in sewage sludge itself. Although the hydrogen content in plant materials was higher than in sewage sludge, no increase in the element content in the mixtures was noted. The oxygen content in sewage sludge and plant materials was varied. However, it should be noted that the addition of plant materials resulted in an increase of this element in the mixtures compared to sewage sludge.

3.2 Energy Potential of the Materials Used in the Study and of the Mixtures Prepared

The study showed that the addition of plant biomass to sewage sludge reduced the moisture content in the mixtures (Table 2). Compared to sewage sludge without any additions, the highest reduction of moisture content was determined in the mixture of sewage sludge and bark (SS + B). This is important information for evaluating the amount of energy needed to drain water from the fuel, the calorific value, and the content of ash generated [13]. As stated by Rulkens [14], the energy efficiency of sewage sludge combustion is strongly influenced by the level of dehydration of such materials.

The ash content was the highest in bark and it was due to the presence of mineral contaminants in the material during the woodworking process (Table 2). This also resulted in the highest content of this component in the mixture of sewage sludge and bark. Compared to other mixtures, the component content was higher by more than 50%, which could significantly affect the content of ash generated (fuel ballast) and its further disposal, and also significantly deteriorate the combustion process and raise the cost of energy production.

Volatile matter is one of the most important components of the fuel that determine the combustion process. The greater the content of volatiles in the fuel, the easier the ignition and the faster the combustion. Insufficient content of volatile matter results in the loss of stability of the combustion process. The addition of plant biomass to sewage sludge in the study increased the content of volatiles in the mixtures (Table 2). Compared to sewage sludge without any additions, the highest increase of volatile content was determined in the mixture of sewage sludge and sawdust. However, it should be noted that this was a lower value compared to that in the sawdust itself.

The addition of plant materials to sewage sludge increased the content of fixed carbon (Table 2). The highest fixed carbon content was found in the mixture of sewage sludge and bark. Regardless of the mixture, the fixed carbon content was

Table 2 Energy potential of plant biomass, sewage sludge, and mixtures

Material	Moisture	Ash	Volatile	Fixed carbon	Heat of combustion	Net calorific value
	M_{ar} [%]	A_d [%]	V_d [%]	C_{fd} [%]	$q_{V, gr}$ [J/g]	$q_{p, net, d}$ [J/g]
WS	7.50	3.95	79.2	16.9	17,560	17,560
B	5.30	44.0	42.2	13.8	12,050	11,880
S	6.80	0.98	84.6	14.4	18,580	18,480
SS	8.90	53.1	46.3	0.61	8810	8830
SS + WS	6.70	26.7	63.5	9.82	13,640	14,050
SS + S	7.80	24.8	66.0	9.21	14,000	14,530
SS + B	6.50	42.5	47.0	10.6	11,540	12,010

lower compared to that determined in plant materials used in the preparation of the mixtures.

The addition of plant biomass to sewage sludge had a significant effect on the heat of combustion in the analytical state of the mixtures prepared (Table 2). The highest heat of combustion value was observed for the mixture of sewage sludge and sawdust, i.e. the material with the lowest ash content and the highest volatile content among the mixtures prepared. However, it should be emphasized that although the heat of combustion of the mixtures prepared was higher than in the case of sewage sludge without any additions, the heat of combustion values were lower than these determined for wheat straw and sawdust. Also Manara and Zabaniotou [15] found that mixing sewage sludge with biomass improves fuel properties and increases the efficiency of the process. In addition, mixing sewage sludge with biomass dilutes toxic components.

The calorific values of plant biomass, sewage sludge and mixtures followed a similar trend compared to the heat of combustion. According to Bożym [13], the calorific value of sewage sludge is derived from the chemical composition and presence of volatiles. The addition of plant biomass to sewage sludge increased the organic matter content, resulting in an increase in the calorific value.

4 Conclusions

The addition of plant biomass to sewage sludge reduced the moisture content and increased the volatile matter content compared to sewage sludge without such addition, in which case the variation was relatively low. For the studied mixtures, larger variations were observed in relation to the ash and combined carbon contents. The highest contents of ash and combined carbon were found in the mixture of sewage sludge and bark. The highest value of heat of combustion was determined in the mixture of sewage sludge and sawdust (14,000 J g^{-1}). Calorific values of the mixture of sewage sludge and wheat straw and sewage sludge and bark were 13,640 and 11,540 J g^{-1}, respectively, and were higher by more than 40% on the average compared to the calorific value of sewage sludge without any additions.

Acknowledgements The Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Werle, S., Wilk, R.K.: A review of methods for the thermal utilization of sewage sludge: the Polish perspective. Renew. Energy **35**, 1914–1919 (2010)
2. Fytili, D., Zabaniotou, A.: Utilization of sewage sludge in EU application of old and new methods—a review. Renew. Sustain. Energy Rev. **12**, 116–140 (2008)

3. Kelessidis, A., Stasinakis, A.S.: Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Manag. **32**, 1186–1195 (2012)
4. Magdziarz, A., Werle, S.: Analysis of the combustion and pyrolysis of dried sewage sludge by TGA and MS. Waste Manag. **34**, 174–179 (2014)
5. Singh, R., Agrawal, M.: Potential benefits and risks of land application of sewage sludge. Waste Manag. **28**, 347–358 (2008)
6. Werther, J., Ogada, T.: Sewage sludge combustion. Prog. Energy Combust. Sci. **25**, 55–116 (1999)
7. Kubica, K., Jewiarz, M., Kubica, R., Szlęk, A.: Straw combustion: pilot and laboratory studies on a straw-fired grate boiler. Energy Fuels **30**, 4405–4410 (2016)
8. Hossain, M.K., Strezov, V., Chan, K.Y., Ziolkowski, A., Nelson, P.F.: Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. J. Environ. Manag. **92**, 223–228 (2011)
9. Hong, J., Hong, J., Otaki, M., Jolliet, O.: Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Manag. **29**, 696–703 (2009)
10. Gondek, K., Baran, A., Kopec, M.: The effect of low-temperature transformation of mixtures of sewage sludge and plant materials on content, leachability and toxicity of heavy metals. Chemosphere **117**, 33–39 (2014)
11. Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M.A., Sonoki, T.: Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences **11**, 6613–6621 (2014)
12. Kim, H.W., Han, S.K., Shin, H.S.: The optimisation of food waste addition as a co-substrate in anaerobic digestion of sewage sludge. Waste Manag. Res. **21**, 515–526 (2003)
13. Bozym M.: Wymagania jakosciowe stawiane osadom sciekowym spalanym w krajowych cementowniach. Chemik **67** (2013)
14. Rulkens, W.: Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options. Energy Fuels **22**, 9–15 (2007)
15. Manara, P., Zabaniotou, A.: Towards sewage sludge based biofuels via thermochemical conversion—a review. Renew. Sustain. Energy Rev. **16**, 2566–2582 (2012). https://doi.org/10.1016/j.rser.2012.01.074

Influence of Parameters of the Torrefaction Process on the Selected Parameters of Torrefied Woody Biomass

Marek Wróbel, Joanna Hamerska, Marcin Jewiarz, Krzysztof Mudryk and Marzena Niemczyk

Abstract The aim of this study was to determine the effect of time and temperature of torrefaction on selected parameters of torrefied woody biomass. The research material was willow and black locust biomass. First species representing the tree of soft wood and second is representative of hardwood trees. The selected species belong to a group of trees cultivated on energy purposes in so-called short rotation. The biomass samples were dried to a humidity of 10% and then was specified the calorific value, heat of combustion, specific density, ash content and volatiles matter. Characterized samples were subjected to torrefaction process in a special research reactor. In the study was planned the torrefaction temperature range 200–300 °C and the duration of the process in the range of 1–3 h which resulted in products of biomass torrefaction about the different degree of the carbonization, which were characterized by the same parameters as before biomass torrefaction.

Keywords Biomass · Energy crops · Torrefaction · Willow · Black locust

M. Wróbel (✉) · J. Hamerska · M. Jewiarz · K. Mudryk
Faculty of Production and Power Engineering, University of Agriculture in Krakow, Balicka 120, 30-149 Krakow, Poland
e-mail: marek.wrobel@ur.krakow.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

K. Mudryk
e-mail: krzysztof.mudryk@urk.edu.pl

M. Niemczyk
Department of Silviculture and Tree Genetics, Forest Research Institute, Braci Leśnej St. no 3, Sękocin Stary, 05-090 Raszyn, Poland
e-mail: m.niemczyk@ibles.waw.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_68

1 Introduction

Lignocellulose biomass, because of its chemical composition, is usually identified with wood derived biomass. According to definition this type covers all sources of biomass which contains lignin, cellulose and hemicellulose in a variety of proportions in the chemical composition [1]. Thus, this type of biomass can be defined as biomass of energy grasses or agricultural waste such as straw.

The level of cellulose in dry deciduous wood is in the range from 43 to 48%, whereas in coniferous from 53 to 54%. Share of hemicellulose is 15–35% and 20–32% respectively. The content of lignin varies between 18–25 and 25–35% [2, 3]. The basic elements that build the wood are carbon (50%), oxygen (44%), hydrogen (6%), nitrogen (0.04–0.3%); On a dry basis, the sulphur and nitrogen content (S + N < 0.3%) is small. The share of volatile components in wood is high and usually may reach to 70–85% of dry matter, and the fixed carbon is approximately 15–30% of dry matter [4]. Ash content in wood does not normally exceed 2% of dry matter, but the amount of mineral matter depends on the species of the tree and the plant part. There are no significant differences in the composition of elemental conifers and deciduous trees [5].

The variability of these parameters makes it possible to find methods of processing which in heterogeneous material is converted into a fuel with uniform parameters. One of the promising technologies is torrefaction which is the process of thermal processing of biomass for solid fuel so-called biocarbon that has properties similar to carbon and can be used not only energetically [6, 7]. The process temperature is usually in the range from 200 to 300 °C, in an anaerobic conditions, for example nitrogen, and at a pressure close to or equal to atmospheric pressure. The duration of the torrefaction depends on the conditions of the process and the expected properties of the product [8].

Mass and energy losses are the basic parameters that assess the quality of the torrefaction process. The amount of this losses is strongly dependent on time, process temperature and biomass type. Typically, at the end of the process, when the temperature is 290 °C, the reduction of sample mass with respect to the initial mass can be from 25 to 40% [9]. The energy loss associated with the volatilization does not normally exceed 10% for temperatures up to 250 °C and 15–20% for temperatures up to 300 °C [10].

During the thermal decomposition of biomass during torrefaction several by-products are obtained. The most common is to classify it according to state of matter [11]:

- solid—biocoal/biochar, ash, saccharides;
- liquid–water, lipid and organic structures (sugars, acids, alcohols, furans, ketones);
- gaseous—carbon oxide and dioxide, hydrogen, hydrocarbons, methane, benzene and other hydrocarbons.

In addition to water, the main products for the heating of biomass are CO, CO_2, CH_4 and organic structures that form joints—humid gas, whose use for process heat production is rather small [12]. In relation to untreated biomass a decrease in hydrogen and oxygen content is observed, with an increase in the carbon fraction [13]. Changes lead to lower O/C and H/C ratios, which makes torrefied biomass properties similar to carbon, both in terms of calorific value, composition, and flammability [14, 15].

Biomass after mild pyrolysis is completely dry and exhibits very limited hygroscopicity, which parameter is strictly connected with process temperature (with temperature above 500 °C the ability to absorb water increase) [16]. The hydrophobic nature of biocarbon limits the absorption of moisture and limits its biological degradation.

The aim of the study was to determine the influence of the torrefaction parameters (time, temperature) on the selected properties of the biocarbon obtained (moisture, combustion heat, ash content, specific density, volatile fraction) from of woody energetic plants (willow larvae, acacia). The first species is represented by softwood trees, while the second is a hardwood species.

2 Methodology

The test material was milled on a knife mill using a 16 mm diameter grinding mesh. In addition to the resulting material, a fraction <3.15 mm was set on the sieve ⌀ = 3.15 mm,

Measurements in most cases were based on the guidelines contained in the standards for solid biofuels:

- Determination of moisture content in analysed sample—PN-EN ISO 18134-3: 2015-11 [17];
- Determination of gross calorific value—PN-EN 14918: 2010 [18];
- Determination of ash content—PN-EN ISO 18122: 2016-01 [19];
- Determination of volatile matter content—PN EN ISO 18123: 2016-01 [20];

The specific density determination was performed with use of Micromeritics GeoPyc 1360 according manufacturer procedure. After determining the weight of the sample, the apparatus measures the volume of powder in the measuring cylinder. Then, after adding the sample to the cylinder, the apparatus measures how much the powder volume has increased after the sample has been added and on the basis of the weight of the sample and difference in volume determines the specific density of the sample.

The torrefaction process was carried out in a small scale batch reactor in the form of a closed cylindrical steel vessel (1) (Fig. 1). Outside the chamber, the heating jacket (2) was mounted to heat up the material inside. Inside the reactor was placed a container (3) for the material. Placing the sample in a smaller tank inside the

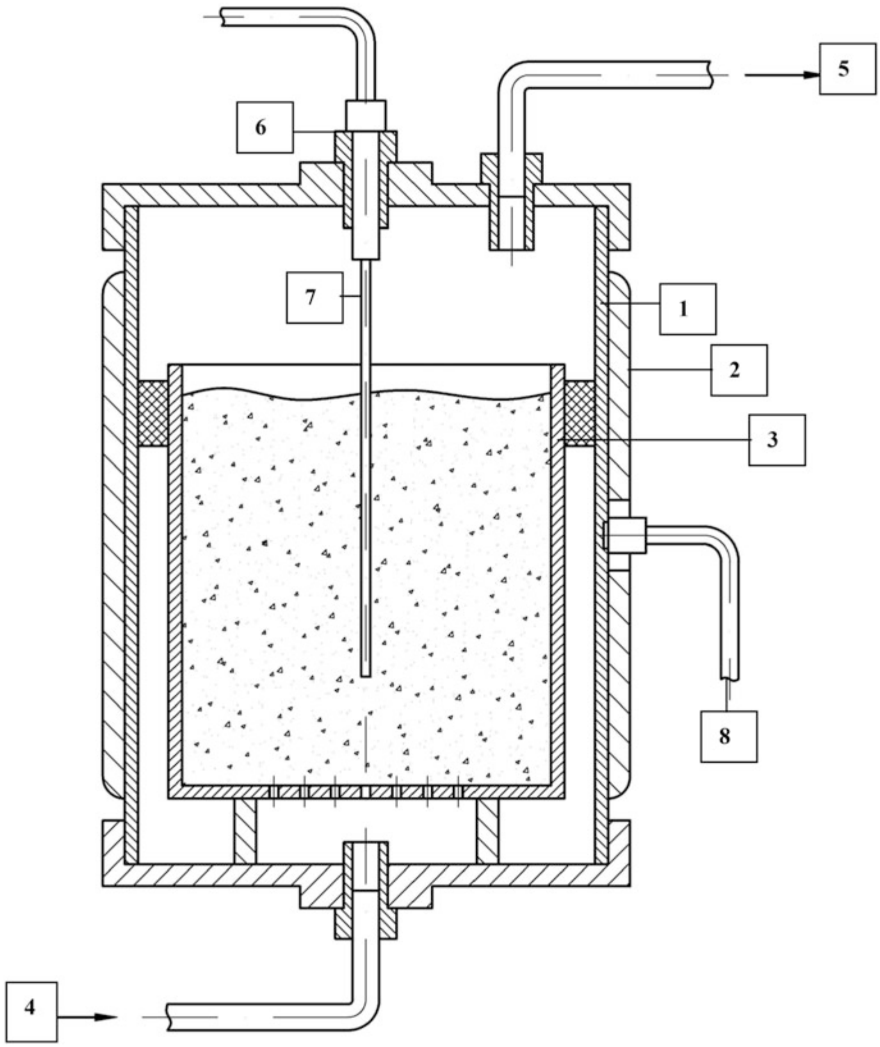


Fig. 1 Scheme of reactor. 1—outern steel chamber; 2—heating jacket; 3–internal vessel; 4—nitrogen stub pipe; 5—gaseous product outlet stub pipe; 6—thermocouple stub pipe; 7—K-type thermocouple; 8—PT-100 thermocouple

reactor was to avoid contact of the material with the reactor walls, which could cause excessive carbonation of the sample outside the vessel. At the bottom of the container were made holes through which nitrogen was introduced into the entire volume of the sample. Nitrogen was fed to the reactor through an intake manifold (4) placed in the bottom of the reactor chamber, the nitrogen volumetric flux was measured and regulated by a rotameter (0.5 l/min). In the upper lid there were two sub pipes through which the volatile products of the torrefaction process are

Fig. 2 Laboratory scale pyrolysis stand

discharged (5) and second for temperature measurements (6) for control purposes, with use of K-type thermocouple (7). A second thermocouple (8) was also placed on the side wall of the reactor, to determine outer surface temperature of the reactor to avoid overheating of the heating jacket.

Once the weight of the empty container was determined, the test material was loaded and re-weighed to determine the starting mass of the material. After the torrefaction process, the sample was weighed to check the weight loss. The view of laboratory stand is shown in Fig. 2. The measurements were made using the following process parameters:

- temperature range: 200–300 °C
- temperature variation: 50 °C
- time range: 1–3 h
- time variation: 1 h

Torrefaction times were measured from the moment in which chamber reached the process temperature.

3 Results

The raw material before torrefaction was analysed to asses fuel quality parameters. The results are presented in Table 1.

Presented values show that despite the fact that the studied biomass was obtained from species with hard and soft wood, the measured parameters differs slightly. The net calorific value, which for end consumers should be the most important

Table 1 Average values of proximate analysis of raw materials

Parameter	Willow	Black Locust
Moisture content M_{ad} (%)	5.14	5.84
Gross calorific value (dry state) $qv_{gr,d}$ (J g^{-1})	18,465	18,783
Specific density (dry state) SD_d (g cm^{-3})	0.579	0.552
Ash content (dry state) A_d (%)	1.58	1.94
Volatile matter content (dry state) V (%)	78.13	77.45

parameter in terms of using biomass for energy purposes, is higher in case of Black Locust (18,783 J/g^{-1}), in case of willow this parameter is only 300 J/g^{-1} lower. As shown in Table 1, more ash contains biomass obtained form—1.94%, with a willow of 1.58%. Therefore, despite the different qualification of the studied biomass (hard and soft wood), the parameters are characterized by a similar level. Therefore, the torrefaction process conducted at the assumed parameters will show whether the obtained biochars quality depends on the structure of the wood or are independent of them.

On Fig. 3 net calorific values are presented for biochars obtained in the different process conditions. Irrespective of the material, similar combustion heat values are obtained. At temperature 200 °C, regardless of the torrefaction time, the combustion heat is in the range 19,770–21,028 J/g, while for 300 °C the values are in the range 26,855–28,122 J/g. In another case, torrefaction at 250 °C, in this case, as well as the increase in process time, we also see an increase in the heating value of willow combustion from 22,380 to 23,688 J/g and for Black Locust from 22,928 to 25,939 J/g. At this temperature, decomposes two main building polymers—lignin (in the wide temperature range from 200 °C) and cellulose which starts to decompose in the range of 250 °C. Depending on their amount in the material this process will occur faster or slower, so the differences in the amount would be noticed in different final product parameters as well as in mass loss.

In Table 2 are collected values of the remaining parameters—particles density, ash and volatile matter content. Changes in these parameters show a typical course observed for biochars. The ash content increases as the process temperature rises, while the same case volatile matter content decreases. As it could be observed in all cases at temperature 250 °C, the changes depend on the torrefaction time. The obtained values of both parameters are similar for the tested materials. A slightly different trend has been observed for changes in the specific density of which the value decreases as the process temperature increases to 250 °C. On the other hand, at 300 °C, the value of specific density during torrefaction increases slightly during longer time processes. This is probably due to the fact that at this temperature the material no longer has volatiles and therefore there is no loss of mass, and as a result of carbonation the material begins to shrink, reducing the volume at the same mass results in an increase in the density of the specimens. The relatively small change in density of willow (0.516–0.343 g/cm^3) relative to Black Locust (0.552–0.311 g/cm^3) is also explained by shrinkage of the material. The willow that has

Table 2 Average values of physical properties of biochars formed during research

Material	Temperature t [°C]	Time T [h]	Solid density SD_d [g cm^{-3}]	Ash content A_d [%]	Volatile matter V_d [%]
Willow	Before torrefaction		0.579	1.58	78.13
	200	1	0.516	1.64	78.02
		2	0.513	1.86	76.32
		3	0.504	1.87	75.62
	250	1	0.463	2.41	68.99
		2	0.489	2.45	67.25
		3	0.421	2.57	61.87
	300	1	0.403	3.82	41.07
		2	0.411	3.87	40.28
		3	0.434	4.05	38.33
Black locust	Before torrefaction		0.552	1.94	77.45
	200	1	0.421	2.34	77.22
		2	0.411	2.12	76.14
		3	0.412	2.14	75.79
	250	1	0.403	2.65	68.52
		2	0.369	2.88	61.51
		3	0.333	3.25	50.31
	300	1	0.294	3.85	43.25
		2	0.299	4.14	42.02
		3	0.311	4.16	41.91

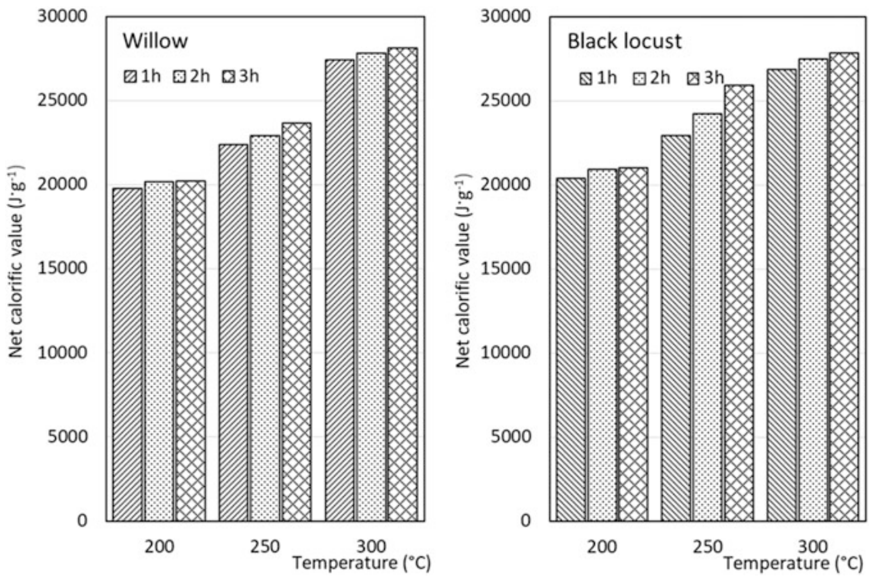


Fig. 3 Changes of gross calorific value according to process temperature, reaction time and material type

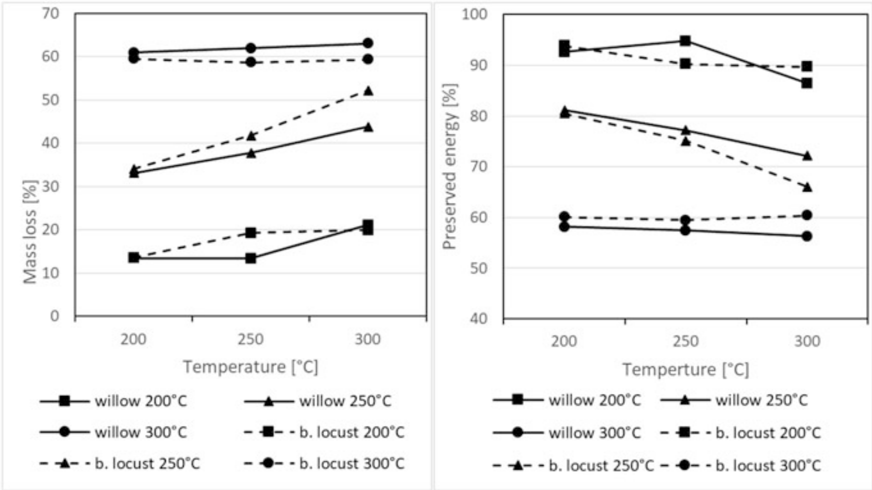


Fig. 4 Mass loss and raw energy preservation for biochars formed

soft wood, losing its volatiles at the same time shrinks, so the density change is negligible. In the case of hardwood Black Locust, the shrinkage is smaller and the weight loss caused by the release of volatiles results in a decrease in density.

During the studies the mass loss was establish for each sample and based on this value and net calorifica value contribution of the initial energy stored in the material to the energy stored in biochars was determined (Fig. 4). For a analysed conditions weight loss is respectively between 13 and 20% (for temperature 200 °C) up to 59–63% at 300 °C. With the loss of sample weights, the share of initial energy in the raw material decreases. Biochar produced at 200 °C retains from 86 to 94% of the initial energy amount. Conversely, product obtained at 300 °C (achieving high energy parameters) retains only 56–60% of the energy of the raw material, as the mass loss was significant.

4 Summary

Based on presented results, several conclusions can be made:

1. The analysed temperature levels are crucial for the quality parameters of produced biochars. This quantities are in relation gradual degradation of the biomass building polymers (lignine and cellulose) components at the consecutive temperature levels.
2. Residence time increase from 1 to 3 h at 200 and 300 °C, didn't cause noticeable changes in the measured parameters. Visible relation was obtained for temperature 250 °C, in which the value of the test parameter changes with

the increase of the torrefaction time. Such change can be due to the slow decomposition of lignin and the initial decomposition of cellulose.

3. The net calorific value for the tested biochars were for the willow ranged from 19,770 to 28,122 J g^{-1}, while in the case of black locust 20,380 to 27,855 J g^{-1}. The increase was directly proportional to the temperature, and in temperature 250 °C the slight increase with residence time could be observed.
4. The specific density of the biochars was lower than for raw materials, and decrease with temperature increase could be observed. The lowest value, 0.26 g/cm^3 was obtained for biochar from black locust in 300 °C. In contrast for the same process parameters, for the biochars form willow, specific density was 0,4 g/cm^3. Such difference was result of different shrinkage of the material during process (hard and soft wood).
5. The ash content in the presented materials was respectively in the range 2.34–4.68% for Black Locust and 1.64–4.05 for willow, and was increasing with the temperature. This is normal due to decomposition of the building polymers. According to that, volatile matter content was decreasing with temperature, for black locust it was ranged from 77.2 to 41.9% and for willow the decrease was higher form 78 to 38.3%.
6. Based on presented results, the most promising results, in case of energy production were obtained for process temperature 200 °C and 1 h residence time. For such parameters energy loss was below 10%, with noticeable increase in product parameters.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Bajpai, P.: Pretreatment of Lignocellulosic Biomass for Biofuel Production. Springer (2016)
2. Rybak, W.: Spalanie i współspalanie biopaliw stałych. ISBN 83-7085-938-0. Oficyna Wydawnicza Politechniki Wrocławskiej. Wrocław (2006)
3. Bergman, P.C.A., Prins, M.J., Boersma, A.R., Ptasinski, K.J., Kiel, J.H.A., Janssen, F.J.J.G.: Torrefaction for Entired—Flow Gasification of Biomass (2004). https://www.ecn.nl/publications//PdfFetch.aspx?nr=ECN-RX–04-046. Last accessed 12 May 2017
4. Kordylewski, W. (ed.): Spalanie i paliwa. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław (2008)
5. Ściążko, M., Zuwała, J., Pronobis, M.: Współspalanie biomasy i paliw alternatywnych w energetyce. ISBN 978-83-913434-3-2. Wydawnictwo IChPW i Politechniki Śląskiej, Gliwice (2008)
6. Latawiec, A.E., Królczyk, J.B., Kuboń, M., Szwedziak, K., Drosik, A., Polańczyk, E., Grotkiewicz, K., Strassburg, B.B.N.: Willingness to adopt biochar in agriculture: the producer's perspective. Sustainability **9**(4), 655 (2017). https://doi.org/10.3390/su9040655. PDF Version: http://www.mdpi.com/2071-1050/9/4/655/pdf

7. Latawiec, A.E., Peake, L., Baxter, H., Cornelissen, G., Grotkiewicz, K., Hale, S., Królczyk, J. B., Kubon, M., Łopatka, A., Medyńska-Juraszek, A., Reid, B., Siebielec, G., Sohi, S.P., Spiak, Z., Strassburg, B.B.N.: A reconnaissance-scale GIS-based multicriteria decision analysis to support sustainable biochar use: Poland as a case study. J. Environ. Eng. Landscape Manage. **25**(02), (2017). https://doi.org/10.3846/16486897.2017.1326924
8. Uslu, A.: Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Energy **33**(8), 1206–1223 (2008)
9. Prins, M.J., Ptasiński, K.J., Janssen, F.: Torrefaction of wood. Part 1. Weight loss kinetics. J. Anal. Appl. Pyrol. **77**(1), 35–40 (2006). https://doi.org/10.1016/j.jaap.2006.01.002
10. Kasparbauer, R.D.: The Effects of Biomass Pretreatments on the Products of Fast Pyrolysis (2009). http://lib.dr.iastate.edu/etd/10064. Last accessed 12 May 2017
11. Bergman, P.C.A.: Combined Torrefaction and Pelletisation: The TOP Process. ECN Publication. ECN-C-05-073 (2005). https://www.ecn.nl/docs/library/report/2005/c05073.pdf. Last accessed 12 May 2017
12. Yoder, J.: Economic tradeoff between biochar and bio-oil production via pyrolysis. Biomass Bioenergy **35**(5), 1851–1862 (2011)
13. Kiel, J.: Torrefaction for upgrading biomass into commodity fuel—status and ECN technology development. In: EUBIONET III Workshop Bioenergy and Forest Industry Proceedings (2011). ftp://ftp.ecn.nl/pub/www/library/report/2011/m11028.pdf. Last accessed 15 May 2017
14. Ścisłowska, M., Włodarczyk, R., Kobyłecki, R., Bis, Z.: Biochar to improve the quality and productivity of soils. J. Ecol. Eng. **16**(3), 31–35 (2015). https://doi.org/10.12911/22998993/2802
15. Prins, M.J., Ptasinski, K.J., Janssen, F.: Torrefaction of wood. Part 2. Analysis of products. J. Anal. Appl. Pyrol. **77**(1), 28–34 (2006). https://doi.org/10.1016/j.jaap.2006.01.001
16. Bergman, P.C., Kiel, J.H.: Torrefaction for biomass upgrading. In: 14th European Biomass Conference Proceedings, Paris, France (2005, October), pp. 17–21
17. PN-EN ISO 18134-3:2015-11 Solid biofuels. Determination of moisture content. Oven dry method. Part 3: Moisture in general analysis sample
18. PN-EN 14918:2010 Solid biofuels. Determination of calorific value
19. PN-EN ISO 18122:2016-01 Solid biofuels. Determination of ash content
20. PN-EN ISO 18123:2016-01. Solid fuels. Determination of volatile content by gravimetric method

Innovative Production Technology of High Quality Pellets for Power Plants

Krzysztof Mudryk, Marek Wróbel, Marcin Jewiarz, Grzegorz Pelczar and Arkadiusz Dyjakon

Abstract The paper presents the results of studies related to the development of quality pellet production technology for the power plants. Presented results shows that the addition of sulfur and kaolinite to the biomass does not significantly affect the basic quality parameters obtained from such pellet mixtures. There is a slight increase in ash value in these pellets, but this is directly related to the fact that kaolinite is a non-combustible mineral material. It has been shown that at the expense of increased ash content in the tested pellets, kaolinite addition virtually eliminates ash slag at all tested incineration temperatures. In the case of pellets from "pure" biomass, this unfavorable phenomenon has already occurred at 1000 °C. The results clearly show that independent of the amount of added sulfur (2 and 5%), the addition of 3% kaolinite effectively prevents ash from slagging in low temperature. Granulation of biomass, supplemented with additive to prevent slagging of ashes, should be regarded as effective and innovative technology of production of granular solid biofuels, which do not cause usual risk of boiler boiler heat exchange surfaces. This technology allows the generation of safe, solid biofuels from a wide range of biomass types available on the market.

Keywords Technical pellets ash slagging · Kaoline · Sulphur · Corrosion

K. Mudryk (✉) · M. Wróbel · M. Jewiarz
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 b, 30-149 Krakow, Poland
e-mail: krzysztof.mudryk@ur.krakow.pl

M. Wróbel
e-mail: marek.wrobel@ur.krakow.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

G. Pelczar
Nowy Projekt Grzegorz Pelczar, ul. Bronowicka 90, Krakow, Poland

A. Dyjakon
Wroclaw University of Environment and Life Sciences, Wroclaw, Poland
e-mail: arkadiusz.dyjakon@upwr.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_69

1 Introduction

One of the elements of the EU 3 × 20 energy policy is a 20% increase in the share of renewable energy in the member countries energy balance. Recent expected share of renewable energy in primary energy consumption should reach 15% in 2020. It is convinced that meeting this ambitious goals depends on the use of different types of solid biomass, i.e. the conversion of their chemical energy into electricity and heat. The problem, however, lies in the fact that the harvesting of wood and waste wood biomass can not grow at such a rate so far. It is a fact that so far, power plants and CHPs mainly use wood chips and pellets, and, to a lesser extent, sawdust, straw and waste from agriculture and the agro-food industry. At the same time, it is important to note that considerable quantities of firewood are burned in households. It is therefore necessary to successively substitute waste biomass from agricultural origin, i.e. from agricultural production or food industry, and from energy crops (which may, however, compete for food crops), as provided for by EU legislation. It is also a way to diversify sources and suppliers of energy, and use local energy resources, instead of fossil fuels (i.e. coal, liquid fuels and natural gas) and nuclear. Such policy should also directly result the creation of new jobs in local areas. Regular acquisition of large quantities of non-forest biomass creates a number difficulties specific for this type of fuels. It is important that biomass, usually has a relatively large share of chlorine, sulfur and alkaline elements (Ca, K, Na) in comparison with woody biomass, what have a negative impact on the operation of the boilers (potential risk of slagging of the heat exchange surfaces and chlorine or chloride corrosion). The utilisation of such biomass species or their co-combustion with coal in power plants could lead to not only a significant emission of nitrogen oxides and sulfur but also a gaseous product such as hydrogen chloride, and alkali metal chlorides which results in lower ash melting temperature [1, 2].

1.1 Sources of Chemical Corrosion in Biomass Thermal Treatment Installations

It is well known that the presence of chlorine, sulfur and alkali in the composition of biomass (especially Agro) is important in case of the energetic use of this materials. The sulfur content of the plants is directly related to the fertilization and the type (sulfur content) of the fertilizer [3]. Sulfur is a micronutrient essential for the growth and proper development of plants. Many fertilizers contain sulfur in the form of salts, e.g. sodium sulphate Na_2SO_4. Sulfur is present in plant material both in organic and inorganic form [4]. Some plants accumulate sulfur like rape. The sulfur content in plant biomass varies from 0.02 to 0.5%, rarely exceeding this value. The highest sulfur content is observed in rapeseed, olive pomace and cereal straw, and also in sea algae. The lowest sulfur content is the grains and bran of cereals, maize and sunflower husks. Especially a small amount of sulfur can be estimated for woody biomass. Sulfur present in biomass is released in the combustion process mainly in the form of sulfur oxides (generally SO_2) and promotes a high risk of corrosion of the boiler heat exchange elements, especially in the case of high alkali content in ash, forming potassium and sodium sulphate deposits. On the other hand chlorine is an element that is needed for plants only in small quantities and may even have toxic effects for them. Chlorine is most commonly found in biomass in the form of Cl-form, and also in small amounts in the form of chlororganic compounds [4]. In general, the chlorine content of biomass does not exceed 2% in dry matter, with the highest chlorine content being olive pomace, maize grain and straw. The smallest chlorine content is found in the pomace and rapeseed.

Alkali occurs in the biomass of its mineral substance. Generally, biomass contains much less ash than typical fossil fuels such as coal or lignite, but the chemical composition of ash from biomass is different from that from conventional solid fuels. Ashes from biomass contain more alkali metals than coal ash. A particularly significant issue in terms of energy use of biomass in combustion and co-burning processes is the relatively high content of sodium and potassium. Alkali metal compounds such as KCl and NaCl easily evaporate during combustion and can form deposits with high chlorine content, which causes high temperature corrosion of the surface of the heat exchanger [5]. The potassium is more harmful, which shows the ease with which to create low-melting eutectic sediments. The highest alkaline content (exceeding 20%) occurs in ash from grains and cereal shells, sunflowers and maize and rape, and in olive pomace. Slightly lower alkali content is characterized by wood biomass.

1.2 Chemical Corrosion in Power Boilers

Due to the different temperature distribution in the individual components of the boilers, high and low temperature corrosion can be distinguished. High temperature corrosion is chemical in nature. The main corrosive agents are flue gas components such as sulfur compounds, chlorine and CO as well as sediments on heat exchange that result from the deposition of particulates and droplets which form fly ash [6]. Due to the need to burn biomass fuels containing a high share of chlorine and alkaline compounds, the problem of high temperature corrosion has become an important aspect in the power plants design [7].

During combustion in the boiler biomass, sulphates and chloride corrosion is a significant threat. The sulphate corrosion occurs in the presence of alkali metals K and Na, which, in combination with sulfur, form sulphate Na_2SO_4 and K_2SO_4 deposits on the surface of the heat exchange surfaces. These compounds in the presence of SO_3 are converted to pyrosulphates and trisulphates with corrosive properties.

Alkali metal chlorides react with sulphites in the presence of sulfur. Due to the absence of water in the reaction medium, chlorine forms in the molecular form, the main cause of chloride corrosion. In the gas phase sulfate formation takes place in the presence of water, which results in the chlorine in the form of hydrogen chloride, and the resulting sulphates are deposited on the surfaces of the plant. However, due to the relatively high melting temperatures of sulphates formed, their effect is not as aggressive as chlorides. Although the melting temperatures of K and Na are high, their chlorides with other metals have a significantly lower melting point [8]. As a result, in the boilers in which chlorine, alkaline and heavy metals are combusted, the corrosion hazard already exists at 250 °C. In order to protect boiler heating surfaces against corrosive effects of biomass combustion and co-combustion, most commonly are used additives to neutralize the corrosive effect of KCl and reduce slagging of ash. Their choice depends on the degree of corrosion hazard, boiler type, process (combustion/co-combustion) and mostly economic reasons.

Deep research into corrosion processes led to formulation of corrosion hazard indicators. The author of one of them was Born [9] who took into account the chlorine and sulfur, and alkali share in the fuel. His approach has been used to formulate a fuel chlorine index (PWk) for biomass using: potassium share in ash as well as chlorine and sulfur in biomass, with notice that sulphur can be added with another fuel.

In the presented risk assessment approach, chemical corrosion is omitted from sodium whose carbon content can be significant but in biomass is negligible compared to potassium. The importance attributed to the contribution of chlorine, assuming that only for Cl < 0.02% PWk = 0, means no risk of corrosion.

In order to illustrate the use of the PWk indicator, several wood and straw biomass species were selected for which a corrosion hazard assessment was made (Table 1).

Table 1 Examples of chloride risk assessment for selected biomass

Type of biomass	Cl (%)	S (%)	K^1 (%)	S/Cl	PW_K	Risk of corrosion
Beech	<0.1	<0.05	8.6	Small	3	High
Oak	0	0.06	9.3	Big	1	V. low
Willow	0.01–0.05	0.02–0.2	23.6	Big	2	Low
Willow bark	0.01–0.05	0.02–0.1	–	Big	1	V. low
Eucalyptus bark	0.26	0.05	7.5	Small	3	High
Pine	0	0.01	10	Big	1	V. low
Wicker	0	0.03	22.5	Big	1	V. low
Sida	0.06	0.06	19.3	Small	3	High
Miscanthus	0.2	0.2	25.4	Small	4	V. high
Bogassa	0.02	0.03	18.9	Small	3	High
Wheat straw	0.1–1.2	0.05–0.2	32.2	Small	4	V. high
Oat straw	0.09	0.08	22.4	Small	4	V. high
Rape straw	0.1–1.2	0.05–0.8	34.4	Small	4	V. high
Grass	0.11	0.12	9.1	Small	3	High

If the fuel chlorine corrosion index PWk indicates corrosion hazard and steam temperature exceeds 420 °C, some steps should be taken to avoid possible corrosion effects. In this case we use term possible, because corrosion is phenomenon difficult to predict and extended over time.

In order to protect boiler heating surfaces against corrosive effects of combustion or co-firing of biomass, protective coatings and additives that neutralize corrosive KCl activity and reduce slag are used. The last one include:

- injection into the furnace of substances to neutralize the corrosive action of chlorine,
- adding to the fuel measures to counter the corrosive action of chlorine,
- injection into the furnace or add fuel reducing compounds to slag and prevent the sintering of the fluidised bed.

The choice of corrosion protection depends on: the degree of corrosion hazard caused by bio-mass combustion, the type and capacity of the boiler, the way biomass is burned (combustion, co-combustion) and economic considerations.

One of the more widespread and recognized methods is to feed furnace or to the fuel of such compounds that reacting with KCl will prevent it from depositing on superheater tubes. Sulphur compounds are most commonly used, which decompose sulphate-soluble SO_3, which decomposes in the furnace. It is also promising to use in limiting the corrosive and slagging effects of KCl aluminosilicates, e.g. kaolinite or halloysite, which act by binding potassium to potassium aluminosilicate.

Kaolinite and halloysite are classed as bilayered aluminosilicates and have the same chemical formula $Al_2Si_2O_5(OH)_4$. During heating, the water evaporates, reducing the distance between the individual lamellas (the main particles under construction) but does not eliminate it, causing the mineral surface to remain unchanged. During further heating at temperatures above 500 °C, water emanating from the crystalline structure is emitted to form metakaolinite or metahaloxide [10, 11].

It should be noticed that this transformation is beneficial from the reaction ability point of view, since the loss of OH groups results in formation of free bonds on the remaining oxygen and Si, Al and other substituted atoms, have strong affinity to many types of ion. The particular affinity can be observed in relation to potassium ions, which is caused by its size, which perfectly matches the cavity size on the outer surface of the grain. Heavy metal ions can also be found in these cavities. The new potassium aluminum silicon compounds produced are extremely stable and their melting point usually exceeds 1500 °C, which makes them virtually non-hazardous to virtually any type of power boiler.

Many studies have shown that potassium compounds at high temperatures react with metakaolinite, whereby the emission of HCl occurs. The amount of potassium actually associated with kaolinite depends on the reaction conditions, including:

- active surface of this mineral,
- dynamics of grain movement,
- the size and shape of kaolinite grains,

– the dynamics of biomass burning molecules,
– the place and method of supplementation of kaolinite,
– the quality of mixing biomass and kaolinite before and during combustion.

The widespread availability of kaolin and its physicochemical properties have made it one of the most commonly used additives for bio-mass combustion. Kaolin was given in various forms and in different places in the power installation. Numerous studies, e.g. [12–15] have shown that the addition of kaolin raises the temperature of agglomeration of fluidized bed grains and reduces the tendency of ash to slag. It was also found that as the amount of kaolin added to the combustion of straw biomass increased, the amount of potassium aluminosilicate in ash increased, while the amount of KCl and KOH was reduced, while the amount of free HCl increased, as demonstrated by the potassium retention in ash. Moreover, kaolin has been shown to have a positive effect on dust emission.

2 Investigation of Pellet Production Process

Based on experience in cooperation with the Połaniec Power Plant (Poland) in the supply of biomass for combustion in a fluidized bed boiler, there was recognized a need to produce an innovative pellet with additive. As in this facility kaolinite and sulphur were used as corrosion preventing additives, this to substances were taken into account, in setting specific composition of the mixtures. From the experience worked out in the Power Plant the addition of kaolinite (Fig. 1) should be in the range of 1–4% by weight based on the dry biomass. On the other hand sulphur (Fig. 1) content in the range of 0.5–3%. These assumptions were the basis for the laboratory research undertaken to develop an innovative product in the form of a functional pellet for the power industry.

Wheat straw as a typical agro biomass used in power industry was used as raw material in this research.

Fig. 1 Sample of sulphur S—99.9% (left) and kaolinite (right)

In the laboratory research wheat straw (SM) was used and additives: sulphur (S) in share 2 and 5% kaolinite (K) in share 3 and 5% from which 4 mixtures were proposed:

– P1 (SM 95%, S 2%, K 3%),
– P2 (SM 93%, S 2%, K 5%),
– P3 (SM 92%, S 5%, K 3%),
– P4 (SM100%)—control sample.

The pellets were produced using a semi-technical line MGL 200 produced by Kovo Novak with a capacity of up to 100 kg/h.

A ribbon mixer was used to unify the blends. The raw materials were mixed for 3 min (mass of 5 kg). The raw materials tested show a high susceptibility to mixing (no caking, delamination, etc.).

Obtained pellets of 8 mm diameter are characterized by typical biofuel quality parameters. The qualitative assessment showed that the values of the tested parameters (Table 2) fall within the permissible limits specified in the PN-EN ISO 17225 standard—Fuel specifications and classes—Part 1: General requirements.

The obtained values of the basic qualitative parameters of the samples showed that the proposed amounts of sulfur and kaolinite did not significantly affect energy parameters and physical properties such as mechanical strength, specific density and bulk density of pellets. The apparent increase in ash content was due to the kaolinite additive which is a mineral fraction.

According to the main objective of the work, which was neutralization of the chloride corrosion risk, samples were incinerated and an assessment of kaolinite interaction in the aspect of counteracting the formation of ash sinter during pellet combustion. This assessment consisted in determining the coefficient of sinterability and estimation of ash fusion temperatures.

The combustion of the samples were made in the laboratory furnace in three temperatures, 900, 1000 and 1100 which are most often temperatures in biomass boilers. The samples were placed in the furnace for 30 min. Attempts to incineration of the tested materials showed significant differences in properties of the ash obtained. In Figs. 2, 3 and 4, three samples of ash obtained from pellets without

Table 2 Results of qualitative research of obtained granulates

Composition of granules	Ash content [%]	Heat of combustion [MJ/kg]	Durability [%]	Solid density [kg/m^3]	Bulk density [kg/m^3]
P1 (SM 95%, S 2%, K 3%)	5.6 ± 0.02	17.75 ± 0.05	96.2 ± 0.28	1095 ± 26	624 ± 13
P2 (SM 93%, S 2%, K 5%)	7.2 ± 0.01	17.29 ± 0.06	96.8 ± 0.12	1114 ± 15	610 ± 15
P3 (SM 93%, S 5%, K 3%)	5.5 ± 0.01	17.50 ± 0.07	97.8 ± 0.32	1105 ± 21	635 ± 24
P4 (SM 100%)	2.6 ± 0.02	18.43 ± 0.07	97.8 ± 0.13	1072 ± 19	614 ± 18

Fig. 2 View of the sample ashes at 900 °C. From left samples with 0; 3 and 5% kaolinite content, sulfur content in all samples 2%

Fig. 3 View of the sample ashes at 1000 °C. From left samples with 0; 3 and 5% kaolinite content, sulfur content in all samples 2%

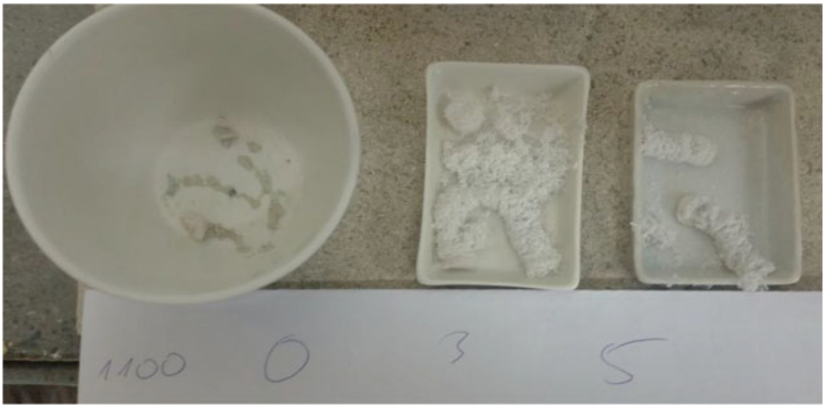


Fig. 4 View of the sample ashes at 1100 °C. From left samples with 0; 3 and 5% kaolinite content, sulfur content in all samples 2%

addition of kaolinite, with addition of 3 and 5% were added as samples (total sulfur in all samples was 2%).

With naked eye, it can be observed that regardless of the temperature, there is a clear difference between pure biomass ash and kaolin ash. As a result, temperatures of 900 °C in all variants did not cause sinter of the ash, but that from untreated biomass was little smaller with more greyish colour. In the case of samples incinerated at 1000 °C, it can be seen that the raw biomass sample is characterized by a small volume, whereas kaolinite-containing samples were characterized by loose, porous structure (particles of the material were burned and the remaining ash retained the shape of the crumbled straw fraction).

For samples incinerated at 1100 °C, full ash deterioration from the kaolinite sample may be observed. In the case of ash, after incineration of the samples in which kaolinite addition was 3 and 5%, it can be observed that the ash is characterized by a white colour and a highly porous structure formed from unmelted minerals that preserves the particle shape of the biomass material. The white colour of the kaoline supplemented pellets is caused by high content of this mineral.

The effects of kaoline on ash melting behaviour were evaluated by sieving the resulting ash through the #1 mm sieve. Based on the amount of residual weight on the sieve to the total weight of the ash, the ash melting index was determined. Basically it represents percentage of slag in the total weight of the resulting ash from the sample. During sieving, the sieve was put into an oscillating motion and additionally ash was distributed on the surface of the screen with a soft bristle brush. The results are shown in Table 3.

Another test aimed at determining the effect of the additives in agro biomass mix on the change of ash parameters was determination of ash fusion temperatures. This measurement was carried out at a specialist stand for ash melting tests in accordance with CEN/TS 15370-1 standard. The results are presented in Table 4 and in the graph (Fig. 5).

Table 3 The values of the ash melting index obtained for the tested granules

Composition of granules	Incineration temperature [°C]	Ash melting index [%]
P1 (SM 95%, S 2%, K 3%)	900	0
	1000	0
	1100	0
P2 (SM 93%, S 2%, K 5%)	900	0
	1000	0
	1100	0
P3 (SM 93%, S 5%, K 3%)	900	1.5
	1000	1
	1100	2
P4 (SM 100%)	900	37
	1000	97
	1100	100

Table 4 Characteristic melting temperatures of the ashes of the pellets tested

Type of pellets	T. of softening	T. of melting	T. of flow
P1 (SM 95%, S 2%, K 3%)	1160	1240	1330
P2 (SM 93%, S 2%, K 5%)	1220	1280	1410
P3 (SM 92%, S 5%, K 3%)	1190	1260	1360
P4 (SM 100%)—control sample	890	960	1180

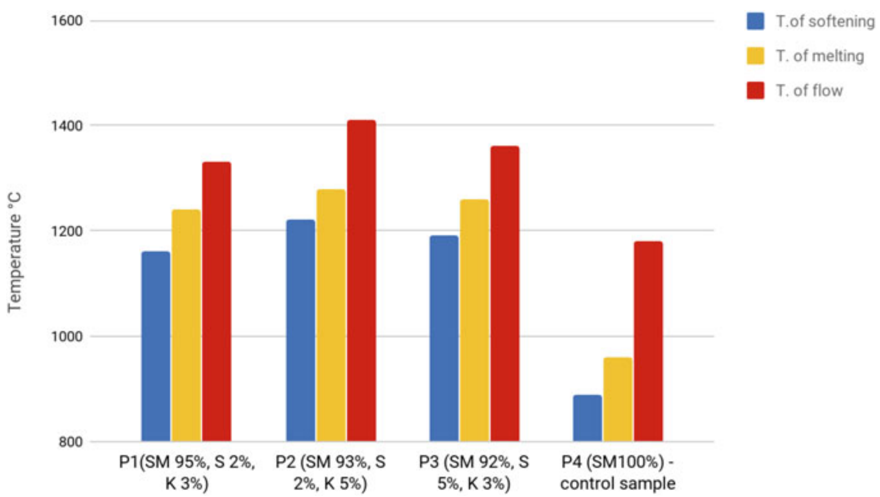


Fig. 5 Characteristics temperatures for ash from tested pellets

Analysis of the obtained results shows that the supplementation of agrobiomass pellets with kaoline increased the melting point of the ash, which is highly desirable. In addition, the added sulphur incorporated in the fuel mix will be able to react better with KC: during combustion, especially in fluidized bed furnaces. The final share of the additives need to be confirmed in industrial scale monitoring, based on biomass type.

3 Summary

The results of the studies show that the addition of kaoline and sulphur to the biomass doesn't significantly affect the quality parameters of produced pellets. There is a increase in ash content in these pellets, but this is directly related to the fact that kaolinite is a non-combustible mineral material.

It has been shown that the addition of kaolinite prevents of ash from slagging at all tested temperatures. In the case of pellets from "pure" biomass, this unfavorable phenomenon has already occurred at a temperature of 1000 °C. The results clearly show that regardless of the amount of added sulfur (2 and 5%), the addition of 3% kaolinite effectively prevents the ash fusion process.

Granulation of biomass, mixed with additive to prevent ash slagging, should be regarded as an effective and innovative technology for the production of granular solid biofuels that do not cause any risk of corrosion of boiler heating surfaces. This technology allows to produce safe, solid biofuels from a wide range of biomass types available on the market. Depending on the type of biomass, at the biofuel production site, additive biomass blends can be prepared in proportions determined on the basis of formulated experimentally verified formulas. Biomass enriched with additives in the form of pellets is delivered to the end user who no longer needs to choose the type and amount of additive, as composition of the fuel blends can be tuned-up to specific requirement of the final installation. What is also important, final blends can be supplemented with other additives.

Adding the additive throughout the volume of granules carries a number of problems: logistics is carried out with one transport stream, only one fuel storage and one fuel supply system is required for the boiler.

In addition, introduced additives work in the high temperature zone, significantly reducing the risk of slagging. The combustible part (biomass) and additives are dispensed with a uniform stream, there are no problems with the uniformity of fuel delivery and the corresponding additive quantities that are now fed into the combustion chamber separately.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Demirbas, A.: Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog. Energy Combust. Sci. **31**(2), 171–192 (2005)
2. Kuramochi, H., Wu, W., Kawamoto, K.: Prediction of the behaviors of H 2 S and HCl during gasification of selected residual biomass fuels by equilibrium calculation. Fuel **84**(4), 377–387 (2005)
3. Ściążko, M., Zuwała, J., Pronobis, M.: Zalety i wady współspalania biomasy w kotłach energetycznych na tle doświadczeń eksploatacyjnych pierwszego roku współspalania biomasy na skalę przemysłową, Energetyka i Ekologia, **2**, s. 207–220 (2006)
4. Król, D., Łach, J., Poskrobko, S.: O niektórych problemach związanych z wykorzystaniem biomasy nieleśnej w energetyce, Energetyka, **1**, s. 53–62 (2010)
5. Ściążko, M., Zuwała, J., Pronobis, M.: Współspalanie biomasy i paliw alternatywnych, Pr. zbior. pod. red., Wyd. IChPW i Politechniki Śl., Zabrze (2007)
6. Hardy, T., Kordylewski, W., Mościcki, K.: Zagrożenie korozją chlorkową w wyniku spalania i współspalania biomasy w kotłach, Archiwum Spalania, s. 181–195 (2009)
7. Pronobis, M.: Modernizacja kotłów energetycznych. WNT, Warszawa (2002)
8. Grabke, H.J., Reese, E., Spiegel, M.: The effect of chlorides, hydrogen chloride and sulfur dioxide in the oxidation of steels below deposits. Corros. Scie. **37**, 1023–1043 (1995)
9. Born, M.: Cause and risk evaluation for high-temperature chlorine corrosion. VGB PowerTech, No. 5 (2005), pp. 107–111
10. Bolewski, A.: Mineralogia szczegółowa. Wydawnictwa Geologiczne, Warszawa (1975)
11. Tran, K.Q., Iisa, K., Steenari, B.M., Lindqvist, O.: A kinetic study of gaseous alkali capture by kaolin in the fixed bed reactor equipped with an alkali detector. Fuel **84**, 169–175 (2005)
12. Öhman, M., Nordin, A.: The role of kaolin in prevention of bed agglomeration during fluidized bed combustion of biomass fuels. Energy Fuels **14**(3), 618–624 (2000)
13. Wei, X., Schnell, U., Hein, K.R.G.: Behaviour of gaseous chlorine and alkali metals during biomass thermal utilization. Fuel **84** (2005)
14. Boman, C., Bostrom, D., Ohman, M.: Effect of fuel additive sorbents (kaolin and calcite) on aerosol particle emission and characteristics during combustion of pelletized woody biomass. In: 16th European Biomass Conference & Exhibition, 2–6 June 2008, Valencia, Spain
15. Konsomboon, S., Pipatmanomai, S., Madhiyanon, T., Tia, S.: Effect of kaolin addition on ash characteristics of palm empty fruit bunch (EFB) upon combustion. Appl. Energy **88**, 298–305 (2011)

Energy Islands as a Potential Source of Securing the Energy Supply of Bio-Feedstock for Biogas Plants

Maciej Kuboń, Jakub Sikora, Elżbieta Olech and Anna Szeląg-Sikora

Abstract The aim of this study was to determine the possibility of building energy islands in the Małopolskie Voivodeship. Their primary source of energy would be the agricultural biogas plants. Such actions result from the necessity of limiting the use of conventional energy, as well as the interest in Renewable Energy Sources (RES), which leads to the search for alternative solutions. To some extent, such actions should secure both national and local energy management. One of the possible solutions includes biogas plants, which is mainly attributable to the raw material resources. The use of co-fermentation from different feedstock fractions increases the possibility of energy production, while reducing the amount of waste from the agri-food industry and the out-of-date food.

Keywords Energy island · Biogas plant · Potential · Security

1 Introduction

As well as merits, the development of civilization unfortunately has some flaws. Waste management and power industry are the areas that cover both economy and ecology [1]. The development of renewable energy is influenced by many factors. It results i.a. from the environmental policy aimed at the gradual reduction of greenhouse gases released into the atmosphere due to the use of traditional fossil fuels [2–3]. In addition to reducing gas emissions, new technologies for the

M. Kuboń (✉) · J. Sikora · E. Olech · A. Szeląg-Sikora
University of Agriculture in Krakow, 30-149 Krakow, Poland
e-mail: maciej.kubon@urk.edu.pl

J. Sikora
e-mail: jakub.sikora@ur.krakow.pl

E. Olech
e-mail: elaolech@gmail.com

A. Szeląg-Sikora
e-mail: aszelag4@o2.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_70

production of energy from renewable sources are currently being introduced. Obtaining renewable energy from biogas may be ideally combined with the proper management of materials. It is for this reason that many agricultural farms would be willing to invest in biogas recovery plants. Biogas production through anaerobic fermentation has increased significantly over the past few years [4, 5]. Biogas (especially agricultural biogas) has extensive resources of raw materials from which it can be obtained. Such materials include bio-waste of animal origin, products and bio-waste of plant origin, as well as of urban and industrial [6, 7] origin. The fact is that the produced biogas is an environmentally benign technology for bioenergy: the production and limiting the negative environmental impact must be rational. The professional sources list significant environmental burdens that should be avoided, but arise from various stages such as: the cultivation of crops, the supply of raw materials (transport), the products and the use of biogas, as well as the management of fermentation [8, 9]. Hence, the so-called energy islands, i.e. the energy-independent (local) systems, are implemented on an increasingly larger scale. They group together producers and consumers, can regulate—in real time—the energy produced and consumed within the system, as well as collaborate with other independent systems and local energy distributors [4, 9]. Such system should serve local organized consumer and producer groups in order to improve their energy security [10]. The main tasks of such islands should include: the optimal use of energy carriers and primary fuels, the use of local surplus energy and fuels, the impact on energy efficiency improvement, reducing the costs of energy requirements, reducing the costs of energy, environmental benefits, and providing more beneficial energy prices for consumers—it concerns not only electricity but also heating and cooling [11]. A huge number of tasks set for the islands prove the need for research and implementation of such projects in micro and macro-regions such as communes or districts.

2 Aim, Research Area and Methods

The Polish energy sector is based on hard and lignite coal. Electricity and heat produced from coal are the cheapest, while it is the electricity is produced in lignite-fired power plants that is the cheapest one. Burning coal, however, produces the highest CO_2 emissions per unit of generated energy. The progress and development of economy goes hand in hand with the necessity to develop the management of energy and the related energy security. According to the Act on Energy Law, such economic situation allows for covering the on-going and prospective demand of energy consumers in a technically and economically justified manner, taking into account environmental protection requirements [12]. Therefore, other alternative sources of energy and energy storage solutions are sought for, the example being the so-called energy islands. The basis for the operation of such energy islands may be agricultural biogas plants, provided that there is an adequate potential of bio-feedstock in the area in order to ensure its proper functioning.

The research was carried out in the area of the Małopolskie Voivodeship in order to verify the possibility of creating exemplary energy islands. It is the region with the lowest number of agricultural biogas plants.

The agricultural land in Małopolska region amounted to 4.4% on the national scale, and the sown area accounted for about 3.1% of the total domestic sown crops. The average area of farms in Małopolska region in 2011 amounted to 10 ha. According to the obtained data, the increase in the area of farms goes hand in hand with the change in the land use structure. The data presented by the Central Statistical Office of Poland shows that the number of sown crops has increased over the years [13]. Figure 1 below shows the structure of land use in Małopolska region in 2012.

The agricultural land in good condition accounted for the largest share, i.e. as much as 77.8%. The remaining share included woods and wooded land which constituted 12.7%. The area of Małopolska region is intensively cultivated except for the higher parts of the Carpathian Mountains. The cultivated land occupies about 58% of the area, including arable land which constitutes on average about 75% of the agricultural land [15].

The aim of this study was to identify a potential agglomeration of communes with biomass potential for methane fermentation which would be predisposed to the construction of the so-called energy islands. The agricultural biogas plants created within such communes could cover the energy demand in these areas. The scope coves all agricultural communes in the Małopolskie Voivodeship. The data on the analysed substance was obtained from the Local Data Bank of the Statistical Office in Cracow. Such data is derived from public statistics and shows what the situation looked like in 2010. The data on the sown area and livestock numbers was collected from the Common Agricultural Census, according to the type of farm at the level of a commune located in the Małopolskie Voivodeship, as well as the population of individual communes as of 31st December 2014. The sorted data was collected in the MS Office Excel spreadsheet where further calculations were performed: yield weight and the amount of waste from animal production. Next, the following

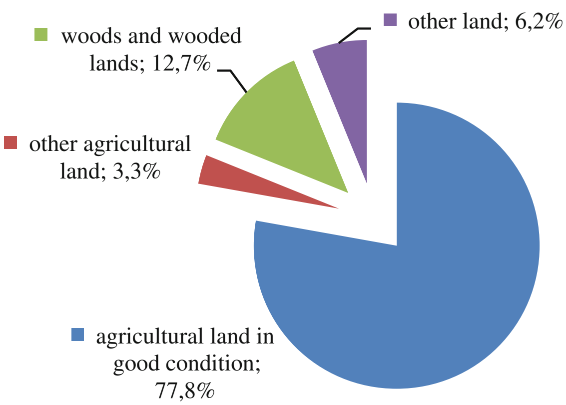


Fig. 1 The structure of land use in agricultural farms in 2012 in Małopolska region. *Source* Jonczyka [14]

factors were specified: the energy potential, the amount of biogas produced, the amount of electricity possible to be produced and the generated power. The Biogas Calculator was used to obtain information about the methane yield from the used fraction. The data obtained with the use of the said calculator is shown in Table 1.

The biogas output and yield from a given substrate is measured in standard cubic meters Nm^3 (dry gas volume in 1 m^3 at 1013.25 hPa, at the temperature of 0 °C) in relation to 3 different types of mass:

- fresh mass, unit: [Nm^3 (Mg *freshmass*)$^{-1}$],
- dry mass in: [Nm^3 (Mg dry mass)$^{-1}$],
- dry organic mass (DOM): [Nm^3 (Mg dry organic mass)$^{-1}$],

The following unit is used as well: [Nm^3 (ha)$^{-1}$] and it tells us how much biogas can be obtained from 1 ha of plant cultivation [16].

The next step was to calculate the nominal power of a generator in the cogeneration system. It is determined from the following formulas:

$$E_{el} = \frac{E_{tot} \cdot \eta_{el}}{T_p} [kW]$$

where:

E_{tot} total heat energy contained in fuel [kWh],
η_{el} efficiency of electrical energy processing [%],
T_p time of biogas input [h]

$$E_{tot} = V_{sub} \cdot Q_{bio} [kWh]$$

where:

V_{sub} biogas volume stream [m^3 (d)$^{-1}$],
Q_{bio} calorific value of biogas [kWh (m^3)$^{-1}$]

Table 1 Methane yield from selected organic fractions

Feedstock type	Annual substrate feedstock [Mg year^{-1}]	Annual methane production [m^3 year^{-1}]
Energy crops and agricultural waste		
Grain–silage	1	111.52
Corn–silage	1	94.11
Industrial crops–silage	1	167.55
Animal breeding waste		
Cattle manure	1	45.07
Pig manure	1	43.30

Source Own study based on Biogas Calculator of Mazowiecka Agencja Energetyczna

In order to obtain the total value of thermal energy contained in the fuel, the annual methane yield was divided into 365 days, which gave information about the daily yield.

$$V_{sub} = \frac{U_{CH4}}{365} \left[m^3 \cdot (d)^{-1}\right]$$

Then the calorific value of biogas equal to Q_{bio} = 6 kWh m^{-3} was adopted. For the purpose of the analysis, the results in kWh were converted to higher units, namely MWh. The energy value obtained in this way was multiplied by the electricity conversion efficiency of η_{el} = 39%. Finally, the obtained energy value was divided by the time (24 h), which gave the value of the system daily power in MW. On the basis of the obtained data and the performed analysis, the division into micro-biogas plants, small biogas plants and large biogas plants was obtained. The intention was to illustrate whether the potential available in communes gives the opportunity to build biogas plants within their area.

The next step was to develop spatial databases in the form of maps. ArcView 10.2.1 spatial database software was used for the data visualization.

3 Research Results and Discussion

The conducted analysis and data obtained from the Central Statistical Office of Poland allowed for the calculation of individual methane yield, as well as for estimating the amount of electricity that can be produced with the use of the generated biogas.

Livestock production gives a by-product in the form of animal excrements which vary according to the used maintenance technology. Liquid manure is produced in a litter-free animal raising system and is a mixture of urine and faeces with process water. Manure is fermented faeces and partially fermented urine and litter. Growing livestock production is causing an increase in the amount of manure stored on farms, which often exceeds their fertilizer demand. The individual methane yields were determined on the basis of the conducted studies and the comparison with the already carried out research provided in the bibliography [16, 3]. The possible yield of biogas, depending on the type of a natural fertilizer, is given in Table 2.

Besides corn, the grains used as a substrate for agricultural biogas plants include the ones with a by-product - straw. However, it is the GPS, i.e. the silage from whole grains, that is an unrivalled substrate. Table 3 shows yields obtained from different grain species.

Corn is the most commonly used substrate for co-fermentation. Corn (*Zea mays*), in comparison to other grain, is characterized by a higher yield of dry mass, higher efficiency of biogas plants and lower costs of cultivation. Moreover, the technology of cultivation, harvesting and silaging of this plant, as well as its storage, is well appreciated. The yield of biogas from silage is shown in Table 4.

Table 2 Yield of biogas from all kinds of livestock faeces

Substrates	Content of dry mass in fresh mass [%]	Content of DOM in fresh mass [%]	Biogas yield Nm^3 (*Mg freshmass*)$^{-1}$	Biogas yield Nm^3 (*Mg DOM*)$^{-1}$	Methane content in biogas [%]
Cow liquid manure	8–11	75–82	20–30	200–500	50–55
Calf liquid manure	10–13	80–84	20–25	220–560	50–57
Pig liquid manure	4–7	75–87	20–35	300–700	50–70
Sheep liquid manure	12–16	80–85	18–30	180–320	50–56
Cow manure	20–26	68–78	40–55	210–300	55–60
Pig manure	20–25	75–80	55–65	270–450	55–60
Chicken manure	60–80	70–85	80–140	260–400	55–65
Dry poultry litter	80–86	65–70	200–230	230–385	50–53
Fresh poultry litter	30–32	63–80	70–90	240–450	57–70

Source Myczko i in. [17]

As follows from the analysed aggregated data on the nominal power volume, the maximum number of group-specific biogas plants in the Małopolskie Voivodeship may be the following:

– micro biogas plants 2
– small biogas plants 6
– large biogas plants 175

Figure 2 shows 40 communes that have the greatest biogas potential in the Małopolskie Voivodeship based on the aggregate data for the analysed subgroups of substrates.

The calculated values included: the agricultural potential that could be used for biogas production and the possible installed capacity. The said calculations and ArcView software have been used used to develop maps that show spatial distribution of the agricultural bio-feedstock potential and places where it would be possible to build energy islands. Figure 3 shows the spatial deployment of biogas power generation potential in the communes.

The energy potential connected with agricultural biomass increases as we move on to the north of the Małopolskie Voivodeship. Spatial distribution of individual crops also shows the soil and climatic conditions of the examined area. It is therefore clear that mountainous areas are not suitable for growing crops for energy

Table 3 The yield of biogas, methane and electricity from different grain species

Grain	Dry mass [%]	Dry organic mass in dry mass [%]	Biogas yield Nm^3 $(Mg\ dry\ organic\ mass)^{-1}$	Methane content in biogas [%]	Methane yield $[Nm^3(Mg\ dry\ organic\ mass)^{-1}]$	Biogas yield $[Nm^3(Mg\ fresh\ mass)^{-1}]$	Methane yield $[Nm^3(Mg\ fresh\ mass)^{-1}]$	Production of electricity (Ee) $[kWh\ (Mg\ dry\ mass)^{-1}]$	Production of heat energy (Ec) $[kWh \cdot (Mg\ dry\ mass)^{-1}]$
Rye GPS (silage)	29.4	92.9	664	52.3	347	182	95	304	379
Wheat GPS (silage)	35.0	94.0	520	52.0	270	171	89	285	355
Wheat grain	86.6	98.0	764	48.0	367	649	312	989	1233
Grain seed average	86.0	98.0	700	53.0	371	597	316	1011	1261
Sorgo (silage)	22.0	91.0	538	54.0	285	108	58	186	270

Table 4 The yield of biogas and methane from corn

Substrate	Content of dry mass in fresh mass [%]	Content of dry organic mass in dry mass [%]	Biogas yield $\left[Nm^3 (Mg\,DOM)^{-1}\right]$	Content of methane in biogas [%]
Green forage made of corn	20–49.1	93.8–96.3	350–642	50–54
Corn silage	18–39.3	85–95.8	300–1130	47–69

Source Romaniuk and Domasiewicz [16]

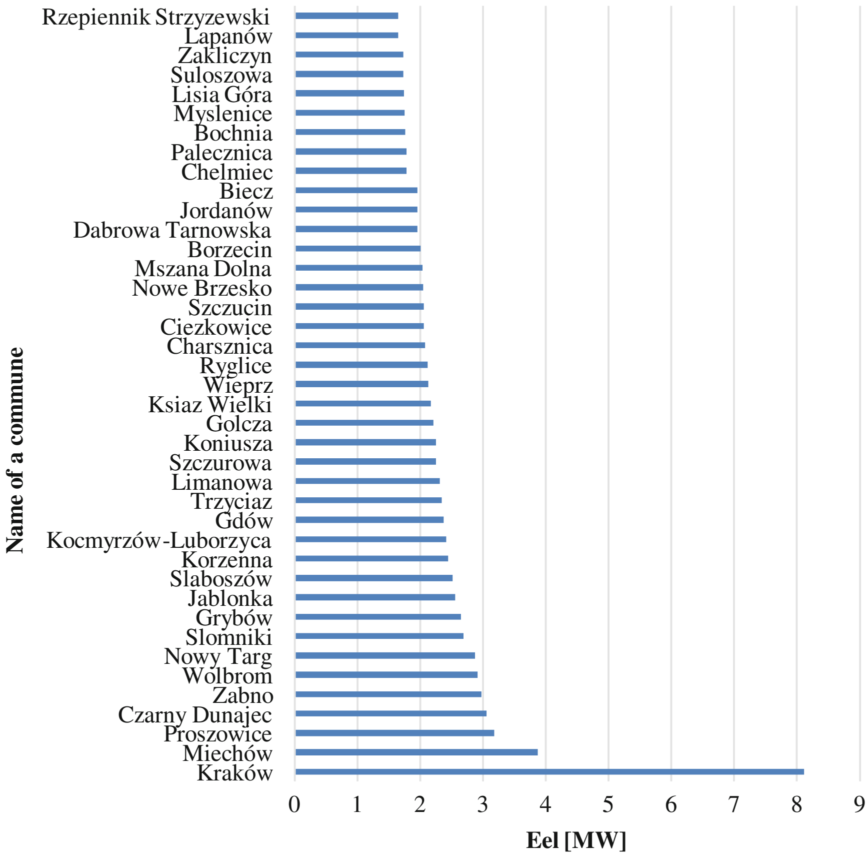


Fig. 2 Communes with the highest aggregate nominal power in the Małopolskie Voivodeship

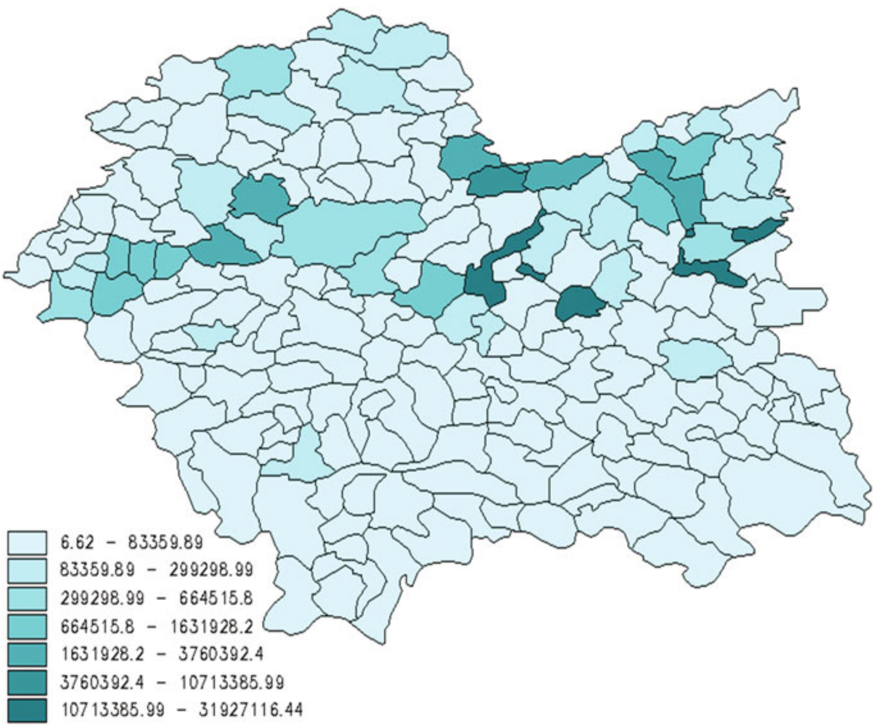


Fig. 3 Spatial distribution of potential to produce electricity [MWh] from agricultural biogas in communes within the Małopolskie Voivodeship

purposes. The raw material potential resulting from animal production (manure, liquid manure) is significantly higher in this area. These areas include farms with a significant land use structure. The amount of energy that can be obtained from the grain (assuming that 20% of such grain is used for energy consumption) and the biogas yield from animal waste at 100% utilization is in the range of 85,347–10,714,485 MWh. Lower boundary values have been obtained mainly form communes located in typically mountainous areas, including Szczawnica, Bukowno and Zakopane, while the upper limit for electricity potential includes communes adjacent to the districts of Dąbrowa, Cracow and Miechowice.

Figure 4 shows the spatial distribution of installed generator power that can be obtained in communes of the Małopolskie Voivodeship.

The analysis of spatial distribution of the potential installed kW generator capacity proves that the system is similar to the electricity potential. Communes with dominant possibility of obtaining high installed capacity are located in the northern part of the voivodeship within the districts of: Dąbrowa, Tarnów, Brzesko, Proszowice, Kraków, Wadowice. The installed generator capacity in this area exceeds 11,000 kW.

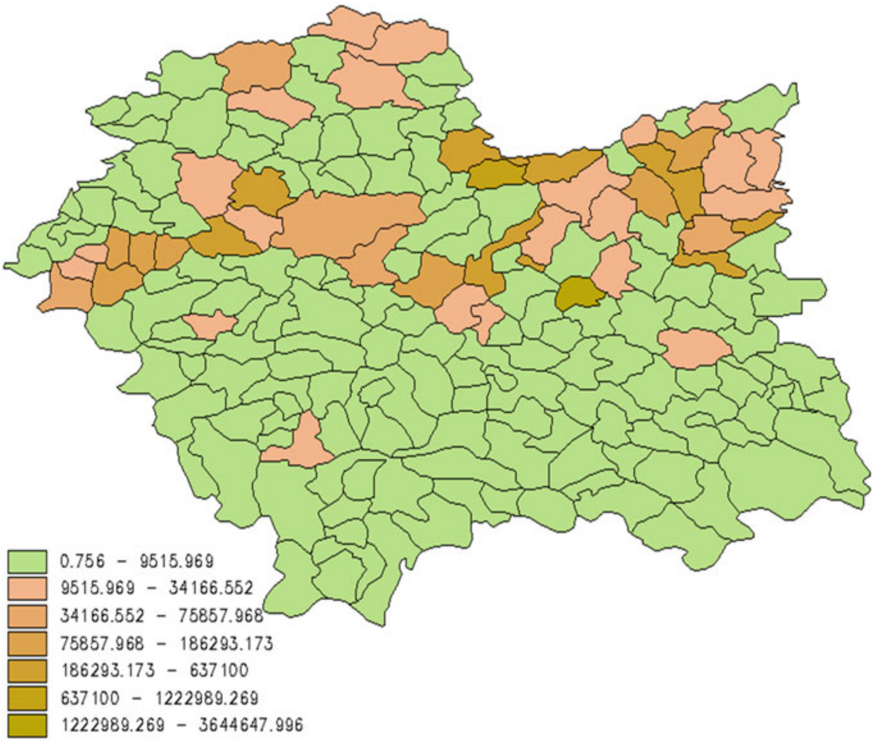


Fig. 4 Spatial distribution of the installed generator capacity [kW] in communes of the Małopolskie Voivodeship

4 Summary

Implementing renewable energy sources, including agricultural biogas plants, is one way of protecting the natural environment and saving fossil fuels with finite resources. Moreover, apart from the benefits such as electricity or heat, the introduction of biogas plants is used for managing agricultural waste, while the waste produced during methanogenesis can be used as a rich organic fertilizer or reused in the next methanogenic cycle. The conducted research and analysis proved that the Małopolskie Voivodeship has the potential of agricultural origin substrates for the construction of biogas plants. Assuming that the use of crops for energy purposes will be at the level of 20% of the yield and 100% of animal production waste, the most favourable conditions are in the northern part of the voivodeship. The situation is similar in the case of a generator in a cogeneration system—the areas within the mountainous range show a low potential for building biogas plants. The analysis of the possible nominal power and the amount of electricity from a cogeneration shows that it is worth making further analyses and calculations for the northern communes of the districts of: Dąbrowa, Tarnów, Brzesko, Proszowice, Cracow and Wadowice in order to determine the location of an energy island that would supply a given area.

References

1. Ministry of Agriculture and Rural Development, Agricultural biogas plants in Poland www.minrol.gov.pl/. Access 22 June 2017
2. Meschede H., Holzapfel P., et al.: Classification of global island regarding the opportunity of using RES. Appl. Energy **175**, 251–258 (2016)
3. Angelidaki, I., et al.: Environmental Biotechnology. AD – Biogas Production. Environment & Resources DTU, Technical University of Denmark (2004)
4. Valenti F., Porto S. et al.: Use of citrus pulp for biogas production: a GIS analysis of citrus-growing areas and processing industries in South Italy. Land Use Policy **66**, 151–161 (2017)
5. Meyer A., Raju C. et al.: The energy balance of utilising meadow grass in Danish biogas production. Resour. Conserv. Recycl. **104**, 265–275 (2015)
6. Appel, F., Ostetmeyer-Wiethaup, A.: Effects of the German Renewable Energy Act on structural change in agriculture - The case of biogas. Util. Policy **41**, 172–182 (2016)
7. Niemiec, M, Sikora J., Szeląg-Sikora, A., Kuboń, M.: Przydatność odpadów organicznych z przemysłu spożywczego w procesie fermentacji metanowej. Przemysł chemiczny (3), 685–688 (marzec 2017)
8. Poeschl, M., Ward, S., Owende, P.: Environmental impacts of biogas deployment—Part II: life cycle assessment of multiple production and utilization pathways. J. Clean. Prod. **24**, 184–201 (2012)
9. Lijó, L., Lorenzo-Toja, Y.: Eco-efficiency assessment of farm-scaled biogas plants. Biores. Technol. **237**, 146–155 (2017)
10. Sikora, J., Niemiec, M., Szeląg-Sikora, A., Cupiał, M., Klimas, A.: Utilization of post-ferment from co-fermentation methane for energy purposes. Ecol. Chem. Eng. A **23**(2) (2016)
11. Bernal A., Silva dos Santos I.: Vinasse biogas for energy generation in Brazil: an assessment of economic feasibility, energy potential and avoided CO_2 emissions. J. Cleaner Prod. **151**, 260e271 (2017)
12. Ustawa z dnia 10 kwietnia 1997 r. - Prawo energetyczne. Dz.U. 1997 nr 54 poz. 348
13. Czarnecka, L., i in.: Environmental report for the Małopolskie Voivodeship in 2012 – waste management, the Voivodeship Inspectorate of Environmental Protection (2013)
14. Czarnecka i in. 2013 Raport o stanie srodowiska w województwie małopolskim w 2012 roku - Gospodarowanie odpadami, WIOS
15. Królczyk, Jolanta B., Latawiec, Agnieszka E., Kuboń, Maciej: Sustainable agriculture—the potential to increase wheat and rapeseed yields in Poland. Pol. J. Environ. Stud. **23**(3), 663–672 (2014)
16. Romaniuk W., Domasiewicz T.: Substrates for biogas plants in Poland, Wydawnictwo Hortpress Sp. z o.o (2014)
17. Myczko, A., i in.: Budowa i Eksploatacja Biogazowni Rolniczych, Wydawnictwo Instytutu Technologiczno-Przyrodniczego (2011)

Analysis of the Combustion Process of Selected Wood Biomass

Szymon Głowacki, Weronika Tulej, Mariusz Sojak, Andrzej Bryś, Jakub Kaczmarczyk, Marek Wróbel, Marcin Jewiarz and Krzysztof Mudryk

Abstract Combustion process of selected woody biomass was investigated. Four types of woody material were used for conducted experiments: poplar, pine, acacia and willow. European Union policy concerning Renewable Energy Resources (RE) is a response to increasing pollution of our globe, and, simultaneously, it introduces additional, independent supplies of energy. With the introduction of legal obligations that regulate these norms, countries that did not have appropriate percentage share of renewable energy had to comply with these regulations by implementing appropriate projects that would allow for supplies of renewable energy shortly. The work presents ecological aspect of selected materials, by showing differences in fuels obtained from woody biomass used in the experiments. It was analyzed the ash and volatile matter content and also calorific value. The experiments also show, which dendromass has the best energetics parameters, and which produces the least pollution. Poplar had the highest net calorific value

S. Głowacki · W. Tulej · M. Sojak · A. Bryś · J. Kaczmarczyk
Department of Fundamental Engineering, Faculty of Production Engineering, Warsaw University of Life Sciences—SGGW, Nowoursynowska 164, 02-787 Warsaw, Poland
e-mail: szymon_glowacki@sggw.pl

W. Tulej
e-mail: weronikabazylak@gmail.com

M. Sojak
e-mail: mariusz_sojak@sggw.pl

A. Bryś
e-mail: andrzej_brys@sggw.pl

M. Wróbel (✉) · M. Jewiarz · K. Mudryk
Faculty of Production and Power Engineering, University of Agriculture in Krakow, 120 Balicka Street, 30-149 Krakow, Poland
e-mail: marek.wrobel@urk.edu.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

K. Mudryk
e-mail: krzysztof.mudryk@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_71

(18,633 J/g), but during poplar combustion, the highest concentration of carbon oxides and nitrogen oxides was found.

Keywords Biomass · Dendromass · Fume · Calorific value

1 Introduction

Wood is one of the oldest materials used by man. It has various uses, which, basically, may be divided into two categories, namely, wood may be used for production and for energy-related purposes. The first category involves, i.a. building or furniture industry, and the second category—combustion and all related processes, i.e. gasification, pyrolysis [1], etc. Energy may be obtained according to the rule of sustainable forest management. Conducted experiments confirm huge potential of waste wood biomass, as renewable energy resource [2, 3]. At present, energy derived from biomass must be considered both in the ecological and economic context, which requires the integration of social, environmental and industrial sphere [4]. Supporting the development of renewable energy resources is an important goal for the European Union [1, 5]. It is estimated that in EU countries, biomass may constitute approx. 2/3 of the declared share of renewable energy in 2020 [6].

Woody biomass, also called dendromass, is organic substance derived from woody plants and bushes. It consists of wood, bark, and green mass—branches and conifer needles (coniferous trees) or leaves (deciduous trees). Dry biomass is composed of the following basic elements: C—carbon (48–51%), H—hydrogen (6–7%), N—nitrogen (0.01–3%), O—oxygen (42–45%). Despite the changeability in different parts of the tree, the composition of phytogenic components of individual trees is similar. Inorganic substances such as ash make up 0.4–0.7%, while their share in bark is higher and amounts to 1–1.5%. Building elements in the organic mass of trees are organized as polymer substances such as cellulose, lignin, hemicellulose, and adventive substances. Solid dendromass fuel consists of combustible material which is the most important, as it is responsible for energy supply in the process of oxidization of fuel during combustion, and simultaneous release of heat [7, 8].

During combustion of dendromass, fuel ballast phenomenon occurs. It is undesirable effect during combustion, and it is formed from ash and water present in the fuel. Wood biomass, compared with other solid fuels has a very low fuel ballast percentage coefficient. However, its negative property is bonding with water. Therefore, the fuel must be dried prior to combustion [9–11].

In terms of energy efficiency of dendromass combustion, the most important fact, taken into consideration is heat of combustion and heat value. Heat of combustion is the heat released during full combustion of fuel, with simultaneous cooling of the temperature of the combustion gas, where steam condensates, while heat value is the heat released during full combustion of fuel, with simultaneous cooling of the combustion gas to the ambient temperature, where water that formed during evaporation stays in gaseous state. Concluding, heat value is heat of combustion minus heat of water evaporation [12].

Increased use of energy plants as fuel will contribute to solving numerous ecological problems. Plant biomass decreases environmental pollution with harmful substances [13].

The work's goal was to determine the difference in combustion quality of selected materials using specialist equipment. The scope comprised specifying the calorific value (heat value) of the samples, volatile parts, ash content, and detailed analysis of combustion gas. The conducted experiments allow to determine, which of the tested wood biomass type is the best in energetic and ecological terms.

2 Experimental Section

Four types of material were used for experiments: poplar, pine, acacia and willow. All the materials were dried in a tunnel dryer at the temperature of 60 °C, and reached the moisture content (M_{ad}) of approx. 7%.

Another aspect considered in the research was the ecological aspect, which required verification of samples using fumes analyzer.

All laboratory analysis was conducted in according to the norm. Samples were prepared according to the PN-EN ISO 14780:2017-07 [14] standard requirements. Test sample was milling in IKA A11 basic analytical mill. The milling was repeated until all grains were smaller than 1 mm.

The moisture content (M_{ad}) in as analysed state (air dry) was determined according to the PN-EN ISO 18134-3:2015-11 [15] standard. In this analysis laboratory dryer (SLN 160, POLEKO) was used. The procedure rely on drying of small amount of the material (1 ± 0.05 g) in air at 105 °C. The moisture content was determined according to difference in sample weight before and after drying [15].

The ash content (A) was determined according to the PN-EN ISO 18122:2016-01 [16] standard from the mass of the residue remaining after the sample was combusted in the furnace (SNOL 3/1100) in air under strictly controlled time and temperature. First, the samples were heated for 1 h in 250 °C, then the temperature was increased up to 550 °C and the samples were kept in this temperature for next 2 h. After cooling down the samples to the ambient temperature, the remained ash was weighed and the calculations according to the formula presented in standard [16] were done.

The volatile matter content (V) was determined according to the method based on the PN-EN 15148:2010 standard [17]. A test portion (1 ± 0.05 g) of each sample was heated in combustion crucible with a lid, for 7 min at 910 ± 10 °C. The percentage of volatile matter was calculated based on the loss in mass of the test portion after deducting the loss in mass due to moisture [17].

The gross calorific value (higher heating value, HHV) was determined according to the method based on the PN-EN 14918:2010 standard [18]. It was performed for samples of 1 ± 0.05 g placed in an isoperibol calorimeter (C 6000 Isoperibol, IKA). Each sample was combusted as compressed pellets, in the calorimetric bomb, in pure oxygen and high pressure. The calorific value was calculated following the equations described in the standard [18] which were implemented to the device operating software. The net calorific value (lower heating value, LHV) was calculated from the relation in which gross calorific value is reduced by value equal to heat utilized for vaporization of water, obtained from the fuel in the combustion of hydrogen and moisture content in the sample. This parameter was calculated using the controlling operation software of the calorimeter following the equations presented in the standard [18].

Analyser of fumes, Testo 300-B and an ordinary standalone furnace were used. The analyser was connected to a personal computer, which recorded the results. The probe of the analyser was inserted in the chimney of the furnace. It was decided to make approx. 50 g samples, which were then combusted. The analyser was turned on, and when one sample was combusted, another 50 g sample was put in the furnace. In this way, a set of data was obtained, which were then processed in order to obtain the required data related to gaseous products. Based on the selected data, graphs that show differences in the content of volatile products were generated.

3 Results

The experiments were conducted using the laboratory equipment mentioned above. This allowed to determine such parameters of dendromass as: calorific value, volatile matter, ash (Table 1), and gaseous products during combustion.

The obtained results indicate that poplar has the highest calorific value (provides the most heat), followed by pine (with similar calorific value). It seems that pine should have much higher heat value than poplar as it is a coniferous tree, and contains a lot of resin, extremely flammable material. Additionally, after removal of crucibles from the furnace, it was visible that crucibles used for combustion of pine had most residues. It is caused by the resin, which, during the process of combustion, releases greasy soot, and deposits inside the crucible. Willow and acacia have similar heat values, with the difference only amounting to a dozen or so megajoules.

Table 1 Parameters of dendromass

Material	Gross calorific value HHV [J/g]	Net calorific value LHV [J/g]	Volatile content V [%]	Ash content A [%]
Poplar	19,581	18,633	85.6	0.47
Pine	19,452	18,534	84.5	0.46
Acacia	18,896	17,978	85.8	0.63
Willow	18,928	18,010	85.1	1.19

During the experiments, for volatile matter extremely interesting results were obtained. These results indicate that the values of this parameter of dendromass reach approx. 85%. All materials assume similar values, and the percentage difference is small. Such a high value may be attributed to very low moisture content of the materials.

The results of measurement of ash content were similar to those presented in literature. Poplar and pine had the lowest content of ash among the examined materials, amounting to approx. 0.47%, while willow had the highest content of ash. Such low content of ash results in low emission of dust (approx. 20 times lower than in the case of coal).

During combustion of different substances, various products are released, including gases. During combustion of biomass, the most important side product of this process is carbon oxide (CO) in a gaseous form; other products include hydrocarbons (CH), nitrogen oxides (NOx), and sulphur oxides (SO). Carbon oxides are inorganic compounds, which consist of carbon and oxygen. Carbon monoxide is a side product of combustion process, and is colourless, odorless and lighter than air. It is often a cause of gas poisonings, which may lead to death (in large quantities) [19]. The results of the conducted experiments show that of all compounds, CO amount was the highest.

Figure 1 shows a graph presenting stages of biomass combustion. In the measured period kindling of biomass takes place within 45 s, characterized by high concentration of CO. Kindling biomass chokes itself, which causes release of large amounts of CO. The next stage is proper combustion, where appropriate flame forms, burning the sample, and supplying energy in the form of heat. This period lasts from 45th to 420th second. This period is characterized by sharp decrease in CO concentration, and increase in oxygen concentration. The last stage is full combustion. In this period, the sample burns to ashes, and the level of CO increases slightly.

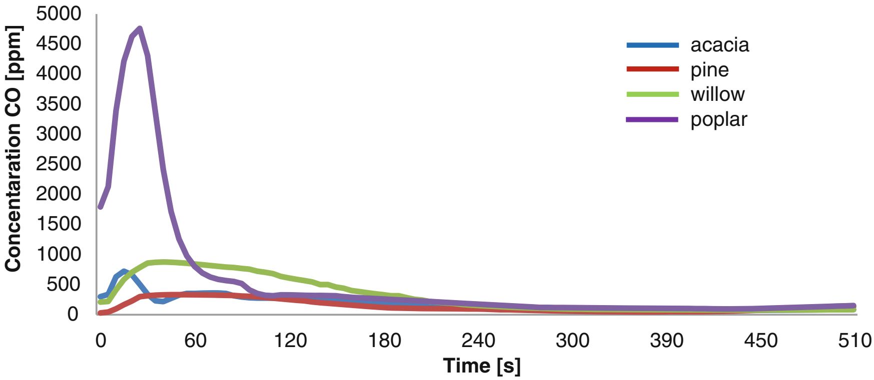


Fig. 1 A graph of CO concentration during combustion for acacia, pine, willow and poplar

Among the tested samples, the highest CO concentration was measured for poplar, exceeding the concentration of CO for other samples by up to 5 times, and reaching the value of 4730 ppm.

Nitrogen oxides (NOx) are inorganic compounds, and consist of oxygen and nitrogen. They are considered one of the most harmful substances that pollute the atmosphere. They are approx. 10 times more harmful than carbon oxides, and a few times more harmful than sulphur oxides. Their presence can be attributed to extremely high temperatures during combustion process with the presence of air.

NOx concentration during biomass combustion behaves in a similar way to CO concentration. Despite the fact that NOx concentration is more than a dozen times lower than CO concentration, it is just as toxic and harmful to our health. Figure 2 shows that the highest concentration is reached at the moment of kindling biomass, when the temperature increases sharply. In the next stages of combustion, NOx concentration changes even with the slightest changes in the way the sample burns, e.g. when the sample starts to glow more violently, NOx concentration also increases (in case of CO the concentration changes are not so significant). The highest concentration of NOx during kindling was recorded for poplar, though during proper combustion, both poplar and acacia samples behave in a similar way, with NOx concentration being higher.

Figure 3 shows a graph presenting H_2 concentration during combustion in the measured period.

In the process of combustion, hydrogen is one of products of the process; it does not have a significant negative impact on the environment. During biomass combustion, mail side-products included carbon oxides and sulphur oxides. Additionally, probes were inserted in the analyser to measure concentrations of hydrogen, sulphur oxides and oxygen.

Oxygen concentration behaved in the similar way as CO concentration (the higher CO concentration the lower oxygen concentration and vice versa) (Fig. 4). Interestingly, sulphur oxides concentration was 0 for all the samples (with the

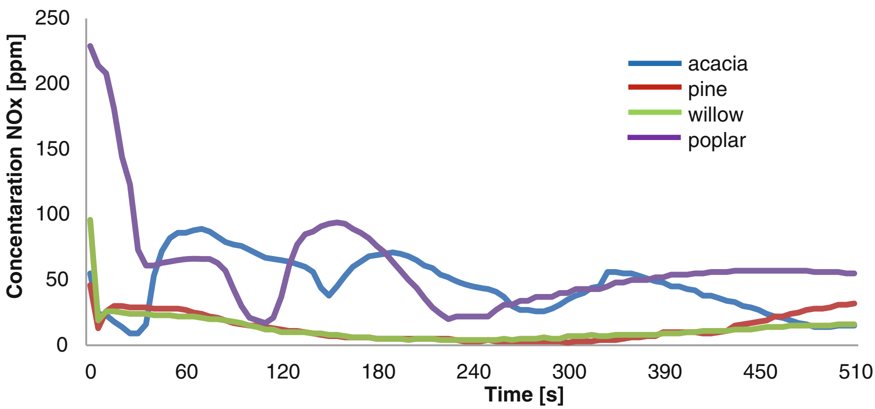


Fig. 2 A graph of NOx concentration during combustion for acacia, pine, willow and poplar

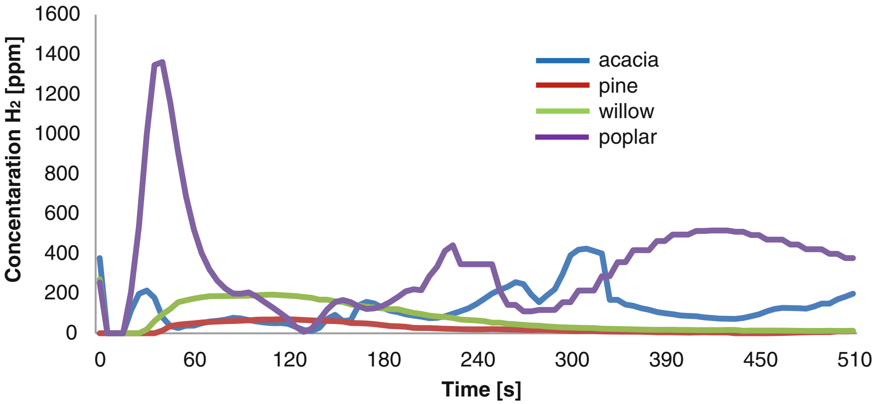


Fig. 3 A graph of H_2 concentration during combustion for acacia, pine, willow and poplar

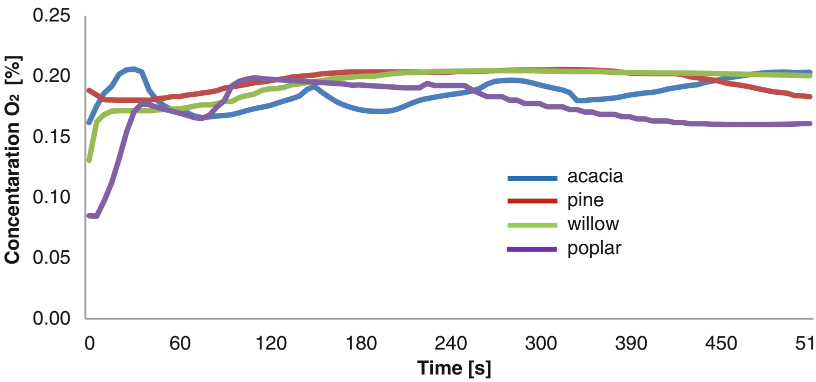


Fig. 4 O_2 concentration during biomass combustion

exception of one experiment, where the probe detected SO concentration near 0). It is connected with the changeability and versatility of the composition.

4 Conclusion

Among all the examined samples of biomass, poplar had the highest net calorific value, i.e. generated the most energy (18,633 J/g), while acacia had the lowest net calorific value, with the average heat value being equal 17,978 J/g. Volatile matter responsible for the flame, had a similar value in each sample, amounting to 85%. It is a very high value, indicative of low moisture of the material. Willow had the highest share of ash among the examined dendromasses, with the percentage share of ash amounting to approx. 1.2%, i.e. more than two times higher than for pine and poplar, for which ash share is equal approx. 0.47%. The best woody biomass material is poplar, due to the highest calorific value and the lowest share of ash, followed by pine, the only representative of coniferous trees. The worst materials of are acacia and willow, as high share of ash (willow) means more frequent cleaning of fire grate, which, considering mass use, would mean the necessity to implement additional technical solutions, or undesirable, increased outlay of labour.

During qualitative analysis of the material, it was determined which dendromass was the most ecological one. Primary pollution can be attributed to carbon oxides and nitrogen oxides. Among the examined materials, the highest concentration of these compounds was found during poplar combustion. However, it is worth noting that mass combustion (e.g. in power plants) does not require repeated kindling since once the material lights up, the fire is fed, and burns continuously. To sum up, the least ecological samples were those of pine and willow. However, the differences between them are small, compared to conventional fuels, such as hard coal or oil; conventional fuels assume values equal to zero.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Nussbaumer, T.: Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. Energy Fuels **17**(6), 1510–1521 (2003)
2. Yang, Y.B., Sharifi, V.N., Swithenbank, J., Ma, L., Darvell, L.I., Jones, J.M., Pourkashanian, M., Williams, A.: Combustion of a single particle of biomass. Energy Fuels **22**(1), 306–316 (2008)
3. Brodziński, Z., Kryszk, H., Kurowska, K.: Market of producers and processors of agricultural biomass for energy purposes. Pol. J. Environ. Stud. **23**(2), 619–627 (2014)
4. Dobrowolska, E., Dzurenda, L., Jabłoński, M., Kłosińska, T.: Wykorzystanie energetyczne dendromasy. Wydawnictwo SGGW, Warszawa (2010)
5. Erol, M., Haykiri-Acma, H., Küçükbayrak, S.: Calorific value estimation of biomass from their proximate analyses data. Renew. Energy **35**(1), 170–173 (2010). https://doi.org/10.1016/j.renene.2009.05.008
6. Frączek, J.: Produkcja biomasy na cele energetyczne. PTIR, Kraków (2009). ISBN 978-83-917053-8-4
7. Gołos, P., Kaliszewski, A.: Wybrane aspekty wykorzystania biomasy drzewnej do celów energetycznych. Biomasa Leśna Na Cele Energetyczne. IBL, Sękocin Stary **76**(1), 78–87 (2015). https://doi.org/10.1515/frp-2015-0009
8. Skodras, G., Grammelis, P., Basinas, P., Kakarass, E., Sakellaropoulos, G.: Pyrolysis and combustion characteristics of biomass and waste-derived feedstock Ind. Eng. Chem. Res. **45**(11), 3791–3799 (2006). https://doi.org/10.1021/ie060107g
9. Gendek, A., Głowacki, S.: Convectional drying of chips for energy purposes. Ann. Warsaw Univ. Life Sci.—SGGW Agric. **53**, 67–72 (2009)
10. Głowacki, S., Gendek, A.: Application of forced drying methods in preparation of forest chips for energy purposes. Ann. Warsaw Univ. Life Sci.—SGGW Agric. **58**, 29–34 (2011)

11. Jasinskas, A., Ulozevićiute, I., Rutkauskas, G.: Plant biomass production and use as an environmentally-friendly local fuel. Pol. J. Environ. Stud. **21**(1), 89–94 (2012)
12. Jasiulewicz, M.: Possibility of liquid bio-fuels, electric and heat energy production from biomass in polish agriculture. Pol. J. Environ. Stud. **19**(3), 479–483 (2010)
13. Najjar, Y.S.H.: Gaseous pollutants formation and their harmful effects on health and environment. Innovative Energy Policies **1**, 1–9 (2011)
14. PN-EN ISO 14780:2017-07 Solid biofuels. Sample preparation
15. PN-EN ISO 18134-3:2015-11 Solid biofuels—Determination of moisture content—Oven dry method—Part 3: Moisture in general analysis sample
16. PN-EN ISO 18122:2016-01 Solid biofuels—Determination of ash
17. PN-EN 15148:2010 Solid fuels—Determination of volatile content by gravimetric method
18. PN-EN 14918:2010 Solid Biofuels—Determination of calorific value
19. Woch, F., Hernik, J., Wyrozumska, P., Czesak, B.: Residual woody waste biomass as an energy source—case study. Pol. J. Environ. Stud. **24**(1), 355–358 (2015). https://doi.org/10.15244/pjoes/29689

Evaluation of Selected Species of Woody Plants in Terms of Suitability for Energy Production

Anna Karbowniczak, Joanna Hamerska, Marek Wróbel, Marcin Jewiarz and Krzysztof Nęcka

Abstract The paper presents results of research on selected fuel quality parameters of five species of woody plants. On the basis of the obtained results an assessment of the suitability of the examined species for energy purposes was carried out. The research material was biomass of willow, poplar, alder, black locust and ashleaf maple. Determined: Moisture content after harvest and after seasoning, ash content, bark and wood content in shoots, gross calorific values and specific density were determined. The research methods used are in line with the guidelines for quality testing of solid biofuels.

Keywords Biomass · FVI · Energy crops · Soild biofuels

1 Introduction

Annual share of biomass in energy production and industrial products is increasing year by year. This is mainly result of increased awareness of the environment and respect for natural resources. For the European Union and the United States these aspects have become a priority [1]. Much attention is paid to the identification of biomass species that can replace conventional energy sources like hard coal and lignite. There are several reasons why there has been a growing interest in biomass

A. Karbowniczak · J. Hamerska · M. Wróbel (✉) · M. Jewiarz · K. Nęcka
Department of Mechanical Engineering and Agrophysics, Faculty of Production and Power Engineering and Agrophysics, University of Agriculture in Krakow, Krakow ul., Balicka 120, 30-149 Kraków, Poland
e-mail: marek.wrobel@urk.edu.pl

A. Karbowniczak
e-mail: ann.karbowniczak@gmail.com

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

K. Nęcka
e-mail: krzystof.necka@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_72

as a source of energy [2–5]. These are technological changes related to conversion, to the use of biomass, as fuel for lower costs and higher conversion capacity [6, 7]. On the other hand, the potential threat posed by climate change (high levels of greenhouse gas emissions) has been a stimulative to the development of renewable energy related technologies [8]. In addition, biomass is an indigenous energy source available in most countries, and it can replace other fuels and contribute to increased energy security [9]. Biomass production also generates jobs in local scale [10–13]. In turn, the use of properly selected crops can contribute to biodiversity and the development of degraded land [14, 15].

Under the climatic conditions of Poland, biomass resources for energy purposes are three groups of plants: trees and shrubs, perennial grass and dicotyledonous perennials [16]. Currently in Poland, biomass for energy purposes comes mainly from forest residues, agriculture, wood industry [17]. Wood is the largest source of energy for the world's population in developing countries, and demand for wood has not declined for decades [18–20].

When evaluating the suitability of plants for energetic purposes, attention should be paid to the method of propagation, growth rate, yield, habitat requirements, moisture content at harvest, energy parameters, especially combustion heat [21–24].

The coefficient describing the pro-energetic value of biomass, based on parameters such as calorific value, specific density, ash content and humidity is the so-called. FVI (fuel value index) [18, 25, 26]. This factor allows to compare different biomass types [27–29].

There is a lack in the literature about FVI for many species of woody plants which would clearly evaluate their pro-energy properties and compare them. The work was carried out for evaluation of biomass of woody plants.

2 Material and Methodology of Research

The research was made on five species of trees, which are usually selected for cultivation of energy crops in Poland. The research material came from experimental plots of high-yield trees of the Department of Energy Plant Collections at the University of Agriculture in Cracow.

Samples were prepared according to the PN-EN ISO 14780:2017-07 [30] standard requirements. The moisture content in fresh biomass (M_{ar}) was determined according to the EN ISO 18134-1:2015-11 standard [31]. The samples were not the milled fraction, but large pieces of wood, to ensure that water don't evaporate during preparation of the sample. Such prepared samples (above 300 g each) were placed in the dryer (SLN 160, POLEKO) and dried until mass of the samples remains constant. The moisture content was determined according to difference in sample weight before and after drying.

The moisture content in analysed state (M_{ad}) was determined according to the PN-EN ISO 18134-3:2015-11 [32] standard. In this analysis also laboratory dryer (SLN 160, POLEKO) was used. The procedure rely on drying of the milled material (1 ± 0.05 g) in air at 105 °C. The moisture content was determined according to difference in sample weight before and after drying.

The ash content (A_d) was determined according to the PN-EN ISO 18122:2016-01 [33] standard from the mass of the residue remaining after the sample was combusted in the furnace (SNOL 3/1100) in air under strictly controlled time and temperature. First, the samples were heated for 1 h in 250 °C, then the temperature was increased up to 550 °C and the samples were kept in this temperature for next 2 h. After cooling down the samples to the ambient temperature, the remained ash was weighed and the calculations according to the formula presented in standard [33] were done.

Share of wood and bark in the in shoots was determined by measuring shoot diameter in several places and then measuring the diameter of shoot after removal of bark. The obtained results were used to calculate the share of wood and bark in the examined shoots.

The wood and bark density measurements were performed with use of The GeoPyc 1360 (Micromeritics Instrument Corp.) based on displacement methods. The sample is placed vessel (diameter 50 mm) filled with Dry Flo is a quasi-fluid composed of small, rigid spheres with high ability to move. The material inside test vessel was agitated and gently compressed (consolidation force is 140 N) and all this parameters are controlled by computer. Before measurement apparatus measures the volume of Dry Flo substance in the same way. After measurement is done, based on the diameter of the vessel, displacement (with and without sample), and mass of the sample, density were calculated, by implemented algorithm.

The gross calorific value (higher heating value, HHV) was determined according to the method based on the PN-EN 14918:2010 standard [34]. It was performed for samples of 1 ± 0.05 g placed in an isoperibol calorimeter (C 6000 Isoperibol, IKA). Each sample was combusted as compressed pellets, in the calorimetric bomb, in pure oxygen and high pressure (3 MPa). The samples were ignited with a cotton thread of known heat of combustion. The calorific value was calculated following the equations described in the standard [34] which were implemented to the device operating software.

The net calorific value (lower heating value, LHV) was calculated from the relation in which gross calorific value is reduced by value equal to heat utilized for vaporization of water, obtained from the fuel in the combustion of hydrogen and moisture content in the sample. This parameter was calculated using the controlling operation software of the calorimeter following the equations presented in the standard [34].

The fuel value indexes (FVI), indicating energetic quality of biomass, were calculated based on the measured parameters [26]:

$$FVI = \frac{HHV * DE_d}{A_d * M} \tag{1}$$

where:

HHV gross calorific value (kJ/g),
DE_d envelope density of biomass (g/cm^3),
A_d ash content in dry state (%),
M moisture content (%).

The density measurements were performed with use of The GeoPyc 1360 (Micromeritics Instrument Corp.) based on displacement methods. The sample is placed vessel (diameter 50 mm) filled with Dry Flo is a quasi-fluid composed of small, rigid spheres with high ability to move. The material inside test vessel was agitated and gently compressed (consolidation force is 140 N) and all this parameters are controlled by computer. Before measurement apparatus measures the volume of Dry Flo substance in the same way. After measurement is done, based on the diameter of the vessel, displacement (with and without sample), and mass of the sample, density were calculated, by implemented algorithm.

3 Research Results

Results of determination of the total moisture content Mar in the shoots of the examined species are presented in Table 1. From the presented data it can observed that among the studied plants, black locust shoots immediately after harvest have the lowest total moisture content (34%). The highest content of moisture is characterized by poplar shoots (59%).

The proportion of bark and wood in shoots was determined on the basis of diameter measurements and results are shown in Table 1. The highest share of bark was estimated for black locust shoots (19.4%) and the lowest share for ashleaf maple (9.2%). Willows, poplars and alders are characterized by similar values in average about 13.4%.

Main quality parameters like ash content, calorific values and envelope (specific) density, both for bark and wood of the tested species are shown in Table 2. All results are presented with reference to the dry state of the sample. As can be seen, the bark contains several times more ash than wood. The highest value was assigned for bark of ashleaf maple (8.54%) and is least identified in the poplar bark (4.05%). The wood of the examined plants has a relatively low ash content, the lowest of which is willow and poplar (0.68%), and most black locust (1.8%).

Table 1 Moisture content and bark share after harvest

Parameter	Willow	Black locust	Poplar	Alder	Ashleaf maple
Moisture M_{ar} [%]	53.1	34.0	58.9	55.9	56.9
Bark share U_k [%]	13.3	19.4	13.4	13.5	9.2

Table 2 Quality parameters of the biomass form different species

Parameter	Material	Willow	Black locust	Poplar	Alder	Ashleaf maple
Ash content A_d [%]	Bark	5.98	7.34	4.05	5.00	8.54
Envelope density DEd [g/cm^3]	Bark	0.82	0.52	0.66	0.81	0.65
Gross calorific value HHV [J/g]	Bark	19663.8	21725.1	22370.1	19949.8	20648.5
Ash content A_d [%]	Wood	0.68	1.80	0.69	1.13	1.04
Envelope density DEd [g/cm^3]	Wood	0.54	0.78	0.40	0.4335	0.52
Gross calorific value HHV [J/g]	Wood	19556.7	19311.4	19970.6	19779.9	19768.8

Poplar, alder, maple and willow populations are characterized by similar density ratios, i.e. the bark of these trees has a higher specific density in relation to wood. In contrast, the bark of black locus has an inverse dependency, and the bark of this tree has the lower density than wood.

The highest values gross calorific value have the bark of each of the studied species. The poplar bark is characterized by highest values of this parameter, and the lowest for willow. In case of wood, the highest heat of combustion was obtained for poplar and lowest for black locust, but results for all plants are quite similar.

In order to compare and evaluate the biomass energy quality, the Fuel Value Index was used, which describes the energy suitability of biomass and includes all tested parameters. Specified FVI for bark and wood and FVI_A is weighted average. The obtained results of the FVI coefficient for material moisture at harvest and at 12% (optimum moisture content of biomass during agglomeration) are presented in Table 3.

Based on the obtained FVI values, it can be noticed that the moisture content during harvesting is relatively low. Biomass obtained from Willow is characterized by the best energy parameters with FVIA equal to 0.26. The worst energy quality was for alder which achieved FVIA result twice as low as Willow (0.12). In the case

Table 3 Fuel Value Index for analyzed species

Parameter	Material	Willow	Black locust	Poplar	Alder	Ashleaf maple
Moisture [%]		53.1	34.0	58.9	55.9	56.9
Fuel value indexes FVI	Bark	0.05	0.04	0.06	0.06	0.03
	Wood	0.29	0.25	0.20	0.13	0.17
Average FVI_A		0.26	0.21	0.18	0.12	0.16
Moisture [%]		12	12	12	12	12
Fuel value indexes FVI	Bark	0.22	0.13	0.30	0.27	0.13
	Wood	1.29	0.70	0.96	0.63	0.82
Average FVI_A		1.15	0.59	0.88	0.58	0.76

of bark, all results are several times lower than wood (due to it is mainly high ash content). By analysis of the average values of FVIA obtained for technological moisture (12%) it should be stated that in this case the willow is characterized by the best proenergetic parameters while the alder biomass obtained the lowest value of this indicator. This is due to the highest ash content in both the bark and the wood of this species.

4 Conclusion

Based on the analysis of the presented results, the following conclusions can be made:

Used to assess the suitability of wood for selected woody plants for energy purposes, FVI_A indicator has shown that the best quality can be obtained for willow biomass and the worst—black locust and alder. This result was influenced by high values of pro-energetic parameters (heat of combustion and specific density) and low content of undesirable ash of willow wood. The low FV_{IA} value for black locus is mainly due to the high ash content and the lowest value of calorific value.

In the case of bark, all FVI results are several times lower than wood (due to high ash content), although in each case the heat of bark burning relative to the wood of the same plant is higher. The bark also contains several times more ash than wood.

The specific density of the bark of poplar, alder, maple and willow has a higher specific density relative to wood. Black locust has the opposite relationship, moreover, the bark of this tree has the lowest specific density among the species tested and the wood is the largest.

The heat of combustion estimated for bark for all plants is higher than the one estimated for wood. In the case of willow and alder, the differences between the bark and the wood are quite small, with a difference of about 900 J/g in the case of the ashleaf maple in favor of the bark. The highest differences were found for bark and wood of black locust and poplar (approx. 2500 and 2400 J/g respectively).

Presented in paper results, shows that all presented spices of high yield plant, are suitable for use for energetic purposes, but best seems to be willow and poplar, as characterized by best fuel value index.

Acknowledgements This research was financed by the Ministry of Science and Higher Education of the Republic of Poland (statutory activities DS-3600/WIPiE/2017, Faculty of Production and Power Engineering, University of Agriculture in Krakow).

References

1. Dyrektywa Parlamentu Europejskiego i Rady 2009/28/WE z dnia 23 kwietnia 2009 r. w sprawie promowania stosowania energii ze źródeł odnawialnych zmieniająca i w następstwie uchylająca dyrektywy 2001/77/WE oraz 2003/30/WE
2. Abuelnuor, A.A.A., et al.: Characteristics of biomass in flameless combustion: a review. Renew. Sustain. Energy Rev. **33**, 363–370 (2014)
3. Corma, A., et al.: Production of high-quality diesel from biomass waste products. Angew. Chem. **123**(10), 2423–2426 (2011)
4. Nunes, L.J.R., Matias, J.C.O., Catalão, J.P.S.A.: Review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renew. Sustain. Energy Rev. **40,** 153–160 (2014)
5. Ruiz, J.A. et al.: Biomass gasification for electricity generation: review of current technology barriers. Renew. Sustain. Energy Rev. **18**, 174–183 (2013)
6. Sahu, S.G., Chakraborty, N., Sarkar, P.: Coal–biomass co-combustion: an overview. Renew. Sustain. Energy Rev. **39**, 575–586 (2014)
7. Scurlock, J.M., Hall, D.O.: The contribution of biomass to global energy use. Biomass **21**, 75–81 (1990)
8. Peter, McKendry: Energy production from biomass (part 1): overview of biomass. Biores. Technol. **83**(1), 37–46 (2002). https://doi.org/10.1016/S0960-8524(01)00118-3
9. Abbasi, T., Abbasi, S.A.: Biomass energy and the environmental impacts associated with its production and utilization. Renew. Sustain. Energy Rev. **14**(3), 919–937 (2010)
10. Fernando, A.L., et al.: Environmental impact assessment of energy crops cultivation in Europe. Biofuels, Bioprod. Biorefin. **4**(6), 594–604 (2010)
11. Kościk, B.: Rośliny energetyczne. Wydawnictwo Akademii Rolniczej w Lublinie, Lublin (2003)
12. Zabalza, B., Ignacio, A.V.C., Usón, A.A.: Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ. **46**(5), 1133–1140 (2011)
13. Zanuncio, A.J.V., et al.: Physical and colorimetric changes in *Eucalyptus grandis* wood after heat treatment. BioResources **9**(1), 293–302 (2013)
14. Frączek, J., Mudryk, K., Wróbel, M.: Klon jesionolistny Acer negundo L.- nowy potencjalny gatunek energetyczny. Wyd. Acta Agrophysica. 313–322 (2009)
15. Matthews, E.: Undying flame: the continuing demand for wood as fuel. Extract from pilot analysis of global ecosystems: forest ecosystems. Earth trends 2001 World Resources Institute (2000)
16. Szczukowski, S.: Wieloletnie rośliny energetyczne. Wyd. MULTICO Oficyna Wydawnicza (2011)
17. Juliszewski, T., Kwaśniewski, D., Mudryk, K., Wróbel, M.: Ocena wybranych parametrów biomasy pozyskanej z plantacji drzew szybkorosnących. Wyd. Inżynieria Rolnicza T.1, 89–97 (2012)
18. Deka, D., Saikia, P., Konwer, D.: Ranking of Fuelwood Species by Fuel Value Index, pp. 1499–1506 (2007). http://dx.doi.org/10.1080/15567030600820476
19. Laser, M., Lynd, L.R.: Comparative efficiency and driving range of light-and heavy-duty vehicles powered with biomass energy stored in liquid fuels or batteries. Proc. Natl. Acad. Sci. **111**(9), 3360–3364 (2014)
20. Saidur, R., et al.: A review on energy analysis of biomass based fuels. Renew. Sustain. Energy Rev. **16**(2), 1217–1222 (2012)
21. Borkowska, H.: Zmiany zawartości suchej masy w plonie biomasy wierzby krzewiastej (wikliny) i ślazowca pensylwańskiego w zależności od terminu zbioru. UMCS, seria E. s. 60, 155–161 (2005)

22. Borkowska, H., Styk, B.: Ślazowiec pensylwański (Sida hermaphrodita Rusby). Uprawa i wykorzystanie. Wydanie II poprawione i uzupełnione. Wydawnictwo Akademii Rolniczej w Lublinie. Lublin (2006)
23. Gradziuk, P.: Energia odnawialna. Wydawnictwo, Wieś Jutra". Płońsk (2008)
24. Strack, Z.: Transport i dystrybucja substancji pokarmowych, a wytwarzanie plonu rolniczego. Fizjologia plonowania roślin pod redakcją Ryszarda Gorskiego i Stanisława Grzesiuka. Wydawnictwo UWM. Olsztyn. s. 282–312 (2002)
25. Goel, V.L., Behl, H.M.: Fuelwood quality of promising tree species for alkaline soil sites in relation to tree age. Biomass Bioenergy **10**(1), 57–61. https://doi.org/10.1016/0961-9534(95)00053-4
26. Klašnja, B., Orlović, S., Galić, Z.: Comparison of different wood species as raw materials for bioenergy. South-East Eur. For. **4**(2), 81–88 (2013)
27. Abbot, P.G., Lowore, J.D.: Characteristics and management potential of some indigenous firewood species in Malawi. For. Ecol. Manage. **11**, 111–121 (1999)
28. Abbot, P.G., Lowore, P., Khofi, J., Werren, C.M.: Defining firewood quality: a comparison of quantitative and rapid appraisal techniques to evaluate firewood species from a southern African Savanna. Biomass Bioenergy **12**(6), 429–437. https://doi.org/10.1016/S0961-9534(96)00084-0
29. Bhatt, B.P., Todaria, N.P.: Fuelwood characteristics of some indian mountain species forest ecology and management. **47**(1–4), 363–366. https://doi.org/10.1016/0378-1127(92)90285-H
30. PN-EN ISO 14780:2011 Solid biofuels - Sample preparation
31. PN-EN ISO 18134-1:2015-11 Solid biofuels - Determination of moisture content - Oven dry method - Part 1: Total moisture - Reference method
32. PN-EN ISO 18134-3:2015-11 Solid biofuels - Determination of moisture content - Oven dry method - Part 3: Moisture in general analysis sample
33. PN-EN ISO 18122:2016-01 Solid biofuels - Determination of ash content
34. PN-EN 14918:2010 Solid Biofuels - Determination of calorific value

Assessment and Development Perspectives of Solar Energy in Khmelnytskyi Region

Vasyl Ovcharuk, Olena Doroshenko, Yaroslava Babiy and Andriy Stepas′

Abstract Condition and development perspectives of solar energy in Khmelnytskyi region are considered in the article. The analysis of information regarding solar power is conducted. There were given characteristics and potential of the region, of existing and new solar power plants.

Keywords Renewable sources of energy · Solar power plant · Solar cell Solar radiation · Power

1 Introduction

The basis of the National Security of Ukraine and its economic independence is a fuel and energy complex, the stability of which is the key to development and potential to implement national strategic programs. The most important sector of the fuel and energy complex of Ukraine is electric power industry.

Entities of electric power industry are united in a single operation mode, together they form a Joint power system (JPS) of Ukraine. Among the tasks now assigned to JPS is to consider in the energy balance most effectively the capacity of source so renewable energy (wind power plants, solar power plants, etc.), which are rapidly developing in recent years [1–3].

The main reasons for such attention to non-traditional renewable energy sources are expected depletion of fossil fuels, a sharp increase of prices, inadequate and inefficient technologies of its use, detrimental impact on the environment, the effects of which are more and more disturbing the international community.

At present, the share of non-traditional renewable energy sources in energy production in the world is not significant yet, but the potential is several orders higher than the world consumption of fuel and energy resources. The rate of growth of energy output from non-traditional renewable energy sources also are signifi-

V. Ovcharuk (✉) · O. Doroshenko · Y. Babiy · A. Stepas′
State Agrarian and Engineering University in Podillia, Podillia, Ukraine
e-mail: vasylovcharuk@mail.ru

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_73

cantly higher than for traditional kinds of energy. In 2015 solar cells produced 1% of the world's electricity, but it amounted to 20% of all new power plants. International Solar Alliance (ISA) set out to increase the amount of added solar power from 71 MW to 3 TW by 2030. However, experts of GA-SERI consider that there can be achieved a figure from 5 to 10 TW. In a publication in the journal Science, scientists propose to improve the quality of solar cells and reduce their cost. Experts also believe it is necessary to create a more flexible power system that can handle a large number of solar modules. Load distribution, installation of energy saving systems and improving the efficiency of energy transfer can help to achieve maximum results by 2030. Authors of the publication also recommend to increase the demand for solar energy, using it for cooling, heating and maintenance of transport [4].

Alternative power industry, including solar, develops with high rates in the US, Europe, India and the CIS.

In the USSR the first industrial solar power plant "SES-5" was built in the Crimea in 1985 near Shcholkino. It had the power of 5 MW. During the 10 years of operation it has given 2 million kWh of electric power. In the middle of the 1990s it was closed. The largest power plant for solar energy in the territory of the former Soviet Union was built in the Crimea, Rodnikove village (Simferopol district). Its construction was completed in 2011. This power plant was an innovative project of the Austrian company ActivSolar. Its peak power is about 100 MW. This project received an award in the competition "Success of the Year" in the category " Leader of Innovations".

In October 2011 the company ActivSolar launched another solar power plant in Okhotnikove village (Saki district), also in the Crimea. Its power was 80 MW.

After the pilot project in Rodnikove village there began the construction of solar power plants in different regions of Ukraine. In Vinnitsa region in January 2011 started solar power plant with power of 35 kW, installed on the roof of industrial building of Hnivan tire-repair plant. There started micro solar power plant in Luhansk region. Its 15 kW power panels are located above the highway "Kharkiv-Rostov". In subsequent years, solar power plants are increasing their power and begin launching in all regions of Ukraine (Tables 1 and 2). In 2014, after the occupation of the Crimea, Ukraine SPP peak power significantly decreased [5].

The most powerful solar plants are located in the south of the mainland of Ukraine. Photoelectric solar power plant was built near the village Starokozache of Odessa region by the group of companies "ActiveSolar", has power of 43 MW. Danube solar power plant is situated in the southern part of Odessa region near

Table 1 Established SPP peak power in Ukraine

Year		2009	2010	2011	2012	2013	2014	2015	2016
Ukraine	MW	0	10	180	320	560	350	360	460
Khmelnytskyi region		0	0	0	1	2.5	5	9	15.5

Table 2 Ukraine zoning for the potential of solar energy

Region	Potential of solar energy				The contribution of direct radiation in total (%)	The frequency of continuous sunshine duration over 6 h (%)	Stability factor of clear weather (%)	Number of clear and half clear days (year)	Assessment of solar energy potential
	Direct radiation perpendicular to the surface (MJ/m^2)		Total radiation (MJ/m^2)						
	April–September	Year	April–September	Year					
Southern coast of the Crimea	3400–3600	4700–4900	3700–3900	5000–5200	0.53	35.0	50	264	Very high potential, the most favorable conditions for the use of solar energy
Black Sea and Azov lowlands	3200–3400	4400–4600	3700–3800	4600–4800	0.49	37.0	48	244	High potential, favorable conditions for yheuse of solar energy
Donetsk and Dnieper uplands	3100–3300	3900–4000	3550–3750	4250–4350	0.44	32.2	47	239	High potential, favorable conditions for the use of solar energy
Transcarpathian lowland	2700–2900	3600–3800	3500–3600	4100–4200	0.41	31.0	46	236	Sufficient potential, quite favorable conditions for the use of solar energy
Podillya and Dnieper uplands	2800–3000	3650–3850	3300–3700	4100–4200	0.42	27.2	40	238	Sufficient potential, quite favorable conditions for the use of solar energy
Polissia lowland	2000–2700	2800–3600	2700–3500	3500–4200	0.41	26.0	39	228	Quite low potential, limited favorable conditions for the use of solar energy
Ukrainian Carpathians and Crimean mountains	1500–1700	2150–2250	2600–2700	3250–3350	0.36	18.7	44	203	Low potential, unfavorable conditions for the use of solar energy

Artsyz town, has power of 42 MW. There are 65 solar power plants acting on the territory of Ukraine with the general power of 460 MW.

The greatest member of the solar energy market of Ukraine is a company CNBM International (China). НайбільшимгравцемнаринкусонячноїенергетикиУкраїни є компанія CNBM International (China). In particular, since the middle 2014 CNBM owns solar power plants, such as: Lymanska Energy 1, Lymanska Energy 2, Pryozerne 1, Pryozerne 2, Franco Solar, Franco Pivi, Danube solar power plant 1, Danube solar power plant 2 (Odessa region), Neptune Solar and VoshodSolar (Mykolaiv region).

The issue of alternative energy production remains a top priority for the development of Khmelnytskyi region.

The first solar power plant in Khmelnytskyi region started in October 2012. The group of companies EkotechnikPraha (Czech Republic) became its investor, 35% of complete equipment of this solar power plant (elements of fastening and gathering glass units of solar convectors) were produced at the industrial enterprises of the region: State Enterprise “Novator”, PJSC “Ukrelektroaparat”, LLC “Antonmash”. Power of the solar power plant at present is 2 MW, which the group of companies eventually plan to increase to 5 MW. The power plant occupies land plot of 5 ha, later it will be expanded to 10 ha. Over the years Yasenivka solar power plant has produced 6.9 million kWh (see Fig. 1).

In the region there are located three acting solar power plants of the total power of 15.5 MW (Demyankivtsi village, Dunaivtsi district, Yasenivka village, Yarmolyntsi district, Vinkivtsi town). Also there goes the construction of four plants, which are designed for the power of 26 MW (Derazhnya town, Shepetivka town, Krasnostavtsi village and Letava village, Chemerivtsi district) (see Fig. 2).

Fig. 1 The first solar power plant of Khmelnytskyi Region, Yarmolyntsidistrict, Yasenivka village

Fig. 2 Solar power plants in Khmelnytskyi region

The main investor of solar power plants located in the region is a group of companies EkotechnikPraha. The total portfolio of projects of the group in Ukraine exceeds 500 MW.

The group of companies EkotechnikPraha intends to invest 400 million euros in the construction of solar power plants in Khmelnytsky region and increase their total installed power to 160 MW. Plans of Czechs are recorded in the memorandum between Khmelnytskyi Region State Administration and LLC "Ecotechnika Ukraine" (Kyiv) on cooperation in the design, construction and exploitation of photoelectric power plants. Construction of such plants is planned in 14 districts, such as: Dunaivtsi, Khmelnytskyi, Vinkivtsi, Yarmolyntsi, Nova Ushytsya, Chemerivtsi, Letychiv, StaraSynyava, Derazhnya, Bilohirya, Horodok, Teofipol, Kamyanets-Podilskyi and Volochysk. In general, the government plans to transfer in rent for EkotechnikPraha 400 ha of land. Implementation of the project will improve the fuel and energy balance, social and environmental situation in districts of the region. Construction and exploitation of solar power plants will provide with 230 additional workplaces and will increase annual revenues to local budgets by 4.4 million.

Alternative power promptly grows not only in conditions of modern cities, but in reality of villages and households in particular. The first quarter of this year was marked by the emergence of more than two hundred new solar power plants of the private use. Their total power was 3.4 MW.

The number of private solar power plants every month in 2017 will increase steadily for a number of obvious reasons.

First, spring and summer are the most favorable to "green" energy, because the amount of solar radiation at this time is maximal. Second, Ukrainians evaluated in practice the benefits of using alternative energy sources and ascertained on the experience of compatriots that payback periods for plants are very small. Thirdly, the Government's policy concerning "green" energy is very loyal and is aimed at promoting its development and spread.

According to estimates of the State Energy Efficiency from the beginning of this year the share of solar power plants of private consumption increased by 18%. Total power of private solar power plants increased by almost 20%.

The implemented in 2015 "green" tariff significantly activates citizens. Excess of electricity produced at solar power plants owners can sell to the public network. And as the "green" tariff in our country is attached to euro rate, then such business makes significant income for the owner's family. Due to the Law of Ukraine of 2015 Ukrainians can sell electricity from private solar power plants for 18.09 cents per 1 kW per hour.

Experts note that the demand for "green" energy is actively increasing with the adoption by the Verkhovna Rada of this draft law. Statistics shows that each quarter after the enactment of this Law was marked with the growing demand to 30–40%. Some periods were marked with the growth by 70%. Experts of the State Energy Efficiency affirm that in Ukraine currently about 1300 households have private solar power plants. These Ukrainian families not only provide their own energy needs through natural sources, but also earn on sale of surplus energy.

We can say that alternative power industry in Ukraine made a huge step towards a safe and inexhaustible energy.

Ukraine has significant potential for the use of alternative renewable energy sources. On the other hand, the problem of efficient use of traditional energy sources in Ukraine is even more acute than in the world or the EU. The reasons for this are outdated technologies, depletion of resources for use of capital assets of electricity and heat generating, which together with low fuel efficiency results in significant emissions of harmful substances. Significant losses during transportation, distribution and use of electricity and heat as well as a monopoly dependence on imported energy further complicate the situation on the energy markets of Ukraine [6].

Ukraine has an urgent need for a new energy strategy, the priority of which is economical consumption and energy efficiency. The new energy strategy envisages that our country almost fourfold will increase the use of alternative energy sources from 10.9 million tons of oil equivalent in 2005 to 40.4 million tons of oil equivalent in 2030.

The highest growth is expected in the use of solar energy, wind power plants and low potential heat, but their massive consumption starts with an insignificant level as at present total installed power (including small hydro power plants) is only 0.18 GW. Nevertheless, the total capacity of power plants for the production of electricity from alternative energy sources (excluding biofuels and small hydro power plants) should grow in 2030 to 2.1 GW.

This time new energy strategy for the Ministry of Energy and Coal Industry of Ukraine was written not by employees of the department, but experts of Razumkov Center and the National Institute for Strategic Studies. One of its developers, the director of energy programs in Razumkov Center Volodymyr Omelchenko said that the new strategy offered exactly the direction—“where,” and guidelines—“how” to develop the energy sector of Ukraine.“The main goal of the strategy is the national energy security and energy saving of resources, using innovative technology”. In the document there is presented an action plan how to achieve this—Ukraine has to focus on minimizing the import dependence by optimizing domestic consumption, instead to prove to the maximum domestic production of various types of fuel, to create strategic reserves, to diversify the sources and routes of energy supply and to take care of the protection of critically important energy infrastructure [7].

The adopted strategy envisages the development of renewable energy sources in correspondence to fundamental principles of the European Security Strategy, competitive and sustainable power industry. In the Energy Strategy of Ukraine set a number of benefits to encourage the production and use of energy from renewable sources are set, but most of them have not yet found a detailed reflection in the legislation.

There is a program for the development of alternative and renewable energy and small hydropower plants. The aim for renewable energy sources for 2030 is 19% of the total volume of generation [7].

1.39 kW/m^2 of solar radiation reaches the border of the earth’s atmosphere, with only 45% of the total radiation reaching the surface of the earth. Out of the remaining 55%, 22% is absorbed by the atmosphere, 8% is scattered in the atmosphere, 17% is lost by reflection from clouds, another 4% is absorbed by clouds and 6% is reflected from the surface of the earth. As a result, approx. 1 kW/m^2 of the total solar radiation reaches the surface of the earth. The total solar radiation is the total of the reflected, direct and scattered radiation. It depends on the latitude, climate of the geographic region and air pollution. Direct solar radiation is the radiation that reaches the surface of the Earth directly from the Sun through the earth’s atmosphere. Reflected radiation is the solar radiation which, on its way to the earth's surface, meets an obstacle such as a cloud or a building and is reflected. Scattered radiation is the radiation deviated in various directions. Solar radiation is electromagnetic wave, which may be divided into: ultraviolet radiation (wave length of 150–400 nm), visible radiation (wave length of 400–750 nm), and infrared radiation (wave length of 750–4000 nm) [8].

A necessary condition for the widespread use of solar energy is reasoned assessment of its potential, the end result of which is a set of objective quantitative characteristics that reflect the variable mode of receipt of this type of energy and limits of their possible variations within space and time. Climate justification of the location and operation of solar power plants should consider, first, the spatial and temporal features of solar energy distribution in a particular place and to identify the necessary conditions and characteristics of the optimal mode of functioning of solar power units [9].

Assessment of the potential of solar energy is conducted across general for all renewable sources of energy principles. This is a complex of natural processes, the implementation of which is a subject to variability. Assessing the potential of solar energy is necessary to consider natural fluctuations of solar radiation astronomical nature (the Earth's rotation around the Sun, the solar constant fluctuations) and geophysical character changes (variations in cloud cover, atmospheric transparency, humidity and aerosol turbidity) [10].

Average annual total solar radiation that comes to 1 m^2 of the surface on the territory of Ukraine is in the range from 1070 kWh/m^2 in northern Ukraine up to 1400 kWh/m^2 and above in the Autonomous Republic of Crimea (see Figs. 3 and 4).

The use in cadastral valuation of solar radiation only average long-term characteristics is impossible without its spatial and temporal variability, since this approach leads to significant errors. Climate solar energy resources should be evaluated on the principle of probability of characteristics of solar radiation, that is maximal approach of observational data to conditions of solar energy use [11].

Evaluation solar energy resources is carried out by the long-term observations of solar radiation.

Important indicators of radiation mode are the duration of sunshine and cloudiness. Variability of cloudiness during the day causes unevenness in operation of solar power plants, particularly of solar concentrators, which receive direct sunlight. In cloudy days significant amount of solar energy is spent on overcoming the inertia of units [12].

Solar energy characteristics are distributed by seasons. In winter, the spatial distribution of the frequency of continuous sunshine duration over 6 h is characterized by a large variability: less than 16% in the north and more than 32% in the south. The amount of solar energy which is generated, and that is a characteristic of the total potential of solar energy during this season, also varies quite significantly: from 200–300 MJ/m^2 in Polissia region to 400–500 MJ/m^2 in the southern part, coast of the Black and Azov Seas [13].

In summer energy resources of the sun are the largest. The frequency of continuous sunshine duration over 6 h varies within 27–41%.

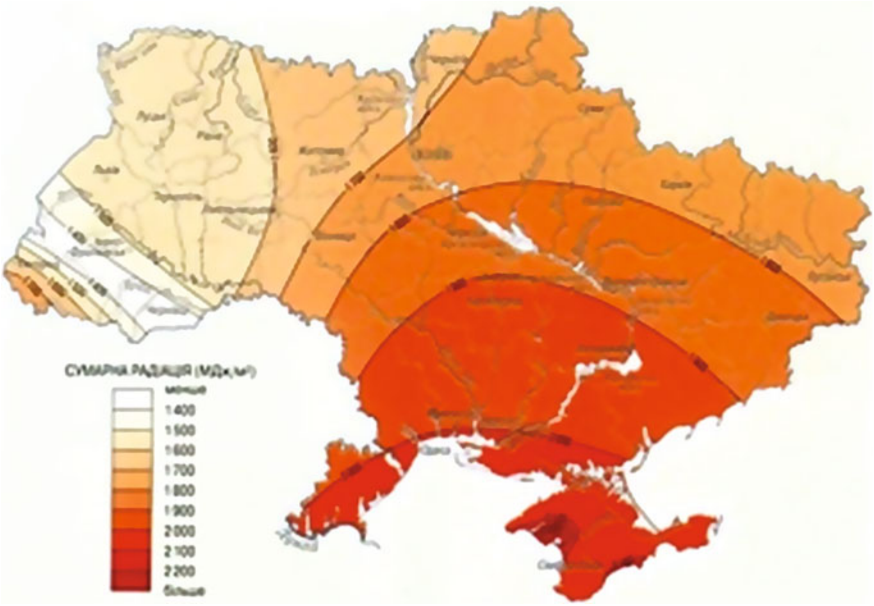


Fig. 3 The total solar radiation (summer), MJ/m^2

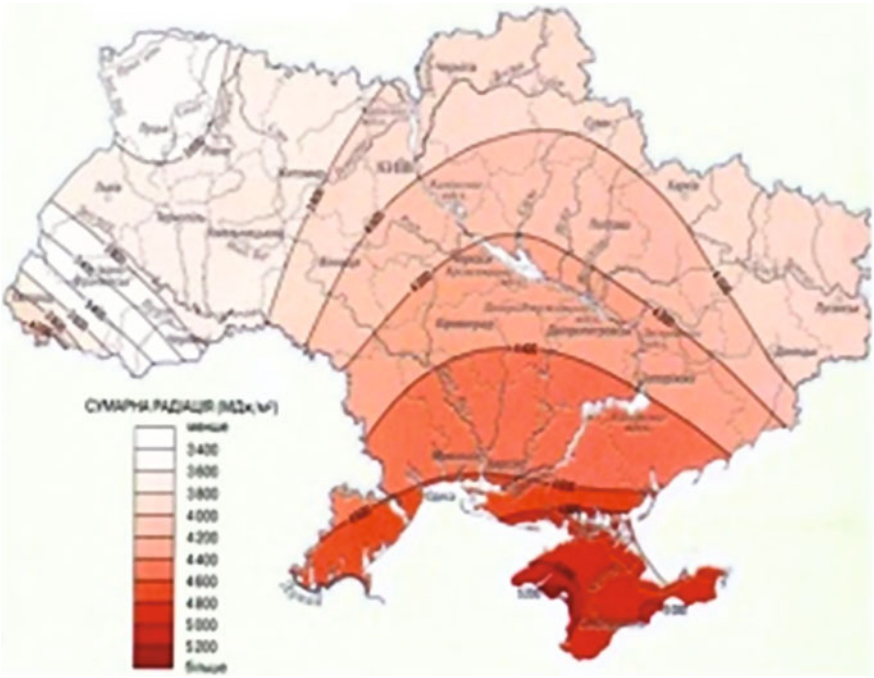


Fig. 4 The total solar radiation (year), MJ/m^2

Scientists of Ukrainian Research Hydrometeorological Institute conducted a zoning based on climatic generalizations of actinometry and meteorological observations using statistical and probabilistic methods (Fig. 2). The complex of special zoning indicators was developed so that they can reflect a long-mode incoming solar radiation as well as its variability [14].

The most appropriate use of solar energy, and hence solar power plants placing is on the southern coast of Crimea, the Black Sea and Azov lowlands, valleys in Transcarpathia.

Great frequency of cloudy days in the Ukrainian Carpathians causes a significant weakening of solar radiation. This demonstrates the unreasonableness of placing solar heat supply systems in these areas.At the same time, high power solar radiation when the sky is clear ensures successful operation of local solar power plants of limited action [15].

Solar power has a great potential and advantages: accessibility, inexhaustibility, safety. But at the same time, there are drawbacks. One of the fundamental problems is the use of large areas of land for power plants, this problem is solved in the case of the use of balloon solar power plants. Technical problems include: the problem of energy storage, which could have made the use of solar power plants more efficient and independent of the time of day and weather conditions and lack of efficiency of solar cells. Probably these technical problems will soon be solved. Despite the ecological cleanliness of the received energy, solar cells themselves contain toxic substances, such as lead, cadmium, arsenic and so on, and their production consumes a lot of other dangerous substances. Modern solar cells have a limited lifespan (30–50 years), and their massive application soon will put a difficult question of their disposal.

The main reasons pointing to the importance of the transition to alternative energy sources [16]:

globally environmental: detrimental impact on the environment of traditional energy producing technologies;

political: developed alternative power makes the country independent interms of energy;

economic: the transition to alternative energy technologies will save fuel resources of the country for processing in chemical and other industries, alternative energy prices are falling, and the traditional—constantly increasing;

social: number and population density is constantly increasing, while it is difficult to find areas for nuclear and hydro power plants' construction, where energy production would be cost-effective and safe for the environment;

evolutionary historical: for the evolutionary development of society it is necessary begin with a gradual transition to alternative energy sources immediately.

2 Summary

Having analyzed the resources of Khmelnytskyi region and Ukraine we find that the region has a great potential for development of a network of solar power plants. There is a program for the development of alternative and renewable energy sources and small hydropower plants. Target for renewable energy sources for 2030 is 19% of the total volume of generation.

References

1. Intehratsiya OES Ukrayiny do kontynental′noyi yevropeys′koyi enerhosystemy ENTSO-E. [Elektronnyy resurs]// Ukrenerho. Natsional′na enerhetychna kompaniya. Proekty z yevrointehratsiyi – Rezhym dostupu: https://ua.energy/diyalnist/projects/realizovani-proekty/
2. Vprovadzhennya novoho rynku elektroenerhiyi v Ukrayini [Elektronnyy resurs]// Ukrenerho. Natsional′na enerhetychna kompaniya. Proekty z yevrointehratsiyi – Rezhym dostupu: https://ua.energy/diyalnist/projects/realizovani-proekty/
3. Enerhetychnyy mist Ukrayina – Yevropeys′kyy Soyuz [Elektronnyy resurs]// Ukrenerho. Natsional′na enerhetychna kompaniya. Proekty z yevrointehratsiyi – Rezhym dostupu: https://ua.energy/diyalnist/projects/realizovani-proekty/
4. Terawatt-scale photovoltaics: Trajectoriesandchallenges. Nancy M. Haegel, RobertMargolis, TonioBuonassisiDavidFeldman, ArminFroitzheim, RaffiGarabedian [Elektronny`jresurs]// Science. 14 April 2017, pp. 141–143–Rezhy`mdostupu: http://science.sciencemag.org/content/356/6334/141
5. Stoyan, O., YU. Svitovyy ta vitchyznyanyy dosvid realizatsiyi mekhanizmiv derzhavnoho rehulyuvannya rozvytku vidnovlyuval′noyi enerhetyky: osnovni tendentsiyi rozvytku ta perspektyvy/ O. YU. Stoyan// Naukovi pratsi [Chornomor. derzh. un-tu im. Petra Mohyly kompleksu “Kyyevo-Mohylyan. akademiya”]. Seriya “Derzh. upravlinnya”. – 2014. – T. 235, vyp. 223. – S. 94–100
6. Machulin, V., Sonyachna enerhetyka: poryadok dennyy dlya svitu y Ukrayiny/ V. Machulin, V. Lytovchenko, M. Strikha// Visnyk Natsional′noyi akademiyi nauk Ukrayiny. - 2011. - № 5. - S. 30–39
7. Proekt novoyi Energety`chnoyi strategiyi Ukrayiny`do 2035: za i proty`. [Elektronny`jresurs]// Centrdoslidzhen`energety`ky`. – Rezhy`mdostupu: http://eircenter.com/ua-analiitika/proekt-novoyi-energetichnoyi-strategiyi-ukrayini-do-2035-za-i-proti/
8. Bazylak, W., Głowacki, S., Bryś, A., Tulej, M., Sojak, M., Książek, I., Yermakov, S.: Solar radiation as a source of energy used in drying processes. Scientific achievements in agricultural engineering, agronomy and veterinary medicine. pp. 42–54 (2017)
9. Spichak, V., Sidorchuk, O., Lub, P., Hutsol, T., Zelensky, O.: Methodology of production-technological risk management on the basis of statistical imitation modeling of projects works. East. Eur. J. Enterp. Technol. **10**(61), 89–92
10. Volodymyr Ivanyshyn, TarasHutsol. 2017. The Ukrainian agricultural groups state and agro-machinery rovision/ Scientific achievements in agricultural engineering, agronomy and veterinary medicine. Monograph – Traikon. Krakov.Vol. 1 – P. 1–13.http://188.190.33.56:7980/jspui/handle/123456789/10
11. Dmy`trenko, L.V., Gejko, L.A. Ocinka klimaty`chny`x resursiv sonyachnoyi i vitrovoyi energiyi (metod. Rozrobky ta rezul`taty doslidzhen`)// Visn. Donecz`koyi derzh. akad. bud-va ta arxit. – 1999. – №99–6(20). – T. 2. – S. 6–8

12. My`sak, J.S. Sonyachna energetyka: teoriya ta prakty`ka: monografiya/ J. S. My`sak, O. T. Voznyak, O. S. Dacz`ko, S. P. Shapoval. – L`viv: Vydavnycztvo L`vivs`koyi politexniky, 2014. – 340 s
13. Dmy`trenko, L.V. Gelio- tavitroenergety`chniresursy// KlimatUkrayiny. – K.: Vy`d-voRayevs`kogo, 2003. – S. 267–279
14. Scientific achievements in agricultural engineering, agronomy and veterinary medicine: Polish-Ukrainian cooperation [Electronic resource]: scientific monograph. State Agrarian and Engineering University in Podilya, Agriculture University in Kraków. vol. I. Kraków: Traicon, 170
15. Energety`chnyjpotencialsonyachnoyiradiaciyinatery`toriyiUkrayiny`/ V. M. Zhely`x, O. V. Omel`chuk, S. P. Shapoval, I. I. Vengry`n// Visny`kNacional`nogouniversy`tetu "L`vivs`kapolitexnika". Seriya: Teoriya i prakty`ka budivny`cztva: zbirny`knaukovy`xpracz`. – 2015. – № 823. – S. 117–121
16. Borovyk, O.A. Doslidzhennya stanu ta perspektyv rozvytku helioenerhetyky v Ukrayini// Materialy III Mizhrehional′noyi naukovo-praktychnoyi konferentsiyi molodykh uchenykh. Suchasni problemy eksperymental′noyi ta teoretychnoyi fizyky. – 2014 – S. 5–11

Biogas Production as a Component of Green Energy Generation

Yulia Ievstafiieva, Viktoria Levytska and Dmytro Terenov

Abstract The article is dealing with biogas production as a component of Green Energy generation, along with issues and prospects associated with biogas production in Ukraine. Biogas role in mitigating energy dependency, in creating new jobs and improving the environment is investigated.

Keywords Biogas · Biogas production and use · Anaerobic reactor
Fuel saving

1 Introduction

Biogas is a gas made of the organic waste (food waste, livestock farming waste) with a help of bacteria with a composition similar to that of natural gas: up to 98% methane along with hydrogen sulfide, carbon dioxide, water, etc. It is produced in the process of methane fermentation of biomass. Biomass decomposition takes place under influence of three main types of bacteria. In this food chain current population of bacteria feed on life activity products of the preceding population. First type of bacteria are hydrolytic, second type are acid formers and third type are methane-oxidizing bacteria. All three bacteria types take part in biogas generation and not just methane-oxidizing ones. Biogas has a number of advantages vs. natural gas, namely:

Biogas is made of biological raw materials, therefore its production and combustion represent stages of natural carbon cycle that does not lead to accumulation of natural gas in the atmosphere and greenhouse effect. Natural gas is extracted from the bowels of the earth and it is not a component of the atmosphere, so its combustion results in accumulation of carbon dioxide.

Y. Ievstafiieva (✉) · V. Levytska · D. Terenov
State Agrarian and Engineering University in Podilya, Kamianets-Podilskyi, Ukraine
e-mail: levytska28@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_74

Biogas is a renewable energy source and this means it will never run down. According to forecasts, current reserves of natural gas and oil at the current rate of their consumption will last for 50 years, not longer than that.

Biogas production facilities are located close to a consumer, raw materials for its production are also found in the proximity of the plants. There is no need to transport gas to long distances.

With a view of dependency of our country on imported energy resources and biogas advantages as opposed to natural gas, investigation of the prospects of its production launching is of high relevance.

Overview of recent studies and publications. Issues of green power generation and consumption is being dealt with by a number of international and domestic scientists, including D. Deublein, A. Steinhauser, N. Board, D. House, G.M. Kaletnik, V.O. Dubrovin, M.O. Korchemnyi, G.G. Geletukha, J.V. Kernasiuk, M. O. Korchemnyi, M. Kobets and others. Most of the authors whether focus on a technical side of biogas productions or on international practices, therefore there is a requirement for justification of financial aspects of biogas production in Ukraine.

Presentation of the essence of the study. Today biogas production as an element of green power generation became the most popular topic for discussion both in Europe and worldwide. Access to biogas supplies would allow many companies to solve number of issues at the same time: reducing energy costs and minimizing dependency on energy supply [1–4].

List of organic wastes suitable for biogas production: manure, droppings, grain and molasses distillery dregs, brewer's grains, beet root pulp, sewage cake, waste of fish factories and slaughterhouses (blood, fat, intestine, paunch content), grass, domestic waste, dairy waste—salty and sweet whey, waste from biodiesel production—technical glycerin, in particular from production of biodiesel made of rapeseed, waste from juice production—fruit, berry, vegetable pulp, algae, waste from the production of starch and syrup—pulp and syrup, potato processing waste, potato chips production waste—peelings, rotten tubers, coffee grounds. In addition to waste, biogas can be produced from specially grown energy crops, such as silage corn, algae.

Biogas yield depends on dry weight of the material and type of the raw material used. One tonne of cattle manure is enough to produce 50–65 m^3 of biogas with methane content of 60%, 150–500 m^3 of biogas with methane content up 70% can be made of various species of plants. Maximum biogas yield of 1300 m^3 with methane content up to 87% can be produced using fat as a raw material. Biogas production helps to reduce methane air emissions.

From 1991 to 2010, renewable energy generation in European Union has doubled up to 12.4% of the total end consumption EU-27.

Biogas production and its use in power generation is one of the key sectors of renewable energy resourcing in the world.

World leaders in biogas production are European Union in general and Germany in particular. Total number of biogas sets or BGS in Europe is over 11 thousand including 7.2 thousand units in Germany [5–7].

The total production of biogas in the EU-25 in 2010 was 10.9 million tonnes (the equivalent of 13.5 billion m^3 of natural gas) including 6.7 million tonnes produced in Germany with the annual volume increase of 31.3%.

In 2011, 56.7% of all biogas produced in the EU was generated in biogas sets using both farming industry waste and plants specially grown for this purpose as a raw material. One third of all biogas was obtained at landfills. The remaining 12% was produced at sewage treatment plants.

Biogas is mainly used for power and heat generation. In 2011, electricity generation from biogas in the EU has increased compared to 2010 by 18.4% to 35.9 TWh. For the same period of time, sales of the heat generated from biogas to the business and heat networks increased by 16% to 2.2 million tonnes.

The share of electricity from biogas in the total electricity generation from renewable energy sources in the EU is 4.5, and 24.4% in the electricity generation from biomass.

According to the forecasted structure of power generation from renewable energy sources presented by the European Commission, in 2020 the share of power from biogas will be 8% exceeding the contribution of small hydropower, geothermal, solar energy and electricity from solid domestic waste [8, 9].

In recent years rapid development of purified biogas production projects has been taking place designed to feed biomethane into natural gas networks.

In 2011, there were about 180 units producing biomethane in EU, 130 of which were supplying biomethane to gas distribution networks. Biomethane from other units was used as motor fuel for vehicles.

The total production of biomethane in eight EU countries in 2010–2011 amounted to 0.5 billion m^3 per year.

Large volumes of biogas and biomethane production are explained by addition of specially grown crops used as raw materials, mainly silage corn. For example, in Germany 1 million hectare was used for this purpose representing 8.3% of the total arable land.

According to analysts, the biogas market continues to grow rapidly substituting other energy sources in the total energy mix of the member states.

There are few examples of biogas technology implementation in Ukraine. The first biogas set was erected in 1993 at the pigfarm owned by Zaporizhstal. Agro-Oven, Elite, Ukrainian dairy company were the next in line (Table 1).

The purpose of the biogas set introduction at Zaporizhstal steel mill was effluents treatment and reduction of power consumption. Biogas is used in generation heat for own needs of the pig farm operated by the steel mill.

At the pig farms operated Agro-Oven corporation electricity produced in the biogas set is used for own needs of the set and those of the location so that the cogeneration plant is not connected to the grid [10, 11, 12].

Operation of BGS owned by Elita company was suspended in 2011 due to its unprofitableness in the absence of “green” rate of GR. The only biogas power generation plant connected to the grid is BGS operating at the farm of “Ukrainian dairy company”.

Table 1 List of operating biogas sets in Ukraine

Company	Year of commissioning	Livestock population	Raw material	Raw material feed, tonnes per day	Reactor volume (m^3)	Power (KW)	Process
Pigfarm of Zaporizhstal steel mill.	1993	12,000	Manure	20–22	595	–	Bigadan Ltd, Denmark
Pigfarm of Agro-Oven corporation, Olenivka, Dnipropetrovsk region	2003	15,000	Manure, waste fat	80	2 × 1000	180	BTG, the Netherlands
Elita farming company, Terezyne, Kyiv region	2009	1000	Manure	60	1500	250	LIPP, Germany
Cattle farm owned by UMK, V. Krupil, Kyiv region	2009	6000	Manure	400	3 × 2400 + 1 000	955	Zorg, Ukraine

In September 2011, construction of a biogas plant commenced at the pig farm in the village Kopanky, Ivano-Frankivsk region.

In 2012, Myronivskyi Khliboproduct commenced construction of biogas set at Oril-Leader chicken farm in the Dnipropetrovsk region. Ukrlandfarming company are planning to implement an ambitious biogas production program involving thirty BGSs.

In 2012, farming and industrial holding Astarta-Kyiv announced construction of a plant at sugar factory in Globino (Poltava region) financed from EBRD loan.

For the last 14 years, Company Enzyme have erected set of treatment plants, which have no analogues in Western Ukraine. Biological methods of wastewater treatment in accordance with international technologies are used here. The company launched the first large-scale environmental project to create an innovative complex of high-tech treatment facilities back in 2002. New phase started in 2016 when modern process line was put into operation, which allows to enhance the process of purification, reduce the load on municipal wastewater treatment plants and receive large quantities of biogas for own needs of the company.

Water treatment facility of Company Enzyme occupies an area compared to that of a football field Basically it is a plant within a plant State-of-the-art equipment from Germany, Netherlands, Switzerland, Poland, France, Italy is used in this facility [13].

In 2016, a new process line for advanced anaerobic wastewater treatment was commissioned. This is a cutting-edge process plant that includes: Wastewater preparation area, anaerobic tanks and biogas conditioning, drying and storage tanks. Modern technology and best practice of the countries of the Western Europe were used in this facility. Sewage treatment process is 100% automatic, including both process control and monitoring.

The plant consists of anaerobic (oxygen free) and aerobic (oxidizing) stages of wastewater treatment. In the process of effluents purification biogas is produced. Key performance indicators of the plant constructed in 2004: approx. 2000 m^3 of biogas per day replacing 20% of demand for natural gas. Plant performance targets for 2016–2017: approx. 7000 m^3 of biogas per day replacing 70% of demand for natural gas. The plant is operated in 24 h a day 360 days a year mode. To ensure uninterrupted operation of a pumping station the backup equipment is installed.

So what is biogas production process? In the anaerobic reactor an energy carrier is produced from raw materials—the organic component—in the form of biogas for own use. The next stage is purification of wastewater in aerobic stations and obtaining organic fertilizers to be sold to farmers.

In addition to biogas, the company uses other methods of the company energy efficiency enhancement. For instance, cogeneration (combined heat and power generation) has been in operation for over 15 years.

Advanced treatment of wastewater takes place in the facility. Water treatment happens in several stages. Industrial effluents proceed to the anaerobic stage first where biogas is produced during the initial treatment. As the next step the water is sent to the second stage of treatment, an aerobic one, at which an organic/mineral fertilizer is produced. Purified wastewater is transported to the municipal treatment plant in a separate sealed manifold in the outskirts of the city.

Biogas production already satisfies 50% of the company demand and the target is to cover 70% of its needs. As one of the largest enterprises in Lviv, the company strives to keep up with environmental trends. To become a standard that can be followed by other companies [13–15, 16].

Since 2004, Company Enzyme have invested in this facility about 9.5 million euro and on the top of that around 2.5 million euro has been invested for the past two years. As a result this environmental project received recognition from many foreign experts and scientists. Thanks to it Company Enzyme recently became the face of the city in 2016 in the category "Green City: Environmental Lviv."

Company Enzyme can boast of such an advanced facility not just in Ukraine but also in Europe as European experts already start to express their interest in these advanced technologies. The company has a long and valuable experience in the area of efficient implementation of environmental projects.

Company Enzyme successfully implemented a large-scale environmental and energy efficient project. It has 14 years of experience in the field of sewage treatment and 12 years of experience in biogas production. Soon such environmental technologies will be widely spread in Ukraine.

There is also a representative example of Astarta agricultural holding that has built a plant for biogas production from beet root pulp at Globinskiy sugar plant. Thanks to availability of biogas, natural gas consumption by the sugar factory dropped by 60%.

A landfill in Rybne village outside Ivano-Frankivsk was the first in Western Ukraine to commission a biogas set. It was supplied on a open tendering basis. The city did not spend a single hryvnia on this project. The works were performed as a part of a capital expenditure project. As a result, 23% of power generated by this project goes to cover the needs of the city. According to Ruslan Mazrtsynkiv, the city major, biogas plant will help to solve not just the issues of waste disposal and power generation but will also prevent self-ignition in the landfill. The BGS equipment was erected in a speedy manner.

On April 20, 2017, the major of Kamyanets Podilsky city Mr. Mykhailo Simashkevych had a meeting with representatives of the International Center for Gas Technologies that came up with offer regarding solid waste to gas processing solution. The cost of the project is 1 million US dollars and its payback period is two years. The first step according to this proposal is drilling boreholes at the local landfill in order to determine the ability of the waste to produce biogas. Such solution has been implemented by this center in Zhytomyr, Boryspil, Kyiv.

There are biogas plants in operation at the landfills in Yalta, Alushta, Lviv, Mariupol, Kremenchug, Lugansk, Kyiv and at Bortnychi aeration plant.

The project at Kiev landfill No. 5 implemented by LNK company is the most successful Ukrainian biogas project. There is a set of five biogas fired engines by TEDOM with installed capacity of 177 KW each.

In 2012, 3.26 GWh was generated, delivered to the grid and sold at economically justified rates set by National Electricity Regulatory Commission (NKRE).

The company is extending capacity of this project—it has commissioned 1063 KW gas fired reciprocating engines manufactured by GE Jenbacher.

In addition to that, in June 2013, LNK commissioned the same model of gas fired engines at the landfill in Boryspil. Since May 2013, LNK have been enjoying the advantage of selling electricity produced from biogas at landfill in Boryspil at the "green" rate that is 134.46 kopecks per kilowatt hour.

Ukrainian farming industry as a producer of big quantities of organic waste owns the resources required to produce biogas in amounts that can replace 1.5 billion m^3 of gas per year. Subject to development of the industry and wide use of vegetative raw materials this potential can be extended up to 18 billion m^3 in the equivalent of natural gas [10, 13, 17].

In the first scenario it is planned to use 6% of arable land in Ukraine for the cultivation of corn for biogas with conservative crop yield of 30 tons per hectare. The second option with the higher forecasted volumes foresees use of 7.9 million of the land free from the crops and assumes higher yield.

A large portion of the potential BGS market in Ukraine can be developed by 2030. Prerequisite for realization of these projects in the first phase is the introduction of economically grounded "green" rate for electricity generated from biogas.

To implement energy efficient biogas projects it is important to encourage electricity generation from biogas derived not only from biomass waste, but also from specially cultivated plants.

In parallel with the power generation it would be feasible to introduce biomethane production for direct replacement of natural gas, or more efficient utilization of biogas derived energy during production of electricity and heat.

One of the internationally proven and effective mechanisms of encouraging development of renewable energy is the use of fixed "green" rates for electricity generated from renewable energy sources.

In Ukraine, for electricity produced from biogas a legislatively guaranteed "green" rate has been in place only since April 2013, it is 0.1239 euro per KWh with 2.3 green to standard rate ratio.

Please see the list of legislative barriers on the way of development of energy generation from biomass accompanied with suggestions as for the ways to overcome them.

1. Unreasonably low green to standard rate ratio for electricity generated from biogas.
2. Incorrect definition of the term "biomass".
3. Ungrounded requirement as for the portion of "local manufacture"—share of the cost of equipment, materials and services of domestic manufacture in a project budget.
4. Terminology errors in the description of the main elements of equipment for biogas fired power generation plants.
5. Discriminatory approach to biogas plants commissioned before 1 April 2013 [8, 18].

Besides legislative barriers, there are other problems of biogas production development.

1. Lack of regulatory framework.
2. Problems with applying tax benefits while importing biomass energy generation equipment.
3. Lack of targeted financing of BGS local manufacture projects.
4. Lack of development program for this sector of the industry.

Given the technical and economic feasibility and the current structure and size of Ukrainian agricultural enterprises the market size for biogas plants is estimated as 1600 units equipped with mini heat stations sizing from 100 KW. Total installed capacity of BGS could reach 820 MW of electric power and 1100 MW of heat energy.

For example, two-thirds the volume of biogas will be produced from silage corn and remaining one third—from waste. The arable land area required to grow the required amount of silage corn is 0.15 million hectare that is 0.5% of its total area in the country or 4.3% of the area of arable land available in 2011.

Potential availability of heat energy produced in mini heat plants is 0.395 and 2.234 million Gcal in 2030. 5200 jobs will be created by 2030 and greenhouse gas emissions reduction will make up 6 million tonnes per year.

For rapid growth of biogas production volumes and deriving energy generation it is necessary to create conditions for development of this business. The priority is increasing "green" rate to 0.1616 euro per KWh for biogas produced from farming waste and to 0.1454 euro per KWh for other biogas types.

With intense construction of biogas plants, investments in this industry sector by 2030 are expected to exceed 15 billion USD [8, 19].

2 Summary

Thus biogas production as element of green power generation has good prospects.

It will be economically viable to cover 9 and 51% of BGS market by 2020 and 2030 correspondingly. The total annual generation of electricity in 2020 and 2030 may reach 0.45 and 2.5 billion KWh correspondingly.

Biogas production is growing rapidly in the world with the trend towards intensification of existing technology and search for new raw materials and their processing technologies, maximization of utilization of biogas energy potential.

In the future, the development of biogas technology in Ukraine will produce 1.5–6 billion m^3 in natural gas equivalent annually. This will be a significant contribution to ensuring energy independence.

Currently biogas production primarily attracts processors that receive biogas from waste recycling and use it for their own purposes. Biogas technology has become a standard for wastewater treatment, farming and municipal solid waste disposal and is in use in most countries of the world.

Biogas production will allow to reduce the energy dependence of our state, create new jobs and solve the problem of waste generation including that of livestock farming, improve the environment.

References

1. Bechin, K.L.: Addressing obstacles in the biomass feedstock supply chain. Biomass Power and Thermal, BBI International (2011)
2. Tomowsky, A.: GTZ Biogas-experience in Africa. Presentation held at international Workshop on the Biogas Sanitation Initiative for Africa'. Amsterdam, Oct 2006. Unpublished. A brief summary of lessons learned by GTZ over more than 20 years of biogas activity in Africa (2006)
3. Suh, Y.J., Roussaux, P.: An LCA of alternative wastewater sludge treatment scenarios. Resour. Conserv. Recycl. **35**, 191–200 (2002)
4. Mudryk, K., Bendera, I., Jewiarz, M.: Scientific achievements in agricultural engineering, agronomy and veterinary medicine: Polish-Ukrainian cooperation [Electronic resource]: scientific monograph. State Agrarian and Engineering University in Podilya, Agriculture University in Kraków, vol. I, p. 170, Traicon, Kraków (2017)
5. Franz, M., von Mitzlaff, K.: The biogas market in Kenya—Status Quo and Potentials. Presentation for combined biogas business and study trip from Kenya and Tanzania, to Hannover, 13 Nov 2009. German Technical Cooperation (GTZ) (2009)
6. Bremdal, B.A.: Prosumer Oriented Business in the Energy Market (IMPROSUME Publication Series#2). Narvik University College and Norwegian Center of Expertise for Smart Energy Markets, Narvik, Norway and Halden, Norway (2011)
7. Oyedepo, S.O.: Energy and sustainable development in Nigeria: the way forward. Energy Sustain. Soc. **2**, 15 (2012)
8. Marchaim, U.: Biogas processes for sustainable development, pp. 1–99. FAO, Italy (1992)
9. Janisch, A., Euston-Brown, M., Borchers, M.: The potential impact of efficiency measures and distributed generation on municipal electricity revenue: double whammies and death spirals. Sustain. Energy Afr. (2012)
10. Raninger, B.: Biomass-waste management—a contribution to a low CO_2-circular economy and an environmental sound urban & rural development. In: Presentation to International Symposium on 'City Group Development Model', Changsha, Hunan, China, 3–4 Dec 2009 (2009)
11. Masiá, A., Ahnert, F., Spliethoff, H., Loux, J., Hein, K.: Slagging and fouling in biomass Co-combustion. Thermal Sci. **9**(3), 85–98 (2005)
12. Spichak, V., Sidorchuk, O., Lub, P., Hutsol, T., Zelensky, O.: Methodology of production-technological risk management on the basis of statistical imitation modeling of projects works. Eastern-European J. Enterp. Technol. **10**(61), 89–92 (2013)
13. Swedish practices of biogas production. Economical development of the community. Issue 1, No. 6 (2005)
14. Kerroum, D., Mossaab, B., Hassen, B.A.: Production of biogas from sludge waste and organic fraction of municipal solid waste. University Mentouri Constantine, Algeria
15. Salam, P.A., Kumar, S., Siriwardhana, M.: Report on the status of biomass gasification in Thailand and Cambodia. Prepared Energy Environ. Partnership (EEP), Mekong Region (2010)
16. Misuk, M., Zahodym, M., Ievstafieva I.: Methodological approaches to assessment of the competitiveness of production of mill-refinery enterprises. International scientific and practical conference World Science vol. 2, No. 5(21), pp. 21–26. ROST, UAE (2017)

17. Weiland, P.: Biogas production: current state and perspectives. Appl. Microbiol. Biotechnol. **85**(4), 849–860 (2010)
18. Ogwueleka, T.C.: Municipal solid waste characteristics and management in Nigeria. Iran. J. Environ. Health. Sci. Eng. **6**(3), 173–180 (2009)
19. UNIDO: Deployment of Technologies for Sustainable Bioenergy: Towards an Agenda for International Cooperation. UNIDO, Vienna (2009)

Energy Parameters' Calculation of a Hybrid Heat Supply System for a Private House in the Conditions of Western Part of Ukraine

Yurii Pantsyr, Ihor Garasymchuk, Taras Hutsol and Ivan Gordiychuk

Abstract In the article the power supply scheme of a private house was developed for the Western Ukraine region conditions with Sun energy usage and soil thermal energy. It was evaluated the annual heat-flux density of the scheme. The solar collectors are justified and selected The parameters have been calculated and the heat pump was chosed The proposed hybrid system of heat supply for a private house with the solar energy usage and soil heat can save more than 5 thousand cubic meters of natural gas per year, which will bring the corresponding economic effect. The payback period of the necessary additional capital investments is just over 6 years.

Keywords Hybrid system · Heat pump · Solar collecting panel

1 Introduction

Completeness of natural gas reserves, as well as other fossil energy carriers, as well as their constant and significant increase in price, necessitate the search for alternative energy sources. In the western region of Ukraine there are many sunny days, so it is advisable to use the thermal energy of the sun for heating, as well as heating the water in a private house. And since in some periods the heat is received from solar collectors may not be enough, and also for more guaranteed provision with thermal energy, it is advisable to use in parallel a heat pump that uses low-potential energy of the soil [1].

Considering this, the goal of the work is the hybrid system development of power supply for a private home due to the energy of the sun and the soil heat.

Y. Pantsyr · I. Garasymchuk (✉) · T. Hutsol · I. Gordiychuk
State Agrarian and Engineering University in Podilya, Khmelnytskyi, Ukraine
e-mail: igorgarasymchuk@gmail.com

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_75

To achieve this goal, it is necessary to solve the following tasks

- To determine the heat load of the heating system;
- To calculate the heat load of the hot water supply system;
- To Estimate the total heat load;
- To select the parameters of the solar power plant;
- To Conduct an analysis of monthly energy balances;
- To calculate the heat pump parameters.

1.1 The Input Parameters of Private House Energy Supply

To calculate the hybrid heat supply system of a private house, let us set the following input parameters (average for a typical private house of a given geographical location)

- The volume of the building by its external dimensions $V = 840\ \text{m}^3$;
- Specific heat dissipation of the house $q_0 = 0.50\ \frac{\text{W}}{\text{m}^2\,\text{gon}}$;
- Minimum temperature of the coldest five-day period $t_{\text{cp}}^{min} = -17\,°\text{C}$;
- The maximum number of people who live or work in this house $N = 10$ pers.;
- Rate of hot water consumption per person $a = 30\frac{l}{\text{pers.}}$;
- Specific heat of soil $q = 20\ \frac{\text{W}}{\text{m}^2}$;
- Other parameters for easy calculation are included in Table 1.

Solar energy is converted into heat in a flat solar collector (SC) and transferred by a liquid coolant to a boiler-heat accumulator, from where it is used, if necessary, in hot water. The solar parameters of installation are calculated for 80% of the degree coverage of the house's need for hot water during the eight-month season: from March 1 till October 30.

The main heat load of the house heating system is provided by a heat pump which takes low-potential heat from the soil. The maximum thermal power of the pump is selected according to the requirements of the full coverage of the building's thermal load in the cold five-day period of the year. In heating systems, the heat pump mainly works at night, when the temperature on the street is low, and the cost of electricity is the least.

Table 1 Average monthly ambient temperatures t_{ns} of tap water t_{cp} and soil temperature t_s

Parameter	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
t_{cp}	−5.4	−5.0	−0.4	8.8	16.4	20.1	24.2	23.1	19.6	10.2	2.0	−2.0
t_{min}	5	5	5	5	6	12	18	18	14	12	8	6
t_{s}	10	10	10	10	11	12	12	12	12	11	10	10

Therefore, a heat accumulator (HA) is also proposed in the heating circuit (possibly combined with a solar system) to accumulate excess heat. During the day, the HA is discharged directly to the heating devices, and if its temperature drops below the allowable temperature, the heat pump starts.

The solar and heat pumps of the heat supply system are more effective than lower temperature at their outlet. Therefore, in the calculations are guided by low-temperature parameters of the coolant, which are inherent in the panel (floor) or air heating circuit. The latter allows the heat pump system usage and in summer—in the air conditioning mode and hot water production as by-side thermal release of the heat pump system.

1.2 Determination of the Heating Load of the Heating System

Calculations used in the work were carried out according to the methods and algorithms were given in [2–5].

The heating system compensates for heat loss at house, the power of which is estimated by the formula

$$P_{\text{heat loss}} = q_0 V_{\text{house}}(18 - t_{\text{cp}}), \text{W} \tag{1}$$

where

q_0	Specific power of heat, W/m^3 gon;
V_{house}	Heating volume of the building, calculated by its external dimensions, m^3;
18 °C	normalized internal temperature
T_{et}	environment temperature.

We'll give an example of calculating the heat loss at the house and in January

$$P_{\text{heat loss}} = 0.50 \cdot 840(18 - 5.1) = 9702\,\text{W}$$

The results of calculating the heat loss of a private house in other months are shown in Table 2.

The maximum capacity of the heating system is designed to provide comfortable conditions in a cold five-day period for a given area t_{cp}^{min},

$$\begin{aligned} P_{heat\,loss}^{max} &= q_0 V_{house}(18 - t_{cp}^{min}), \text{W} \\ P_{heat\,loss}^{max} &= 0.50 \cdot 840(18 + 17) = 14{,}700\,\text{W}. \end{aligned} \tag{2}$$

Average daily heat load of the heating system is calculated monthly, for the average monthly temperature of the environment t_{cp}:

Table 2 Results of thermal loads calculation Q in MJ, P in kW

Parameter	Months												The yearly tale
	1	2	3	4	5	6	7	8	9	10	11	12	
$Q^{d}_{heat\ loss}$	838.3	834.6	667.7	333.8	–	–	–	–	–	283.0	580.6	725.8	–
$Q^{\min}_{heat\ loss}$	25,986	23,369	20,699	10,014	–	–	–	–	–	8773	17,418	22,500	128,765
Q^{d}_{hw}	114.6	114.6	114.6	114.6	110.2	99.0	82.0	79.3	87.8	96.3	104.8	110.2	–
$Q^{\min}_{hw}$	3552.6	3208.8	3552.6	3438	3416	2970	2460	2458	2634	2995	3144	3416	37,244
$Q^{\mathrm{M}}_{\mathrm{TL}}$	29,538.6	26,578	24,251	13,452	3416	2970	2460	2458	2634	11,774	20,562	25,916	166,009
P^{M}_{hw}	1.32	1.32	1.32	1.32	1.27	1.14	0.94	0.91	1.01	1.07	1.21	1.27	–
P^{M}_{NL}	11.03	10.25	9.36	3.49	1.31	1.14	0.95	0.95	1.01	4.53	7.91	9.97	–
P_{me}	9.7	9.7	7.7	3.9	0.7	–	–	–	–	3.3	6.7	8.4	–

$$Q^{d}_{heat\,loss} = 86.4\,q_0 V_{\text{house}}(18 - t_{cp}), \text{kJ} \quad (3)$$

1.3 The Heat Load Determination of Hot Water Supply System

The daily heat load of hot water supply system of a private house is calculated by the formula

$$Q^{i}_{hw} = 1.2\,a\,c_p \rho(t_{hw} - t_{\min}) \cdot N, \text{kJ} \quad (4)$$

where:

Q^{i}_{hw} Daily heat load, kJ;
a Rate of hot water consumption per person in l/day;
c_p 4.19 kJ/kg gon—Specific heat of water;
ρ 1.0 kg/l—density of water;
N Number of persons;
T_{hw} 45 °C—Normalized temperature of hot water;
$t_{\min}$ cold tap water temperature at the inlet to the heating device.

The same formula calculates the monthly average daily load of a hot water supply system Q^{d}_{hw} using the average monthly cold water temperature t_{min}. For example, the value of the average daily load for January:

$$Q^{d}_{hw} = 1.2 \cdot 30 \cdot 4.19 \cdot 1.0(45 - 5) \cdot 10 = 114{,}638.4\,\text{kW}.$$

Similarly, calculations for other months are carried out, and its results are listed in Table 2.

Average monthly values of the daily capacity of the hot water supply system in kilowatts are calculated by the formula

$$P^{M}_{hw} = 1.15 \times 10^{-5} Q^{d}_{hw}, \text{kW} \quad (5)$$

For January, it is

$$P^{\mathcal{M}}_{hw} = 1.15 \times 10^{-5} \cdot 114{,}638.4 = 1\,\text{kW}.$$

In the solar system of hot water supply we assume a backup electric heater. Its power is selected provided that the specified volume of low-temperature water is fully heated during the night energy tariff (8 h):

$$P_{res}^{M} = \frac{Q_{hw}^{d}}{6} \cdot 0.000278 = 114{,}638.4 \cdot 4.6 \times 10^{-5} = 5.3\,\text{kW}.$$

In particular, reserve capacity is required for January

$$P_{res} = 5.3 \cdot 1.32 = 7.0\,\text{kW}.$$

The monthly load of the hot water supply system is calculated by the daily average for the number of days in a month

$$Q_{hw}^{M} = 114.6 \cdot 31 = 3552.6\,\text{kJ}.$$

The annual load of the HW system is calculated as the monthly sum

$$Q_{hw}^{\text{p}} = \sum_{i=1}^{12} Q_{hw}^{\text{M}} = 14{,}991\,\text{kJ} \tag{6}$$

The calculation results are listed in MJ and are listed in Table 2 Conversion kJ into kW h is performed according to the relation

$$1\,\text{kJ} = 0.000278\,\text{kW h}.$$

1.4 Calculation of the Total Heat Load

The monthly heat load of the heat supply system is calculated as the sum

$$Q_{\text{TH}}^{\text{M}} = Q_{\text{ОП}}^{\text{M}} + Q_{\Gamma\text{В}}^{\text{M}}, \text{kJ} \tag{7}$$

In January the calculation result will be as follows:

$$Q_{TL}^{M} = 25{,}986 + 3552.6 = 29{,}538.6, \text{kJ}.$$

The annual thermal load of the system is equal to the sum of the monthly ones:

$$Q_{TL}^{p} = \sum^{12} Q_{TL}^{\mathcal{M}} = 81{,}495\,\text{kJ}.$$

The monthly average load capacity of the heat supply system in kilowatts is calculated by dividing the monthly heat load in kJ by the number of seconds in a month:

$$P_{TL}^{\mathcal{M}} = \frac{Q_{TL}^{\mathcal{M}}}{24 \cdot n \cdot 3600}, \text{kW} \quad (8)$$

In January, the average capacity of the heat supply system is

$$P_{TL}^{\mathcal{M}} = \frac{29{,}538.6}{24 \cdot 31 \cdot 3600} = 11.03\,^{\circ}\text{C}.$$

In addition, the maximum heat loss capacity in a cold five-day period

$$P_{TL}^{max} = P_{heat\,loss}^{max} + P_{hw}^{1} \quad (9)$$

where $P_{hw}^{1} = 1.15 \times 10^{-5}\, Q_{hw}^{1} = 1.15 \times 10^{-5} 114{,}638.4 = 1.3\,\text{kW}$;

$$P_{TL}^{max} = 14.7 + 1.3 = 16\,\text{kW}.$$

The results are listed in Table. 2.

1.5 The Solar Energy Amount Determination of Entering the Solar Collector

For the calculations were used the values of the average daily solar radiation fluxes to the horizontal surface, which were taken from meteorological data.

$H_{th}^{\text{d}}, \text{J/m}^2$	Average daily intake of total solar radiation per month on a horizontal surface;
$H_{dh}^{\text{d}}, \text{J/m}^2$	Average daily intake of scattered solar radiation per month on a horizontal surface;
β	angle of inclination of the heliocollector surface to the horizon, degrees;
m	the ordinal number of the day in a year;
δ	solar declination for the current day of the year, gon;
φ	geographical breadth of region, gon, P Sh;
A_h, A_β	the azimuthal angles of the sunset direction for the horizontal plane and inclined at an angle β to the horizon, gon;
r	is the reflection coefficient of the sun's rays by the soil surface.

The ordinal number of the day in the year is calculated as of the 15th day of each month: January 15 m = 15; February 15, m = 31 + 15 = 46, etc.

The solar declination δ is calculated by the formula:

$$\delta = 23.5\,\sin\frac{284 + m}{365} \cdot 360\,\text{gon}. \quad (10)$$

In summer, $\delta > 0$, in winter $\delta < 0$, and on the day of the spring and autumn equinox (March 21 and September 21) $\delta = 0$. In January, for example, the solar declination is

$$\delta = 23.5\ \sin\frac{284 + 15}{365} \cdot 360 = -21.3\,\text{gon}.$$

The inclination optimal angle of the solar collector to the horizon is calculated from the formula

$$\beta = \varphi - \delta_{cp}, \text{gon} \tag{11}$$

where δ_{cp}—Means value of solar declination for the billing period:

$$\delta_{cp} \cong \frac{1}{12}(\delta_1 + \delta_2 + \delta_3 + \delta_4 + \delta_5 + \delta_5 + \delta_7 + \delta_8 + \delta_9 + \delta_{10} + \delta_{11} + \delta_{12}), \text{gon}. \tag{12}$$

The value of the solar declination at the middle of each month from January 1 to December 31 is taken from meteorological data. The average seasonal declination δ_{cp} calculated from these data and the optimal inclination angle β level:

$$\delta_{cp} = \frac{1}{12}(-21.3 - 13.3 - 2.8 + 9.4 + 18.8 + 23.4 + 21.2 + 13.8 + 2.2 - 9.6 - 19.2 - 23.4) = 0.2^\circ;$$

$$\beta = 50–0.2 = 49.8^\circ.$$

The sunrise azimuth angle for the horizontal plane is calculated by the formula

$$A_h = \arccos[-tg\varphi \cdot tg\delta], {}^\circ. \tag{13}$$

In January, for example, the azimuth angle of sunrise is

$$A_h = \arccos[-tg50 \cdot tg\delta(-21.3)] = 62.3^\circ.$$

The azimuth angle of the sunrise for the case of the surface of the SC inclined at an angle β to the horizon is calculated from

$$\begin{aligned} A_\beta &= \arccos[-tg(\varphi - \beta) \cdot tg\delta], {}^\circ. \\ A_\beta &= \arccos[-tg(50 - 49.8) \cdot tg(-21.3)] = 90.03^\circ. \end{aligned} \tag{14}$$

In January, the sunrise angle for the inclined plane exceeds that for a horizontal surface is impossible. Therefore, by fulfilling the additional condition $A_\beta \leq A_h$, the azimuthal sunrise for the older collector is assumed to be the same as for the horizontal surface: $A_\beta = A_h = 62.3^\circ$.

The recalculation of the arrival of only direct radiation from the reference value for the horizontal surface to the value for the surface inclined at an angle β to the horizon and oriented in the south direction is carried out through the auxiliary coefficient R_β:

$$R_\beta = \frac{\cos(\varphi - \beta) \cdot \cos\delta \cdot \sin A_\beta + \frac{\pi}{180} A_\beta \sin(\varphi - \beta) \cdot \sin\delta}{\cos\varphi \cdot \cos\delta \cdot \sin A_h + \frac{\pi}{180} A_h \sin\varphi \cdot \sin\delta} \quad (15)$$

In particular, in January the auxiliary coefficient is

$$R_\beta = \frac{\cos(50 - 49.8) \cdot \cos(-21.3) \cdot \sin 62.3 + \frac{\pi}{180} 62.3 \sin(50 - 49.8) \cdot \sin(-21.3)}{\cos 50 \cdot \cos(-21.3) \cdot \sin 62.3 + \frac{\pi}{180} 62.3 \sin 50 \cdot \sin(-21.3)} = 3.8.$$

The conversion factor R of the total solar radiation input from the value for the horizontal surface which was given in the directory to the value for the inclined surface was calculated by the formula

$$R = \left(1 - \frac{H_{dh}}{H_{th}}\right) R_\beta + \frac{H_{dh}}{H_{th}} \cdot \frac{1 + \cos\beta}{2} + r \frac{1 - \cos\beta}{2} \quad (16)$$

The value of albedo r in summer is taken equal to 0.2, and in winter—0.7.

For example, this factor for January will be

$$R = \left(1 - \frac{2.592}{3.678}\right) 3.8 + \frac{2.592}{3.678} \cdot \frac{1 + \cos 49.8}{2} + 0.7 \frac{1 - \cos 49.8}{2} = 1.8.$$

The average daily (per month) intake of total solar radiation per 1 m^2 of the inclined surface of the SC is calculated by multiplying:

$$H_\beta^{д} = RH_{th}, MJ/m^2 \quad (17)$$

In January, the average daily supply of solar energy to the inclined surface of the SC will be:

$$H_\beta^{д} = 1.8 \cdot 3.093 = 5.78 \; MJ/m^2.$$

Monthly and annual intake of total solar radiation per 1 m^2 of the inclined surface of the SC is calculated by multiplying by the number of days n in a month and the subsequent summation of monthly correspondences:

$$H_{\beta}^{\text{M}} = nH_{\beta}^{\text{Д}}, MJ/m^2; \tag{18}$$

$$H_{\beta}^{p} = \sum_{i=1}^{12} RH_{\beta}^{i}, \text{MJ/m}^2. \tag{19}$$

The calculation of the corresponding values for January and the year as a whole are given below:

$$H_{\beta}^{1} = 31 \cdot 5.78 = 179.33\,\text{MJ/m}^2;$$

$$H_{\beta}^{c} = \sum_{i=1}^{12} RH_{\beta}^{i} = 4465.6\,\text{MJ/m}^2.$$

The calculations' results for the remaining months of the year are summarized in Table 3.

2 Analysis of Monthly Energy Balances

The solar heat supply system peculiarity is the uneven generation of heat energy during the year with the practically stable heat load of the hot water supply system. Seasonal unevenness of the thermal energy can be partially smoothened by changing the angle of inclination of the solar collector to the horizon β. But at the same time, the volume of heat production decreases [6, Fig. 1.8].

The increase in the number of solar collectors will increase the reliability of the heat supply system and expand the season of using solar energy, but due to the increase in the cost of the installation. Conversely, if the total area of the SC is reduced, the effective life of solar installations is limited only by the warm period of the year. Therefore, the final recommendations on the operating parameters of the proposed solar plant will be developed based on the analysis of monthly energy balances. It also concludes that:

- correspondence of monthly solar energy input from the calculated amount of SC to the needs of the hot water supply system in house;
- the electricity amount or heat necessary to compensate for the insufficient capacity of solar collectors in covering the needs of hot water supply during periods of solar radiation low level;
- the solar energy share in covering the total heat loss in house during the winter (four-month) period with the selected area of the SC;
- the excess energy amount in summer;
- The need to correct the number of solar collectors (Fig. 1).

Table 3 Results of calculation of solar energy parameters

Mom	H_{th}, $\frac{MJ}{m^2}$	H_{dh}, $\frac{MJ}{m^2}$	H_0 $\frac{MJ}{m^2}$	*m*	δ, gon	A_h, gon	A_β, gon	*r*	R_β	*R*	$\dot{H}_\beta^{д}$ R' $\frac{MJ}{m^2}$	H_β^{M}, $\frac{MJ}{m^2}$
1	3.093	2.383	9.0	15	−21.3	62.3	−92.5	0.7	3.8	1.79	5.78	179.3
2	5.35	3.846	14.5	46	−13.3	73.6	−91.5	0.7	2.6	1.63	9.07	254.1
3	9.78	5.434	22.3	74	−2.8	86.6	−90.3	0.7	1.67	1.32	13.04	404.5
4	13.96	7.399	31.2	105	9.4	101.4	−88.9	0.2	1.13	0.98	13.92	417.7
5	18.78	9.447	38.1	135	18.8	113.9	−87.8	0.2	0.84	0.85	16.81	521.3
6	21.82	10.24	41.2	166	23.4	121.0	−87.2	0.2	0.73	0.79	17.52	525.9
7	20.48	9.865	38.6	196	21.2	117.5	−87.5	0.2	0.78	0.82	17.96	556.8
8	17.18	8.151	33.8	227	13.8	107.0	−88.5	0.2	0.99	0.94	16.93	525.1
9	12.62	5.894	25.4	258	2.2	92.6	-89.7	0.2	1.47	1.21	15.88	476.6
10	7.315	3.782	16.7	288	−9.6	78.4	−91.1	0.2	2.23	1.49	10.67	330.9
11	2.968	1.797	10.3	319	−19.2	65.5	−92.2	0.7	3.25	1.63	4.65	139.8
12	2.132	1.714	7.6	349	−23.4	59.0	−92.8	0.7	4.3	1.91	4.31	133.7

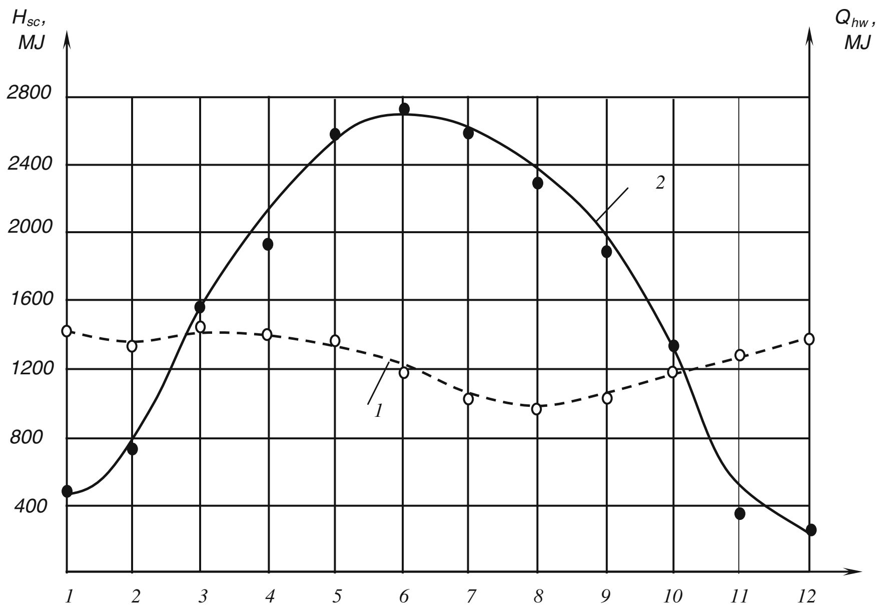


Fig. 1 Monthly energy balance of the solar hot water supply system

2.1 The Parameters' Calculation of the Heat Pump System

The heat pump work is possible in two modes—monovalent and most suitable for our case bivalent (Fig. 2). In the first mode, as a rule in winter, the heat pump completely covers the heat load at home, and in the second - it works together with the solar system. In addition, it is possible to break the power supply three times a day at 2:00, which occurs in rural electricity networks.

Necessary for the calculation of the pumps' operating characteristics in the linear dependences form of the thermal power of the P_{HP}, the electric power P_{el} and the conversion factor ε on the temperature of the primary heat source, in this case—the soil temperatures t_{soil} are taken from [7]. The heating medium output temperature is chosen equal to 35 °C, which completely satisfies the requirements of the floor heating system.

The heat pump brand is chosen according to its rated capacity P^0_{HP}, sufficient to compensate for the maximum heat load of the building in a cold five-day period = $P^{max}_{TL} = 16\,\text{kW}$. This takes into account the limited period of its operation due to possible power outages three times two hours during the day. Then the rated power must correspond to the value

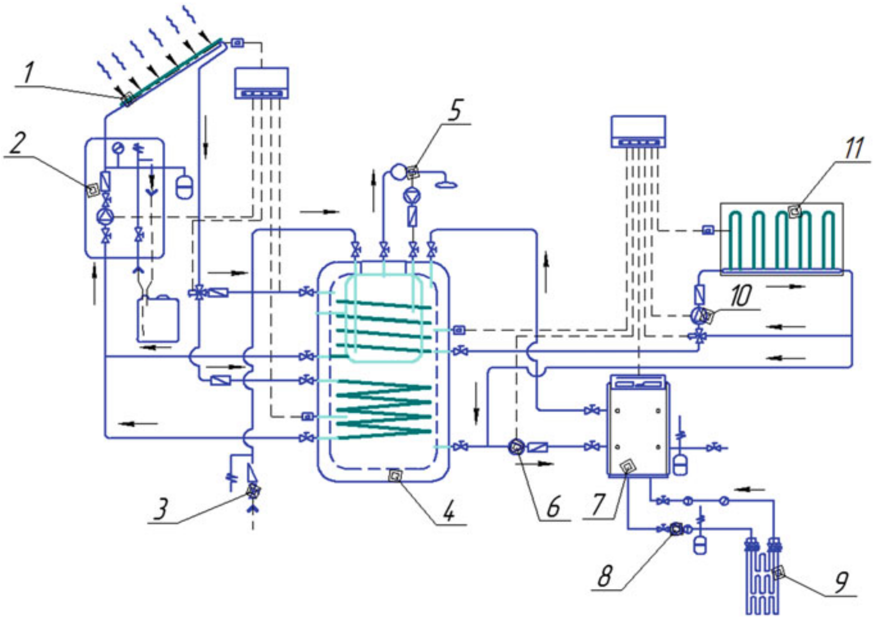


Fig. 2 Hybrid scheme of heat supply in the solar installation and heat pump: 1—solar collectors; 2—pump group and control unit; 3—tap water inlet; 4—universal heat exchanger-heat accumulator; 5—the mixer; 6, 8, 10—circulation pumps of circuits 7—heat pump; 9—screw heat exchanger; 11—panel (floor) heating device

$$P^0_{HP} \geq \frac{24 \cdot P^{max}_{TL}}{18 + 2} = 1.2 P^{max}_{HP}$$
$$P^0_{HP} = 1.2 \cdot 16 = 19.2\,\text{kW}. \quad (20)$$

Two in the denominator are introduced as an amendment to the thermal inertia of the house.

The received value of thermal power corresponds to the pump BW110 with the corresponding energy and performance characteristics. The current average monthly operating modes of the selected heat pump—thermal $P^{\mathcal{M}}_{HP}$ and electrical P^{M}_{HP} power and conversion factor ε^{M}—are set from the operating characteristics in accordance with the monthly average soil temperature.

The average daily τ^{d} and monthly τ^{M} the heat pump operation duration is calculated by dividing the average monthly heat load Q^{M}_{TL} (in kW hours) which are given in Table 2, the current capacity of the heat pump, is determined from its performance [8, 9, Fig. 3.11, p. 64], taking into account the number of days *n* in the month:

$$\tau^d = \frac{24P_{TL}^M}{P_{HP}^M}; \quad \tau^M = n\tau^d, \text{h.} \tag{21}$$

For example, in January, these values are

$$\tau^d = \frac{24 \cdot 11.03}{20} = 13.2;$$
$$\tau^{\mathcal{M}} = 31 \cdot 13.2 = 409.2\,\text{h.}$$

The daily and monthly values duration of the pump were determined.

Monthly and annual electricity consumption for driving the heat pump is calculated by formulas

$$\begin{aligned} W_{\text{el}}^{\text{M}} &= \tau^{\mathcal{M}} P_{el}^{\mathcal{M}}; \\ W_{\text{el}}^{\text{M}} &= 409.2 \cdot 5.9 = 2414.3\,\text{kW} \end{aligned} \tag{22}$$

$$\begin{aligned} W_{\text{el}}^{\text{p}} &= \sum_{\mathcal{M}=3}^{10} W_{\text{el}}^{\text{M}}; \text{kW h} \\ W_{\text{el}}^{\text{p}} &= 2414.3 + 2029.6 + 2054.4 + 741.0 + 279.0 + 235.0 + 189.1 + 189.1 \\ &\quad + 201.3 + 936.0 + 1467.9 + 2194.8 = 12931.0\ \text{kW h} \end{aligned} \tag{23}$$

The temperature regime of the floor is regulated by changing the flow rate of the heat transfer medium G_{HP} with the temperature difference Δt (input t_{hw} = 35 °C and output, inverse t_{reverse} = 30 °C):

$$\Delta t = t_{hw} - 30\,^{\circ}\text{C} = 45 - 30 = 15\,\text{gon.}$$

The circulation pump selection for the water heating circuit is made at the flow rate of the heat carrier at the heat pump maximum power:

$$G_{HP} = \frac{P_{HP}^{max}}{c_p \cdot \Delta t} = \frac{22.0}{4.19 \cdot 15} = 0.35\,\text{kg/s.} \tag{24}$$

To estimate the necessary heat removal capacity of the soil, the maximum value of the thermal power of the heat pump is divided by its corresponding value

$$P_{\text{soil}} > P_{HP}^{max} - P_{el} = P_{HP}^{max} - \frac{P_{HP}^{max}}{\varepsilon_{max}^{\mathcal{M}}} = 22.0 - \frac{22.0}{3.6} = 17.9\,\text{kW.} \tag{25}$$

The area of the land plot for the soil heat selection is determined by dividing the required heat removal capacity of the soil P_{rp} (determined in W) by the specific heat output of the soil q_{soil}, in W/m^2:

$$S_{\text{гр}} > \frac{P_{гр}}{q_{гр}} = \frac{17900}{20} = 895\ m^2 . \tag{26}$$

The polyethylene pipe length with a diameter of 25 mm, which will ensure an effective selection of soil heat, is calculated through the specific length of heat removal, permissible for 1 m^2 of the area L_0=1.7 m/m^2:

$$\begin{aligned} L &\geq S_{\text{soil}} \cdot L_0 \\ L &= 895 \cdot 1.7 = 1521\,\text{m}. \end{aligned} \tag{27}$$

In the case of laying the pipeline in zigzag, the distance between two parallel branches can not be less than 0.6 m. To ensure an acceptable level of hydraulic resistance, the one branch length of the pipeline is chosen not to exceed 100 m.

3 Summary

In the article the power supply scheme of the private house is developed for the Western Ukrainian region conditions with the energy usage of sun and thermal energy of soil.

The annual thermal load of the system is estimated at 128,765 MJ.

The heat load of the hot water supply system has been determined, and an electric heater with a capacity of 5.3 kW is provided as a backup source of hot water.

The average monthly capacity of the heat supply system and the maximum heat loss capacity in the cold five-day period of the year, which is 16 kW, are calculated.

The calculations allowed to substantiate the necessary of solar collectors' total area, which is 8.34 m^2. Five thermal solar collectors are selected for the given conditions.

The parameters were calculated and the heat pump with the nominal power of 19.2 kW was selected.

To drive the heat pump, the annual electricity consumption will be 12,931 kW per hour.

The proposed hybrid system of heat supply for a private house with the solar energy usage and soil heat can save more than 5 thousand cubic meters of natural gas per year, which will bring the corresponding economic effect. The payback period of the necessary additional capital investments is just over 6 years.

References

1. Ulbrich, R.: Audyt Energetyczny. A Dom Energooszedny, p. 141s. Politecnika opolska, Opole (2001)
2. Myrovsky, A., Lange, G., Elen', I.: Materials for the Design of Boiler Rooms and Modern Heating Systems, 293 p. Ecoinform, Lviv (2005)
3. Syvoraksha, V.Yu., Markov, V.L., Petrov ta B.Ie.: Thermal Calculations of Solar Systems, 132 p. vyd-vo DNU, Dnipropetrovsk (2003)
4. Shcherbyna, O.: Energy for all. Technical Reference Book, 192 p. vyd-vo V. Padiaka, Uzhhorod (2003)
5. Ivanyshyn, V., Hutsol, T.: The Ukrainian agricultural groups state and agro-machinery provision/scientific achievements in agricultural engineering, agronomy and veterinary medicine. Monograph. Traikon. Krakov. **1**, 1–13 (2017). http://188.190.33.56:7980/jspui/handle/123456789/10
6. Tvajdell, J., Weir, A.: Renewable Energy Sources, 392 p. M.: E'nergoatomizdat (1990)
7. Zawadzki, M.: Kolektory Słoneczne, Pompy Ciepła—Na Tak.—Warszawa: Polska Ekologia, 276 s (2003)
8. Halchak, V.P., Boiarchuk, V.M.: Alternative Energy Sources. Energy of Sun: A Study Guide, 135p. Lviv (2008)
9. Nowak, J., Hutsol, T., Bendera, I.: Grounding the parameters of the pneumatic device for pests collecting/Teka Komisji Motoryzacji i Energetyki Rolnictwa, pp. 35–40 (2007). http://www.pan-ol.lublin.pl/wydawnictwa/TMot7a/Gucol.pdf

The Prospects of Solving Energy Issues by Local Self-government in Podilya Under the Territorial and Administrative Reform Conditions in Ukraine

Vasyl Vakhnyak, Igor Ryhlivskiy, Valerii Havryliuk and Valery Tarasyuk

Abstract The first steps of decentralization in Ukraine are described in the article. State legislative initiatives to enhance local self-government, issues and achievements of voluntary united local communities are described in the article. It is noted that for the purpose of revenues to local budgets it is appropriate to carry out energy saving measures. Wide implementation of renewable energy sources, including biomass, is offered in the article. It is noted that Khmelnytskyi region has favorable natural and economic conditions for the implementation of energy willow plantations as local renewable energy sources. On the example of a particular local community there is reflected an actual use of natural gas and solid fuel during the heating season of 2016–2017 and possibility of creating energy willow plantations and use of chopped wood for heating of social sphere premises are grounded.

Keywords Decentralization · Local self-government · Local community
Renewable energy · Energy willow · Biomass · Khmelnytskyi region

In Ukraine the right of citizens to solve issues of local importance is guaranteed by the state and is the real ability of local communities [1] that in most of them remain unfulfilled. Self-sufficient and strong local communities are the basis of the local and regional development of any country. It is also a feature of quality and efficiency of local self-government, less bureaucratic to facilitate the development of local democracy, supporting the initiatives of citizens. The main reasons for inadequate development of local self-government in Ukraine are economic (lack of material and financial resources), political (lack of real self-sufficient local communities with appropriate formation of local budgets), legal (lack of legal support for the organization and functioning of local self-government, its relationship with the community members, community organizations, businesses and institutions), psychological (existence of the old stereotypes concerning the local self-government in the minds of citizens).

V. Vakhnyak (✉) · I. Ryhlivskiy · V. Havryliuk · V. Tarasyuk
State Agrarian and Engineering University in Podilya, Khmelnytskyi, Ukraine
e-mail: wastep@meta.ua

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_76

In the development of reforms towards decentralization Ukraine uses European Charter of Local Self-Government [2, 3] and European experience. Power decentralization is a complex process that involves diverse aspects most important of which are the budget and fiscal decentralization, the possibility of forming independent community budgets. Specific changes in the direction of decentralization in Ukraine appeared after the adoption of the basic legal documents for improving and strengthening the independence of local communities by the Verkhovna Rada of Ukraine in 2014 [4]. Especially important was the approval of the Cabinet of Ministers of Ukraine the Concept of reforming the local government and the territorial government in Ukraine [5] and the action plan for its implementation [6]. Adoption of the Laws of Ukraine On Amendments to the Tax Code and the Budget Code [7] became a stimulus for communities to unite and increase their self-sufficiency.

Since 2015 with the support of the US Agency for International Development, the Council of Europe and some other countries of the world in Ukraine there are real changes in local self-government, which began with local elections in municipalities (October) and the creation of the first 159 voluntary united local communities (ULC) that function since the 1st January 2016. In Khmelnytskyi region 231 of 605 communities (38.2%) or 531 of 1451 settlements (36.6%) have united. There were established 22 local communities (ULC) with an area of 428,000 ha [8].

Creation of conditions for communities to exist with a full value, formation of adequate legal and economic framework for their development are the main priorities of the planned changes. During one and a half year of existence of voluntary united local communities there have taken place significant changes in their financial situation and therefore development opportunities. Planned indicators of local budgeting on the results of 2016 were exceeded by all communities, which increased their incomes per capita nearly 3 times.

During the first six months of 2016 the state granted targeted subsidies for united local communities of the region in amount 358 million UAH, of which 72 million UAH are intended to form the infrastructure. Also in 2016 by the state there was allocated 1 billion UAH to infrastructure forming for 159 ULC, which was distributed with the regard to the number of rural residents and area. Khmelnytskyi region received 216.4 million UAH [8]. This allowed to implement a number of important for communities infrastructure projects: improvement of water supply by constructing artesian wells, water pipelines; reconstruction of sewage treatment plants; the purchase of special equipment (including fire engines); overhaul of roads; capital repairs of schools, pre-schools, administrative offices; street lighting. At the same time energy efficiency projects were almost not implemented.

The well-known problem of Ukraine's energy dependence is caused by the high energy intensity of different branches of the national economy and overspending of energy by municipal objects and people. The state has enormous renewable energy sources, but the development of alternative energy sources is growing very weakly. According to the State Statistics in Ukraine in 2013 the share of renewable energy in gross final use was 3.62%, including biomass—2.28% (2.7 million tons of conventional fuel). In 2014 "National action plan on renewable energy by 2020" was adopted in Ukraine [9]. According to this plan the share of renewable energy sources in the final use should be 11% and biomass of them should be 85%. But it is clear already now that this plan will fail because there are no effective mechanisms of the state support for financing projects, and also just a few projects are proposed by local communities.

Among the fifteen ULC of Khmelnytskyi region only in three implementation of energy saving technologies, switch over of boiler houses to alternative fuels, modernization of systems of consumption of thermal energy are declared for the future. Only in one of ULC (village Chornyi Ostriv of Khmelnytskyi region) owing to local agricultural firm there was planned implementation of technologies using renewable energy sources, "to promote the development of production and use of biofuels, the creation of local raw materials for biofuel production".

There are various sources of renewable energy, biomass in Ukraine is preferred. However, in conditions of intensive farming, with a constant decrease in soil fertility, it is inappropriate to alienate a significant number of plant residues after harvesting (according to various estimates, it is possible to take from fields 10–30% of the biomass after harvesting). But studies of the authors showed that the current structure of crop areas and yield of field crops and the lack of livestock industry in Khmelnytskyi region are making insufficient plowing even of all plant remains to ensure non-deficit balance of humus [10]. Therefore, biomass from energy crops should be preferred.

Energy willow has its biological and technological features that allow it to be considered as the main energy crop for Khmelnytskyi region. The conditions of the region are suitable for this crop both from the point of view of natural resources (climate, soils, hydrology of the territory) and economic resources (inefficient use of other land rather than arable land, environmental problems related to the intensive agricultural sector and high plowing of the territory, availability of equipment at agricultural enterprises, which can be adapted for the technology of crop cultivating, experience of using alternative fuel based on chopped wood, etc.). In view of the territorial diversity of natural and economic conditions, we consider the raise of energy crops to be only as a local resource for improving the economic activity of local communities, local enterprises, etc.

The northern part of the region is situated in Polissya (forest zone), the rest—in the western forest-steppe zone. The moisture content of the territory, excepting a number of recent years, is sufficient. According to a comprehensive, qualitative land evaluation (100 point scale), which includes fertility indices, pollution level, erosion, hydromorphism and climatic conditions, the soils of the arable land in Khmelnytskyi region belong to the following groups (Table 1). In modern conditions, the agrarian sector of the economy in Ukraine is one of the main ones that fills the budget and is strategically important. Therefore, the most fertile soils should be used to grow the main field and fruit crops, and it is expedient to use low-quality soils, not higher than 40 points, for energy willow. The area of such soils in the region is 51.6 thousand hectares, but they also include eroded lands, which

Table 1 Qualitative estimation of the arable land of Khmelnytskyi region [11]

Land quality	Category	Points	Area, thousands of hectares	% of arable land
Very high	1	91–100		
	2	81–90		
High	3	71–80	8.0	0.9
	4	61–70	107.7	11.6
Increased	5	51–60	308.7	33.2
Middle	6	41–50	294.1	31.6
Low	7	31–40	159.4	17.1
Very low	8	21–30	49.5	5.3
	9	11–20	2.1	0.3

moisture content may not be sufficient for energy willow. Among the forest-steppe districts of the region, the soil of low quality is found to be from 1.1% in the relatively flat Teofilpol district to 45–53% in Letychiv, Derazhnya and Nova Ushitsya districts with difficult terrain.

Different processes of soil degradation according to Krupennykov's classification [12], which are the cause of poor quality of land, appear in the districts of the region. In this case, there appears their distinct geographical distribution. Processes of chemical (dehumidification, decalcification, worsening nutritional regime, secondary acidification) and physical degradation (loss of structure, compaction) appear almost on the entire arable land, physical—hydrogenous—mainly in the southern and eastern parts (water erosion), northern (waterlogging) [10].

However, it is possible to use other lands, for example, hayfields and pastures, some of which are located on periodically (temporary) or permanently waterlogged soils. Soils with sufficient moisture reserves should be preferred when placing energy willow plantations, especially considering the current trend of global warming and more frequent droughts.

Table 2 shows those agro-industrial groups of soils of the region that have genetic signs of overflow. Predominant among them are fluvisols, histosols and pheozems [13], the main arrays of which are confined to a particular geographic environment. Totally in the region there are 60.8 thousand hectares (4.8%) of meadow and marsh soils (permanently waterlogged) [14]. In the forest-steppe part of the region, their area occupy from 0.7 thousand hectares (1.0%) in Dunaivtsi district to 5.2 thousand hectares (6.3%) in Volochysk district.

In different united territorial communities there is a different soil cover structure by the suitability for high efficiency of energy willow plantations. For example, in Berezdiv ULC of Slavuta district there are relatively large areas of histosols, in Medzhybizh ULC of Letychiv district there are large areas of fluvisols due to placement in the lowland area, in the Kolybaivka ULC of Kamyanets-Podilskyi district glued varieties of pheozems (bedded with waterproof clay) are the predominant resources for energy willow.

Table 2 Distribution of waterlogged soils in Khmelnytskyi region

Soil groups in the classifications of Ukraine and world		Territorial placement in the region
Nomenclature list of soils of Ukraine	World Reference Base for Soil Resources (WRB) [15]	
Clear gray and gray forest ashed loam, gleyic and surface-gleyic	Pheozems endogleyic, gleyic, luvic	Forest-steppe part, mainly southeastern
Dark gray and chernozems ashed loam, gleyic and surface-gleyic	Pheozems endogleyic, gleyic, luvic	
Meadow-marsh, mud-marsh and peat-marsh	Fluvisols gleyic	Locally across the region
Peat-marsh and shallow peatlands	Histosols	Preferably, in Polissya part, locally everywhere
Medium and deep peatlands medium and strongly decomposed	Histosols	
Meadow-chernozem loam and gleyic	Umbrisols gleyic Chernozems luvic	Locally in depressions of the forest-steppe part
Turf shallow and deep gleyic and loam	Arenosols mollic, haplic Gleysols umbric, luvic	Preferably Polissya, rarely in the south
Alluvial	Fluvisols gleyic Umbrisols gleyic	Floodplains and terraces of rivers

It should also be noted that the region has a relatively large territory for a natural reserve, which is one of Europe’s largest National Natural Park “Podilsky Tovtry”. Therefore, placement of energy willow plantations in the park’s economic zone and other reserves will increase the effectiveness of preserving natural landscapes and biodiversity, and increasing the ecological stability of landscapes. This is very important for the protection of wetlands, restrictions on the intensive use of land near water bodies, increasing erosion stability of landscapes, regulation of water regime of territories.

On the example of Kolybaivka UTC in Kamyanets-Podilskyi district, it is possible to understand the problem of the need to preserve energy sources and to increase energy efficiency (Table 3). The largest consumers of gas are the school and village council in the village Kolybaivka, of coal and firewood—other schools and kindergartens. The cost of used gas and solid fuels is different—2707.1 thousand UAH were spent on the purchase of gas, 277.3 thousand UAH were spent for coal and firewood.

In our opinion, the main arguments for the use of energy willow as an alternative source of energy specifically for the Kolybaivka territorial community are as follows:

1. On the territory of the UTC there are 306.9 ha of reserve land, 550.6 ha of land stock. The communal property has 245.5 ha of land. In the community, it is possible to implement the most economically advantageous closed cycle in the cultivation of biodiesel and its use (processing) [8].
2. Agricultural enterprises on the territory of communities own only arable land (5765 ha), they have no other land. Considering the specialization of farms

Table 3 The actual use of fuel for heating of objects of social sphere in the heating season 2016–2017 in Kolybaivka UTC in Kamyanets-Podilskyi district

Objects	Heated area, m^2	Type of fuel	Type of boiler	Spent on heating in 2016–2017	Cost of heating, thousand UAH
Schools					
Village Khodorivtsi	1291	coal	Calavi 130	52 tons	178.8
Village Kolybaivka	1002	gas	Modular boiler	19.5 thousand m^3	173.2
Village Ostrivchany	598	coal	Cadvis	11 tons	38.8
Village Knyahynyn	298	coal	Stove heating (6 pc.)	6 tons	20.3
Kindergartens					
Village Khodorivtsi	210	Gas	Convectors	9.8 thousand m^3	87.0
Village Kolybaivka	113	Gas	Convectors	4.8 thousand m^3	42.7
village Ostrivchany	186	Coal	Calavi	9.3 tons	31.5
Village Knyahynyn	168	Electricity	Dnipro	22.5 MWt	50.5
Administrative buildings					
Village council	867	Gas	Convectors (14 pc.)	264.6 thousand m^3	234.5
Post offices (4 departments)	62	Gas	Convectors (4 pc.)	3.3 thousand m^3	29.2
	34	Coal	Stove heating (2 pc.)	1.7 tons	5.8
Medical establishments	Outpatient clinic, medical center	Gas	Convectors	2.1 thousand m^3	18.6
	2 medical centers	Coal	Stove heating (2 pc.)	1.8 tons	6.1
Library		Gas	Convector	1.32 thousand m^3	10.8
Clubs	Periodically are heated by the stove heating				

Notes 1. The service of boilers and oven by operators of ovens is not taken into account. 2. The actual price of natural gas was 8862 UAH per 1000 m^3, coal—3390 UAH t^{-1}

(field crop production), it is impossible to count on their active participation in the laying of willow plantations. Relatively low, as for chernozems, the organic matter content in arable soils (at the level of 2.18–3.42) causes the need for planting residues to be halved, and not to use them as biofuels. However, they can provide technical assistance, for example, covered canopies for storing chopped wood and its final drying.

Along with this, on the territory of the community 68 people cultivate the land with total area of about 160 ha on their own. Among them 16 families own land plots from 2 to 8 ha (total 62 ha). The sole commodity producers have 12 tractors, 2 trucks, 1 combine. The efficiency of their production is extremely low, therefore some of them are ready to co-operate, including for the implementation of new projects.

3. On the territory of the community there are insufficiently fertile and difficult to use periodically waterlogged gleyed types of gray forest soils, suitable for growing energy willow.
4. In UTC there is a placement of social facilities in settlements (educational, cultural, medical facilities), which allows them to be combined into a single heating network from one boiler house, to modernize the heat transfer to the premises.
5. The UTC territory is fully included in the National Natural Park "Podilsky Tovtry", which imposes certain restrictions on the use of natural resources and necessitates the implementation of environmental projects. The cultivation of energy willow has an ecological orientation. Also, for the community and for the tourist city of Kamyanets-Podilskyi, some nuisances create an unpleasant smell from the fields of the local distillery. Growing willow in these fields would obviously contribute to a partial resolution of the problem.
6. The region has an experience in growing willow and an experience of using wood chips for heating. Municipal enterprise of the city of Kamyanets-Podilskyi uses a boiler-house on chopped wood and pellets, own raw material base is created. In the neighboring Ivano-Frankivsk, Lviv, and Volyn regions there are firms that grow and sell willow seedlings with a relatively low cost, provide services for planting and growing plantations. The company "Salix energy" in Volyn region grows Swedish energy willow on an area of 1.5 thousand hectares and provides the heat supply for the State District Administration, department of education, schools, kindergarten, museum, district hospital.
7. In Ukraine, there is, albeit an imperfect, market of equipment of various capacity for combustion of chopped wood of willow of different humidity. The cost of boilers is available to the community budget.

Taking into account volumes and cost of consumption of gas and solid fuel by objects of social sphere, cultivation and use of energy willow for heating of premises is economically expedient. First of all, it should be noted that the cost of 1 GJ of energy received from natural gas combustion in Ukraine is 0.097 UAH, coal—0.054 UAH, and crushed wood of energy willow—only 0.007 UAH [15]. If we consider the productivity of an energy willow plantation at the level of 10 odt with a lower heat of combustion of 18.5 GJ t^{-1}, then 1 ha of willow will provide an output of 185 GJ t^{-1} per year [16]. And this is equivalent to 5.18 thousand m^3 of natural gas (combustion heat 35.88 GJ 1000 m^{-3}) or 7.11 tons of coal (combustion heat 26 GJ t^{-1}). Accordingly, the cost of gas equivalent to the energy of 1 hectare of willow is 45.7 thousand UAH, and the cost of coal at actual prices as for the heating season 2016–2017 is 24.1 thousand UAH. It should be noted that for the next heating season in the budget of the local community, the price of coal is set at 3600 UAH t^{-1}, and it is expected to be higher. In this case, the project's efficiency increases.

The cost of cultivating energy willow is, according to various estimates, from 4.7 to 7.7 thousand UAH ha^{-1} [17] up to 7–8 thousand UAH [16]. However, taking into account the dynamics of prices in Ukraine, according to our calculations, the cost is 11–13.5 thousand UAH ha^{-1} (taking into account the cost of seedlings, technological operations of planting, caring for plantation, harvesting, transportation, crushing and storage of crushed wood). The cost of one ton of crushed wood is from 190 to 220 UAH t^{-1}. Therefore, the replacement of natural gas gives it an effect of about 32 thousand UAH per hectare of plantation, and coal—about 11 thousand UAH.

The need for an area of willow plantation is 70–80 ha for the complete replacement of natural gas and solid fuels in the united territorial community, which frees up to 2 billion UAH in the budget. Taking into account the length of use of plantations of energy willow (25–30 years), its implementation in the community is perspective.

Conclusions

Ukraine has established a regulatory framework for administrative and territorial reform. The processes of decentralization of power in Ukraine contribute to the autonomy of local communities and call for the search for effective projects to improve their economic situation. Implementation of the production of chopped wood of energy willow in local communities is expedient in terms of increasing the efficiency of the use of natural resources and saving budget funds for the heating of objects of social sphere. Natural and economic conditions are favorable for the implementation of energy willow plantations and the use of its biomass for the production of heat. Replacement by the crushed wood of energy willow of 305.4 thousand m^3 of natural gas and 81.8 tons of coal in a specific territorial community frees about 2 billion UAH of budget funds for the year.

References

1. Konstytutsiia Ukrainy. Zakon № 254 k/96-VR vid 28.06.1996. Vidomosti Verkhovnoi Rady Ukrainy, № 30, st. 141 (1996)
2. Ievropeis'ka khartiia mistsevoho samovriaduvannia m. Strasburh, 15 zhovtnia 1985 roku (Ofitsiinyi pereklad). Ofitsiinyi visnyk Ukrainy vid 03.04.2015, № 24 (2015)
3. Zakon Ukrainy № 452/97 vid 15.07.1997 "Pro ratyfikatsiiu Yevropeis'koi khartii mistsevoho samovriaduvannia". Vidomosti Verkhovnoi Rady, №38 (1997)
4. Zakon Ukrainy №1508-18 vid 17.06.2014 Pro spivrobitnytstvo terytorial'nykh hromad. Vidomosti Verkhovnoi Rady, № 34 (2014)
5. Rozporiadzhennia KMU: Pro skhvalennia Kontseptsii reformuvannia mistsevoho samovriaduvannia ta terytorial'noi orhanizatsii vlady v Ukraini, vid 1 kvitnia 2014 r. № 333-r (2014)
6. Rozporiadzhennia KMU: "Deiaki pytannia realizatsii Kontseptsii reformuvannia mistsevoho samovriaduvannia ta terytorial'noi orhanizatsii vlady v Ukraini, № 688-r. vid 22 veresnia (2016) r
7. Zakon Ukrainy №1789-19 vid 20.12.2016 "Pro vnesennia zmin do Biudzhetnoho kodeksu Ukrainy". Vidomosti Verkhovnoi Rady, № 2 (2017)
8. Iatskovs'kyi S.V.: i in. Ob'iednani terytorial'ni hromady Khmel'nychchyny. Rik pershyi/ Iatskovs'kyi S.V., Liubenchuk V.A., Bilyk I.A., Fosolia O.I. ta in. Khmel'nyts'kyi. 266 c (2016)
9. Rozporiadzhennia KMU: Pro zatverdzhennia planu zakhodiv schodo realizatsii Kontseptsii reformuvannia mistsevoho samovriaduvannia ta terytorial'noi orhanizatsii vlady v Ukraini, vid 18 chervnia 2014 r. № 591-r (2014)
10. Vakhnyak, V.S., Kozhevnikova, V.L.: Dehradatsiini protsesy v hruntakh Khmel'nyts'koi oblasti. Okhorona hruntiv. Vyp.1. Kyiv. S.205–208 (2014)
11. Havryliuk, V.B., Halyschuk, V.I., Strilets'kyi, O.V.: Hrunty Khmel'nychchyny. Suchasnyi stan; zberezhennia, vidtvorennia ta polipshennia yikh rodiuchosti. Kam'ianets'-Podil's'kyi, 124 s (2010)
12. Krupennykov, Y.A.: Chernozemy. Voznyknovenye, sovershenstvo, trahedyia dehradatsyy, puti okhrany i vozrozhdenyia. Kyshynev. Pontos. 270 s (2008)
13. Pol'chyna, S.M., Vakhnyak, V.S., Havryliuk, V.B.: Zastosuvannia mizhnarodnoi systemy klasyfikatsii hruntiv WRB do karty hruntovoho pokryvu Khmel'nyts'koi oblasti/Naukovi zapysky Ternopil's'koho natsional'noho pedahohichnoho universytetu imeni Volodymyra Hnatiuka. Seriia: heohrafiia. Ternopil'. №3 (vypusk 33). S.18–26 (2012)
14. Havryliuk, V.B., Vakhnyak, V.S., Yavorov, V.M., Rodiuchist' hruntiv Khmel'nychchyny i problemy yii zberezhennia i vidtvorennia. Okhorona hruntiv. Vyp.1.- Kyiv. S.218–221 (2014)
15. Lopushniak, V.: Bioenergetic and economic estimation of sewage sludge use in osier cultivation. In: Lopushniak, V., Lopushniak, G., Grytsyliak, G. (eds.) Teka: Commission of Motorization and Energetics in Agriculture, vol. 16. No. 3, pp. 26–31 (2016)
16. Pyrikov, O.V.: Poetapnyi pidkhid do vysadky enerhetychnykh roslyn. Praktychnyi posibnyk. Kyiv. 99 s (2016)
17. Lopushniak, V.I., Hrytsuliak, H.M.: Bioenerhetychna efektyvnist' vyroschuvannia verby enerhetychnoi za vnesennia osadu stichnykh vod na dernovo-pidzolystykh hruntakh Peredkarpattia/Visnyk L'vivs'koho NAU: ahronomiia. L'viv. №20. S.165–171 (2016)
18. FAO.: Guidelines for Soil Description, 4th ed (Rome, 2006)
19. Zakon Ukrainy №1797-19 vid 15.04.2017 "Pro vnesennia zmin do Podatkovoho kodeksu Ukrainy schodo pokraschennia investytsiinoho klimatu v Ukraini". Vidomosti Verkhovnoi Rady, № 5–6 (2017)
20. Rozporiadzhennia KMU: Pro Natsional'nyi plan dii z vidnovliuvanoi enerhetyky na period do 2020 roku, № 902-r vid 1 zhovtnia (2014) r

Spread Mustard and Prospects for Biofuels

Tetyana Kozina, Olena Ovcharuk, Ivan Trach, Viktoriya Levytska, Oleg Ovcharuk, Taras Hutsol, Krzysztof Mudryk, Marcin Jewiarz, Marek Wrobel and Krzysztof Dziedzic

Abstract The paper presents research aimed to determine the potential of waste biomass from the processing of mustard. Raw material for research came from the central part of Ukraine. Studies have shown that mustard residues are a valuable raw material for the production of solid biofuels in the form of briquettes or pellets. Values of quality parameters (such as calorific value, durability, density) are comparable to those found in commercial solid biofuels. Analysis of ash content showed an increased content of mineral fractions, which were the source of plant surface impurities applied by atmospheric agents (rain, wind).

Keywords Mustard · Solid biofuels · Pellet durability · Waste biomass

1 Introduction

In the modern developed world, a lot of energy is used: for domestic needs, transport, industry Combustion of fossil fuels is the most common way of producing energy. However, each stage of it negatively affects to the environment: CO_2, SO_2, NO, particulate matter and dust are released. In addition, oxides of heavy

T. Kozina · O. Ovcharuk · I. Trach · V. Levytska · O. Ovcharuk (✉) · T. Hutsol
State Agrarian and Engineering University in Podillia, Khmelnytskyi, Ukraine
e-mail: ovcharuk.oleh@gmail.com

T. Hutsol
e-mail: pro-gp@pdatu.edu.ua

K. Mudryk · M. Jewiarz · M. Wrobel · K. Dziedzic
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 B, 30-149 Krakow, Poland
e-mail: Krzyszto.Mudryk@ur.krakow.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

M. Wrobel
e-mail: marek.wrobel@urk.edu.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_77

metals are emitted into the atmosphere. CO_2 is the main component of greenhouse gases, contributes to global warming, while other SO_2 and NO acid gases form acid precipitates, impair the air quality. The combustion of fossil fuels, including motor fuels, is the source of approximately 80% of the emissions.

Therefore, the actual task is to find fuel that can replace the practical properties of oil, but won't pollute the environment. At least in part this can only be provided by biofuels.

For Ukraine, which, on the one hand, is 55% dependents on imported fuel, and on the other—not fully utilizes the potential of agriculture, biomass-based energy production would overcome dependence on imported energy, to approach Europe and to contribute to climate change prevention This requires the biofuel market creation as an alternative energy source. Thanks to this, it is possible to receive about 15 million tons of equivalent fuel, if 5 million ha of land is considered as a potential for growing energy plants and mastering the processing of crop residues. Having such a potential, it is possible to maintain wasteless agriculture and ecological state improvement of the environment [1].

The biomass usage for energy production already now accounts for about half of all renewable energy sources in the world, in Europe it reaches 70%, Sweden—64%, Denmark and Austria—33%. After 20 years, biomass prices will be as good calculated as to coal, oil or gas. Experts expect, that investments in the market of growing energy plants will increase until 2020 up to 25 billion dollars [1].

For Ukraine, bioenergy is one of the strategic directions for the renewable energy sector development. Sufficient energy potential of straw and plant wastes was noted. A significant part of the straw after harvesting is pressed into bales, briquettes and pellets and is used for heating. At 14 enterprises of oil industry, more than 500 thousand tons of sunflower husk is burnt and 120 thousand tons of it is granuled.

Among the biofuel recovery biofuels, a significant proportion is occupied by solid biofuels. The oldest fuel used by mankind is wood. At present, energy forests consisting of fast-growing breeds (poplar, eucalyptus, etc.) are growing in the world for the production of firewood or biomass. Modern biofuels are fuel pellets and briquettes. These are pressed products from wood waste (sawdust, chips, bark, thin and substandard wood, residues from logging operations), straw, agricultural waste (husk of sunflower, nutshell, manure, chicken manure) and biomass. Wood pellets are called pellets, they have the shape of cylindrical or spherical granules with a diameter of 8–23 mm and a length of 10–30 mm [2–5].

Energy carriers of biological origin (mainly manure, etc.) are also known. They are briquetted, dried and burned in fireplaces of apartment houses and furnaces of thermal power stations, producing cheap electric power.

Potential is the crop waste usage, namely untreated or with a minimum degree of preparation for incineration: sawdust, chips, bark, husk, straw, etc.

The solid biofuel industry in Ukraine is fully oriented for export, as more than 90% of fuel pellets and briquettes are exported from the country. The main importers of solid biofuels are Poland, Germany, Italy. The solid biofuel industry in Ukraine continues to grow at a rapid pace, as evidenced by the following data: in 2008. In Ukraine, pellets and briquettes were produced together with

77 thousand tons; In 2009—350 thousand tons (pellets—260 thousand tons, briquettes—90 thousand tons) [6].

Research work is part of the research conducted by the Department of Ecology and Balanced Nature Management, the Faculty of Agrotechnology and Balanced Nature Management of the Podilskyi State Agrarian and Engineering University in cooperation with the Renewable Energy Laboratory of the Engineering Institute of Krakow Agricultural University.

The work aim is the effective solve of the biofuel production problem due to a comprehensive assessment of residues of crops' various types and their wastes during post-harvest processing.

The target of research is the process of determining effective sources of raw materials and establishing the productive, energy potential of mustard plants.

The experimental unit is the vegetational remains of mustard.

As a work result, important scientific and practical results have been obtained, which consist in identifying promising sources of biofuel on the basis of an integrated assessment of the potential of mustard plants stubble remains, developing biofuel production technologies and introducing them into Ukraine's energy sector, which is of immediate interest today.

The economic importance of research results lies in: increasing the diversity of raw materials at the expense of agricultural plants; Identification of effective non-traditional and alternative sources of biofuel feedstocks; technology creation for fuel production based on the energy efficiency of mustard plants [7–9].

According to the State Statistics Service of Ukraine, according to the results of 2016 the area of mustard sown area was 44.5 thousand ha. The main areas are located in the regions, thousand hectares of Khersonska—11.1, Zaporizhka—4.9, Khmelnytska—1.5, Cherkaska—1.0, Vinnytska—1.1, Kyivska—1.7, Poltavska—1.4, Luganska—3.1, Donetska—5.7, Chernihivska—2.6, Kharkivska—1.2 and others (see Fig. 1).

It was analyzed the data of sown areas, we found that mustard crops are located on 75% of the territory of Ukraine.

Agroecological advantages of growing mustard in Ukraine, its medicobiological properties, high profitability of production contribute to the further development of the sales market, its processing and increasing the culture profitability.

Taking into account the multifaceted national economic importance of mustard (oil, technical, fodder, sideral, nectareous) and unpretentious it has recently attracted attention as a raw material base for the replenishment of plant resources in agriculture.

In the western regions of Ukraine, the mustard stems reach height from the main and post harvest spurting 120–130 sm. The mustard sticks and stubble residues are not widely used, in most cases remain on the field. Therefore, there is a need to conduct research on mustard raw materials for suitability for biofuel production in the form of pellets and briquettes.

The effectiveness of the bioenergy development in Ukraine depends on the work coordination in this sector and the proper choice of priorities. First of all, at the governmental level, there should be defined a single state body that would deal with

Fig. 1 The region of mustard cultivation in Ukraine (year 2016)

all issues in the bioenergy sector and coordinate the work of other involved organizations and institutions. Priority areas of development should be defined in the state program for the development of bioenergy in Ukraine, while ensuring its financing and improving the legislative sphere.

2 Materials and Methods

The study material was mustard residue containing both damaged seed as well as seed coat and stem fragments. The research material was obtained after processing the 2016 crops in Ukraine. On Fig. 2 is presented sample of research material that has been subjected to a detailed analysis of physicochemical properties in terms of energy potential.

The test material was sampled and prepared according to the PN-EN 14778_2011e and PN-EN 14780_2011e standards. Based on prepared samples complex analysis of physicochemical parameters was performer. The estimated quantities were:

– Moisture content,
– Bulk density,
– Volatile matter content,
– Ash content,
– Higher and lower heating value,

Fig. 2 Sample of raw material

– Mechanical durability of formed granulates,
– Specific density.

Moisture content M_{ar} [%] assigned according to the PN-EN ISO 18134-1:2015-11 standard. Material sample of weight aprox. 300 g placed in the dry container was dried in convective drier in 105 °C ± 2 for 4 h, or when mass will remain constant.

Bulk density BD [kg m^{-3}] of the raw material and produced pellets was measured according to the PN-EN ISO 17828:2016-02 standard based on measurement of sample mass, placed in the vessel with known volume.

Volatile matter V_d [%] determined according to the procedure proposed in PN-EN 15148_2010e standard. The dry crucible with lid filled with the test material (1 ± 0.1 g), is weight (accuracy 0.0001 g) and treated in furnace for 7 min in 910 ± 10 °C.

Ash content [%] was determined according to the guides in PN-EN ISO 18122:2016-01 standard. The test sample was placed in the annealing dish, weighed (accuracy 0.0001 g) treated in furnace for 3 h in 550 ± 10 °C.

Gross calorific value $qV_{gr,ar}$ [J g^{-1}] **and net calorific value $qp_{net,ar}$** [J g^{-1}] were estimated on high class automatic, isoperibolic calorimeter C6000 produced by IKA. The measurement is made according to the PN-EN-14918:2010 standard, based on sample mass (accuracy 0.0001 g) and temperature difference.

Mechanical durability of briquettes DU [%] measurement was based on guidelines presented in PN-EN ISO 17831-2: 2016-02 standard and consisted of weighing the briquettes on the RadWag laboratory weight to the nearest 0.1 g and placing them in tester drum. The mechanical durability test at a rotational speed of 21 rpm takes about 5 min (one test). After that briquettes were sieved through an orifice hole with a diameter of 32 mm to remove fractions created during crashing of the briquette. The prepared pellets were weighed using a laboratory scale to the nearest 0.1 g.

Mechanical durability of pellets DU [%] the test goes according to similar procedures as for briquettes in chamber appropriate shape and dimensions of the chamber in accordance with PN-EN ISO 17831-1:2016-02. The test chamber is smaller and rotates at a speed of 50 rpm. The duration of one test is 10 min. At the end of the test, the pellets are screened through an orifice hole with a hole diameter of 3.15 mm. Screening of the sample is made to remove fine fractions that have detached from the granulate during the test. The material remaining on the sieve is weighed on a laboratory scale to the nearest 0.1 g.

Specific density of the briquettes and pellets SD [kg/m^3] was assigned based on geometry measurements (height and diameter), made with use of calliper, and weight of the individual granules. The measurement was made on 10 randomly chosen granules.

Granulation of the samples to the briquettes was done using a POR ECOMEC Junior briquetting machine. It produces a briquette with a diameter of about 50 mm and a length dependent on the bulk density of the raw material (smaller density of raw material results in shorter length of briquettes and vice versa). This machine has possibility of regulation of the working pressure in the compaction chamber. When the pressure in the hydraulic system changes, the force that affects the piston changes as the pressure in the compaction chamber changes. The hydraulic pressure of the press is controlled by a sensor and could be also read on the pressure gauge. The agglomeration pressure was set at 47 MPa (the highest working pressure of Junior briquettes allowed for continuous work).

Samples of pellets were made on Kovo Novak MGL 200 which is semi-industrial line for pelleting organic fractions with capacity up to 100 kg/h. According to the discernment of the market, the diameter of the designed pellet was set at 8 mm and the length of about 10–15 mm.

3 Result and Discussion

The conducted research allowed to collect important data allowing to assess the energy potential of the mustard residues and susceptibility to agglomeration processes.

Table 1 shows the results of the basic material characteristics in terms of energy use. It need to be noticed that the value of the ash content over 12% suggests that there could considerable contamination of the raw material with mineral fractions (mainly soil). The analysis of harvesting and post-processing technology of mustard plants showed that the source of pollution was the mineral fractions deposited on the plant during the vegetation season by atmospheric agents (rain and wind). The remaining tested parameters are satisfactory and similar to those of other recognized energy commodities such as cereal straw or miscanthus from energy crops [6, 10].

Table 1 Results of qualitative assessment of raw material

	Moisture content M_{ar} [%]	Ash content A_{ar} [%]	Net calorific vaule $qp_{net,ar}$ [MJ kg^{-1}]	Volotile matter V_{ar} [%]	Bulk density BD_{ar} [kg m^{-3}]
1	11.2 ± 0.08	12.75 ± 0.4	16.48 ± 0.12	68.2 ± 0.56	195 ± 4.6

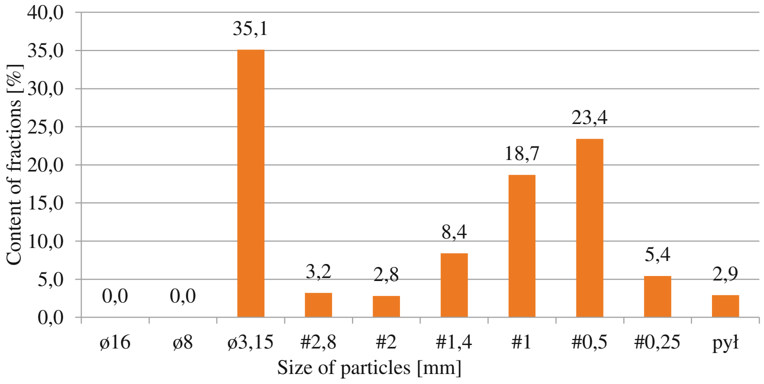


Fig. 3 Granulometric composition of raw material

Raw material was then subjected to agglomerated to two forms briquettes (aprox. 50 mm diameter) and pellets (diameter 8 mm). One of the most important parameters determining the course of the process is the grain size distribution of the raw material. The results of the sieve analysis are shown in Fig. 3. By analysis of the obtained data, it can be seen that the main fraction (35.1%) were particles that have been sieved through a screen with 8 mm holes and retained on a 3.15 mm hole sieve. The second main fraction can be distinguished by a geometry of 1.4–0.5 mm (sieved through a 1.4 mm sieve and sequentially stopped on a # 1 mm perforated sieve and # 0.5 mm) which together sum up to 42.1%. Such grain size distribution is proper for agglomeration processes. The contribution of both larger particles and smaller ones is essential for the proper formation of internal forces between particles, which determines agglomerates' durability [11].

Conducted agglomeration tests both to form of briquettes and pellets results in good quality agglomerates. The detailed results are presented in Table 2. In both cases, high value of specific density, for pellets even above 1 g/cm^3.

Table 2 Results of qualitative assessment of granulates

Type	Mechanical durability DU [%]	Specific density SD [kg m^{-3}]	Bulk density BD [kg m^{-3}]
Brykiet	94.3 ± 0.2	936.5 ± 15.8	479 ± 19.5
Pelet	95.6 ± 0.4	1146 ± 25.1	683 ± 14.4

The obtained results clearly indicate that using the classic methods of agglomeration it is possible to obtain from the tested raw material granulates with satisfactory quality parameters. The density of granules as well as their durability clearly indicate that it is possible to produce high quality granules in the form of briquettes or pellets on industrial scale, even for demanding purposes like heating plants or households usage.

4 Conclusions

The use of waste materials from various industries is a very important element in the energy sector economy. Raw materials often have properties imparted in processing processes that are beneficial from the point of view of their energy use (humidity, grain size, etc.). Therefore, the production of biofuels, including solid fuels, is often relatively inexpensive compared to the biomass obtained from targeted plantations. This is the case such types of raw material were examined. Characteristics of the material predispose it to the conversion to solid fuels. Both briquetting and pelleting methods have shown great agglomeration potential. Depending on market demand (pellets, briquettes), the use of this raw material in production processes can be easily controlled. The results of our research have confirmed that in the agricultural residue sector have a high potential for fuels that can be quickly applied.

References

1. Kaletnik, H.M.: Development of the Biofuel Market in Ukraine: Monograph, 464 p. Ahrarna nauka, Kiev (2008)
2. Zhuchenko, A.A.: Adaptation Potential of Cultivated Plants (Ecological and Genetic Basis), 768 p. Kishenev: Shtinitsa (1999)
3. Zanuda, A.: Biofuel is another chance for Ukraine. Electronic resource: http://www.bbc.co.uk/ukrainian/business/2011/04/110405_bioenergy_az_ob.shtml (access mode)
4. Scientists have created an almost perfect biofuel. Club "The Financier". http://news.finance.ua/ua/~/1/0/all/2013/03/01/297700. Access mode
5. Dubinevych, Yu.: Economic feasibility of production of biofuel from rape in Ukraine. Electronic resource: http://archive.nbuv.gov.ua/portal/chem_biol/vldau/APK/2012_19_1/files/12dujriu.pdf. Access mode
6. Mudryk, K., Fraczek, J., Slipek, Z., Francik, S., Wrobel, M.: Chosen physico-mechanical properties of cutleaf coneflower (*Rudbeckia laciniata* L.) shoots. Eng. Rural Dev. Jelgava (2013). Available at: http://tf.llu.lv/conference/proceedings2013/Papers/122_Mudryk_K.pdf
7. Levytska, V., Mushynskyi, A., Hutsol, T.: Histological Changes in Kidneys of Rabbits Affected by Spontaneous Encephalitozoonosis Scientific Achievements in Agricultural Engineering, Agronomy and Veterinary Medicine. Monograph, Vol. 1, pp 77–93. Traikon, Krakov (2017). http://188.190.33.56:7980/jspui/handle/123456789/15

8. Kravchuk, A.: The formation of the raw materials market for the bio-fuel production. Electronic resource: http://archive.nbuv.gov.ua/Portal/soc_gum/znptdau/2012_4/20–25.pdf. Access mode
9. Bulgakov, V., Adamchuk, V., Gutcol, T.: Theory of the ploughing mechanism of the sugar beet combine harvester (Theorie der rodewerkzeuge der zuckerrübenerntemaschinen). Agric. Eng. (Inżynieria Rolnicza) (2014) http://ir.ptir.org/artykuly/en/152/IR(152)_3606_en.pdf
10. Wrobel, M., Frączek, J., Francik, S., Slipek, Z., Mudryk, K.: Influence of degree of fragmentation on chosen quality parameters of briquette made from biomass of cup plant *Silphium perfoliatum* L. Eng. Rural Dev. Jelgava (2013). Available at: http://tf.llu.lv/conference/proceedings2013/Papers/121_Wrobel_M.pdf
11. Fraczek, J., Cieślikowski, B., Kuboń, M., Mudryk, K., Sikora, J., Szeląg-Sikora, A., Wcisło, G. Wróbel, M.: Produkcja biopaliw—problemy wybrane,. PTIR, Kraków (2014). ISBN 978-83-64-64377-04-4

Prospects of Growing Miscanthus as Alternative Source of Biofuel

Volodymyr Ivanyshyn, Ulyana Nedilska, Veronika Khomina, Rita Klymyshena, Vasil Hryhoriev, Oleg Ovcharuk, Taras Hutsol, Krzysztof Mudryk, Marcin Jewiarz, Marek Wróbel and Krzysztof Dziedzic

Abstract The paper presents the results of research work aimed at determining process parameters for production of quality briquettes from Miscanthus raw material. Raw material was obtained from southern Ukraine from the autumn harvest. The obtained results clearly indicate that adequate grinding, humidity reduction of less than 15% and application of agglomeration pressures above 37 MPa, results in obtaining satisfactory quality briquettes. Compliance with the developed technological assumptions should not in practice lead to technical problems that will have a significant impact on the dissemination of this activity in rural Ukraine.

Keywords Miscanthus · Briquettes quality · Jakość brykietu · Density Mechanical durability

V. Ivanyshyn · U. Nedilska · V. Khomina · R. Klymyshena · V. Hryhoriev · O. Ovcharuk (✉) · T. Hutsol
State Agrarian and Engineering University in Podillia, Podillia, Ukraine
e-mail: ovcharuk.oleh@gmail.com

T. Hutsol
e-mail: pro-gp@pdatu.edu.ua

K. Mudryk · M. Jewiarz · M. Wróbel · K. Dziedzic
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 B, 30-149 Krakow, Poland
e-mail: krzysztof.mudyrk@ur.krakow.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

M. Wróbel
e-mail: marek.wrobel@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_78

1 Introduction

In modern conditions for agricultural development urgent problem is meet the ever growing needs of mankind, especially energy. Today 35% of the world's energy needs through use of available oil, coal, natural gas, which are non-renewable. Renewable energy sources for real opportunities to increase their share are very limited. Demand for energy from renewable sources in Ukraine is growing every year. Search for effective alternative sources of renewable energy is very urgent. One of them is the aboveground vegetative mass of plants that accumulate through photosynthesis, solar energy into vegetative organs and biomass can be converted into biofuel.

A key area of innovation identified at this stage of research the possibilities of using bioenergy crops as an alternative fuel. Today, the structure of the world of alternative energy biomass is about 13%. Subsequently, the share of renewable energy by 2040 will reach 47.7% projected researchers. The largest share of biomass in energy production typical for the EU: Latvia—26%, Finland—20%, Sweden—19%, Denmark—13%, Portugal and Austria—12% [1]. International experience shows that a promising feedstock for biofuel production is bioenergy plants. Interest in the growth and implementation of highly herbaceous plants such as species of the genus *Miscanthus Anderss*. is increasing [2].

The problem of biofuels can be solved in several areas: the use of the most efficient sources of biofuel from plant resources, improving technology transformation of raw materials for biofuels and biofuels feasibility study. Organizing of wide biofuel production in Ukraine has all the prerequisites, but their share in the energy balance is low. Ukraine has a great potential of biomass available for energy use, as G.G. Heletuha marks [3].

Today priority crops are already well defined that analyzed as a source of biofuels. However, the choice of effective raw materials depending on soil and climatic conditions of cultivation has its own feature. Among others herbaceous power plants including one of the highest ranks of introduced plants Miscanthus or "elephant grass". It belongs to the Department of angiosperms (Angispermal), class monocots (Monocatyledoneace), number (Glumifloreae), cereals family (Gramineae), kind (Anderssons), species (*Miscanthus giganteus*). This is hybrid of Miscanthus Chinese (*M. sinensis Anderss*., Diploid) and Miscanthus sugar flower (*M. sacchariflorus* (Maxim.) Benth., Tetraploid). In a temperate climate in the third year of growing Miscanthus productivity ranges from 10 to 30 t/ha dry weight, calorific value—from 14 to 17 MJ/kg [4]. It was first tried in Denmark. Biomass can be collected annually. From one hectare in temperate climates can be got 25–35 tons of dry mass per year and even more in irrigated field [5].

The largest plants impairment by frosts was observed in the first year of wintering after planting. Freezing may be subject to 90% of the plants. Large plants winter better (over 5 buds) than small (5). Small snow or complete absence makes the plant vulnerable to frost and promotes freezing. Mulching with straw crops Miscanthus crops can increase the level of wintering to 79–92%. Spring frosts lead to only minor yield losses due to the high regenerative ability of plants. Further plant adapts and tolerates winter. Starting from the second year of vegetation Miscanthus, plant resistance is higher in winter. Miscanthus belongs to thermophilic and moisture-loving plants.

Giant Miscanthus (*Miscanthus giganteus*) is a perennial grass plant, which is typical for C4-photosynthetic way. Unlike sugar cane, sorghum, corn and other C4-plants Miscanthus can grow in cool climates. This feature allows Miscanthus to realize its potential productivity in more northern climates, but it is different biomass feedstock for biofuels and cellulose [6]. You can see that in these plants during photosynthesis is complete utilization of carbon dioxide is not released into the atmosphere, and re-use process. Biomass while burning does not create the greenhouse effect.

Homeland of Miscanthus is vastly Japan, Manchuria, Korea, Thailand, the US east coast. Under natural conditions, this plant grows to a height of 6 m in diameter stems can be up to 6 cm. After planting a single culture can be harvested annually for 15 years or more, and vegetation can take up to 30 years. At the beginning of the V century Miscanthus was grown only in China as erosion culture. In Europe it was in the XVI century, but was considered only as an ornamental plant.

Miscanthus plants during the growing season require a small amount of water, characterized by rapid growth and development of stems and leaves. For the production of the dry weight of Miscanthus requires annual precipitation at 600–700 mm. To start the growth of leaves required minimum temperature + 5 + 10 °C. Daily temperatures in terms of European countries and Ukraine are sufficient to obtain high yields of biomass [7].

Miscanthus has a well-developed root system (2.5 m deep), characterized by rapid growth and relative stability to low temperatures. This root system promotes the use of batteries and water from the soil. It is suitable for growing in medium-fertile soils with low groundwater [8, 9].

The stem is very strong and has great endurance to mechanical damage, because it contains large amounts of lignin and cellulose.

Yield of energy crops depends on the climate, soil and other conditions. Depending on the type of energy crops cultivation process has its own characteristics. Conditions of Ukraine are suitable for growing Miscanthus. As for Ukraine Miscanthus is a new crop cultivation which requires the introduction and study in different soil-climatic zones—forest-steppe of Western. In the western steppes of Ukraine significant portion of soil is degraded and low-subject to reclamation. As for growing crops they are unsuitable, but appropriate in growing bioenergy crops.

Considering the urgency, the purpose of the analysis was a new culture—Miscanthus and outline the prospects for its use as a source of high-quality raw materials for Fitoenergetik in Western Forest.

Field research was conducted by conventional agronomic research and special techniques. The studied areas are directly in the middle of the southern slope of 2–3° slope. The depth of the water table 4–6 m topsoil generating breed—carbonate loess-like heavy loam. Profile soil humus formed by accumulative type of soil formation. The morphological features are typical black earth soil deep on loess loam. The humus content in the upper horizon is 3.39%, which corresponds to the level of family—little humus. With the depth the humus content decreases to 2.68% in the upper horizon and the transition to 1.25% in the lower transition horizon. Reaction environment is neutral with a tendency to increase water pH from 6.8 to 7.0 with depth, hydrolytic acidity decreases from 0.70 to 0.35 mg-eq./100 g of soil parent material. For agrochemical providing nutrients available to plants, soil belongs to the following gradation: alkaline hydrolyzed nitrogen is very low maintenance, mobile forms of phosphorus is standard, exchangeable potassium is increased.

Growing Miscanthus for improving processes for providing biomass will help to successfully implement the production of biofuels from raw materials of vegetable origin. It is given the simplicity of the plants to soil conditions, it is advisable to grow on unproductive soils. It grows on fields that are unsuitable for agriculture—too acidic, waterlogged or contaminated, but give environmentally friendly materials.

Miscanthus is sensitive to the quality of the soil, so the fertile soils yield can reach up to 30 t/ha per year, and the poor—barely reach 10 t/ha. For growing Miscanthus most suitable loamy, sandy and degraded lowland peat with stable for years during the growing season with supply of moisture. Do not lay Miscanthus plantations on sandy soils with low and unstable supply of moisture and high weediness perennial rhizomes and weeds. By moving the contents of elements phosphorus and potassium can be used soils with low to medium security.

Bookmark Miscanthus plantations should be placed on favorable crop rotation and degenerate in the fields of natural and cultivated grasslands and pastures and degraded soils not suitable for agricultural use.

The cultivation of the soil should be directed at creating conditions that would ensure the full shooting, good growth and development of plants throughout the growing season. Tillage system for heavy accumulation of moisture and nutrients involves peeling disc followed by deep plowing and cultivation. When laying areas after Miscanthus grasses and meadow lands launched to reduce the use of old vegetation herbicides of continuous action (4–6 l/ha) and conduct multiple processing turf disc harrows, cultivators or cutters.

Phosphorus, potassium and nitrogen fertilizers are applied to soil fertility of middle of spring pre-sowing cultivation at the rate of nitrogen, phosphorus, 40–60 kg/ha of potassium and 100–120 kg/ha of a.s. In soils of high fertility fertilizers do not make any major power in the soil, no fertilizing after planting Miscanthus. In low fertile soil in the second year after planting nitrogen, phosphate and potash fertilizers are applied in doses of 45–50 kg/ha of a.s., and potassium—90–100 kg/ha a.s. On the third and following years fertilizers are not contributed under Miscanthus. Until now fallen leaves of Miscanthus accumulate as litter which decomposes the source of supply and a strong root system increases the salinity of the soil and uses remote forms of nutrients from the soil.

For planting should be used high yield Miscanthus varieties with high potential for adaptability to soil and climatic conditions of the region growing and hybrids that have been tested in research institutions.

Miscanthus is propagated vegetatively as triploids, pollen is sterile and does not form seeds. More often propagated Miscanthus rhizome division (rhizomes), parts (segments) roots 10–12 cm, weighing 20–50 grams, which have at least 5–6 buds. For this planting material Miscanthus rhizomes should hummock second or third year of vegetation, even when they are at rest divided into fragments, i.e. rhizomes.

Planting is carried out in early spring in moist soil. Not allowed planting in later periods in dry soil. In this regard, planting should be carried out in early April, when the upper most soil saturated with moisture. Planting Miscanthus rhizomes segments held or stored freshly prepared on the day of planting. The density of planting is 1 ha within 10–16 thousand units landing (rhizomes). The width of the rows is 70 cm. The distance between plants in a row is 70 cm. The depth of planting rhizomes is 8–10 cm.

In the first year after planting and germination Miscanthus clear expression of its line, and the emergence of weeds, loosening held rows and weed protection zone with a width of 1–12 cm from each side of the line. Two to three weeks after first loosening the appearance of weeds between the rows held reprocessing rows using a cultivator.

In the second year after planting in soils of low fertility it is carried feeding of complete mineral fertilizer at the rate N60P40K120 kg/ha of a.s. Mineral fertilizer is introduced in early spring before the row cultivation. After fertilization and germination of weeds one must spend loosening rows cultivators width buffer zone on each side of the line to 18 cm.

In the third year after planting rows loosening does not hold, as Miscanthus plants to cover the soil then aisle space and overgrown its rhizomes, because weeds are not competitive.

The results of our research on energy crops of Miscanthus deserve considerable attention as a source of fuel energy. This high-performance culture provides a large output of dry matter and energy of aboveground mass. Giant Miscanthus Test results give reason to believe that it is highly flexible and high-performance culture.

It has been studied the biological, ecological, morphological features of plant, defined yield of vegetative mass. It has been found Western forest-steppe conditions are favorable for growth and development of giant Miscanthus. It analyzes the engraftment rate of plants, which amounted to 91%, while planting using irrigation in conditions of sufficient soil moisture (60–70%), it increased to 97%. Under western steppes giant Miscanthus shoots appear at 28 days after planting, which is held in early April. Sprout shoot one, sometimes two, depending on the number of sprouted buds simultaneously rhizome. The period from germination to full unit lasted 15 days. Plants growing in the second year of vegetation are characterized by intense regrowth that occurs in the second week of April. The next phase of growth and development has three leaflets that last long. The plants quickly form new meromes body that analyzes the tillering stage, or buds formation in the second week of June. This phase occurs in plants have long growing season to late autumn. For plants, this phase is characterized by the development of roots that will serve as a full planting material and significant accumulation of reserve substances and use them during wintering. The appearance of nodes on the stem, and a significant increase in leaf analyzes the phase out of the tube, which can be seen in the second week of August. Later on the plant ejection panicles is observed in the third week of September, and then comes the flowering. During the growth and development of plants Miscanthus growing in terms of the transition average daily temperatures fall below 10 °C, during which observations came in the second week of October, causing shrinkage puff-stems mass. In plants under such conditions suspend growth processes of development. Nutrients of puff stem mass transport to the roots, where it accumulates.

The main morphological parameters of giant Miscanthus are plant height, number of stems and leaves depended on the phases. During intense growing season, when it is the beginning of technical maturity, the plants reach maximum size. The height of plants in panicle emergence stage reached in the first year growing to 180 cm. Number of shoots observed 8.2 units, respectively, the number of sheets counted 72.6 pieces per plant. For the analysis of plant in a phase of exit in the tube plant height was 144.1 cm, while the number of shoots 6.8 pc and leaves—46.6 pieces per plant. The slightest manifestation of morphological parameters is observed on the plants during tillering, which analyzes the height, which is 50.4 cm, the number of shoots—5.2 units, and the number of leaves only 25.8 units per plant. In contrast, plants in the second year after regrowth of vegetation marked the height of a much larger, indicating that the resulting rate is 61.2 cm. Under such features growing season of plants growing in the second year charged to 22 stems. This analysis indicators show a rapid increase vegetative mass as feedstock for biofuel production.

Vintage biomass first year is going, as it is in most 1–3 t/ha. With 2-year yield collected annually because it can reach up to 10 t/ha or more, and the 3rd and the next is 15–20 t/ha.

Harvesting is carried out after the plants after the growing season and frosts are almost dry (20–25% moisture) and soil-frozen and is suitable for the passage of heavy machinery. The snow is little (2 cm) or missing. Harvesting is carried out in a dry and clear weather.

When wet biomass and the presence of snow harvesting is carried out in spring after drying, good pass technique on the field to dry clear weather.

Harvesting is conducted by direct combine harvesting, crushing biomass in special vehicles and delivering them to their storage and processing. Use self-propelled forage harvesters, or other available units. Mowing height should not exceed 10–12 cm from the ground. The resulting mass can be used directly for heat processing into briquettes, pellets or granules.

Subject to the requirements and productivity of manufacturing operations for growing Miscanthus provided energy plantations use areas—15–20 years or more.

Growing crops benefit only large scale (to reduce cost) when receiving the harvest of at least 15 tons/ha. Revenue can also be raised if the use of planting crops for the next breeding and sale of planting material.

The analysis of the prospect of growing Miscanthus, it should be noted that this hardy plant that grows 20 years and over. Culture requires virtually no costs for tillage and after planting does not require treatment. Low operating costs growing open up the possibility of using this crop in Ukraine and it is appropriate for the conditions of forest-steppe of Western. Vintage going through the normal harvesting and the resulting mass can be used directly for heat or processing into briquettes or pellets. One ton of dry weight Miscanthus is equivalent to 400 kg of crude oil. Yield can be increased if the use of crops for further breeding culture and implementation of new parties of rhizomes as planting material.

Experience shows that a high yield of Miscanthus is only possible by careful adherence to all elements of growing technology and first it is time planting. It was established on the basis of morphological parameters of formation of vegetative mass acts as feedstock for biofuel production. Plants are characterized by large growth rates during the active growing season. Miscanthus giganteus most marked in terms of height and length of plant leaves, which indicates accumulation of biopotentials as plant material for use in bioenergy.

The situation in Ukraine, unfortunately, is not as developed as in neighboring Poland, although our capacity no less, and perhaps more. We just have not fully realized that all around us there are many resources that can be used as local biofuels.

2 Material and Methodology of Research

The material for the study was biomass of giant Miscanthus (*Miscanthus* × *giganteus* Greef et Deu) collected from an experimental plantation co-hosted by the State Agrarian and Engineering University in Podillia (Fig. 1). The harvested biomass in November 2015 was crushed on a axle cutter with a cutting length of 20 mm reflecting the conditions of a single-stage harvest using self-propelled choppers. The raw material prepared has been seasoned to obtain a moisture content of 12–14%. Moisture at this level is recommended for solid biofuels produced from agro feeds. A further stage of research was conducted at the Laboratory of Technology for Production and Quality Assessment of Biofuels in Cracow.

The material of 14% moisture content was milled on a POR ECOMEC hammer mill using 10 and 15 mm sieves.

The raw material through the proper agglomeration (Fig. 2) was analyzed to determine the key parameters relevant for energy utilization. The moisture content of the raw material was determined in accordance with PN-EN ISO 18134-1: 2015-11. The test sample weighing more than 300 g was placed in a calcined and weighed to 0.1 g weighed cell and dried at 105 °C ± 2 until weight was determined.

The bulk density BD [kg m^{-3}] was measured in accordance to the procedure described in PN-EN ISO 17828: 2016-02 by determining the mass of the material in a known volume.

The granulometric composition of the crushed biomass according to PN-EN 15149-2: 2011 standard was also determined using the ø 8 hole sieves; 3.2 mm and weave sieves # 2.8; 2; 1.6, 1.4; 1; 0.5; 0.25 mm.

The ash content according to the methodology proposed in PN-EN ISO 18122: 2016-01 was also measured. The ash content was determined by calcining the

Fig. 1 Collection of giant Miscanthus shoots using Solo saw *Source* Own elaboration

Fig. 2 Shredded Mushroom Shoots: from the right grinded on the ax cutter, then ground on a mill with ⌀15 mm and ⌀10 mm sieve *Source* Own elaboration

sample to constant weight at 550 ± 10 [°C]. It was also marked one of the most important energy parameters which is calorific value. This parameter allows to determine the amount of energy that can be generated by burning a fuel unit. High quality isoformibolithic C6000 calorimeter from IKA was used in this study. The device is fully automatic and only the placement of a properly prepared sample in the crucible is required. Calculations are performed in the device based on EN-14918: 2010.

Then the prepared raw material was subjected to a pressure agglomeration process on a hydraulic briquette machine with an open hydraulic working chamber made by POR ECOMEC model Junior. This briquetting machine produces briquettes with a diameter about 50 mm and a few centimeters in length. The agglomerations of the material were carried out at three working pressure values of 27, 37 and 47 MPa.

Next, the briquette was tested for durability after 24 h to determine durability index DU (%). The measurement was performed according to PN-EN ISO 17831-2: 2016-02 standard which was based on weight loss information during the test. For each fraction of material two tests were performed for the individual agglomerations pressure.

The specific density of analyzed briquettes was also determined on the basis of geometric measurements (volume determination) and masses. The sample consisted of 10 randomly chosen pieces of granulate.

3 Result and Discussion

The research presented in accordance with the previously methodology allowed to collect information characterizing the raw material in terms of energy use. Table 1 shows the basic data characterizing the material.

Table 1 Results of qualitative research of raw material

	Moisture content M_{ar} (%)	Ash content A_{ar} (%)	Calorific value $qp_{net,ar}$ (MJ kg^{-1})	Bulk density BD_{ar} (kg m^{-3})
1	13.31 ± 0.12	3.67 ± 0.23	17.52 ± 0.23	169.5 ± 3.9

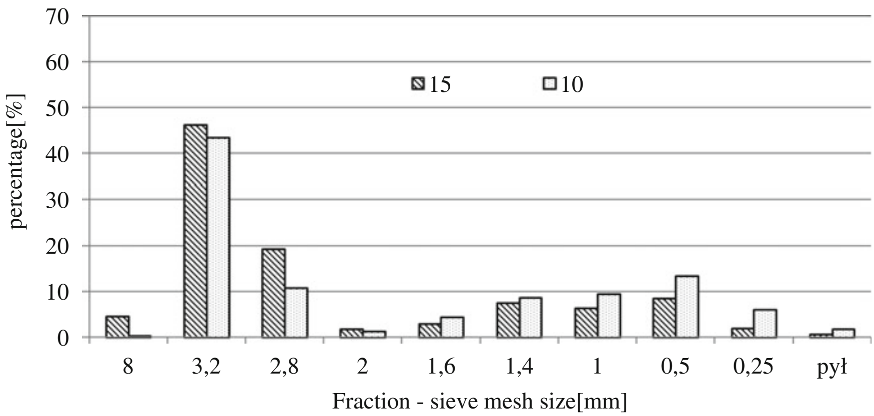


Fig. 3 Granulometric composition of raw material after milling on sieves ⌀15, ⌀10

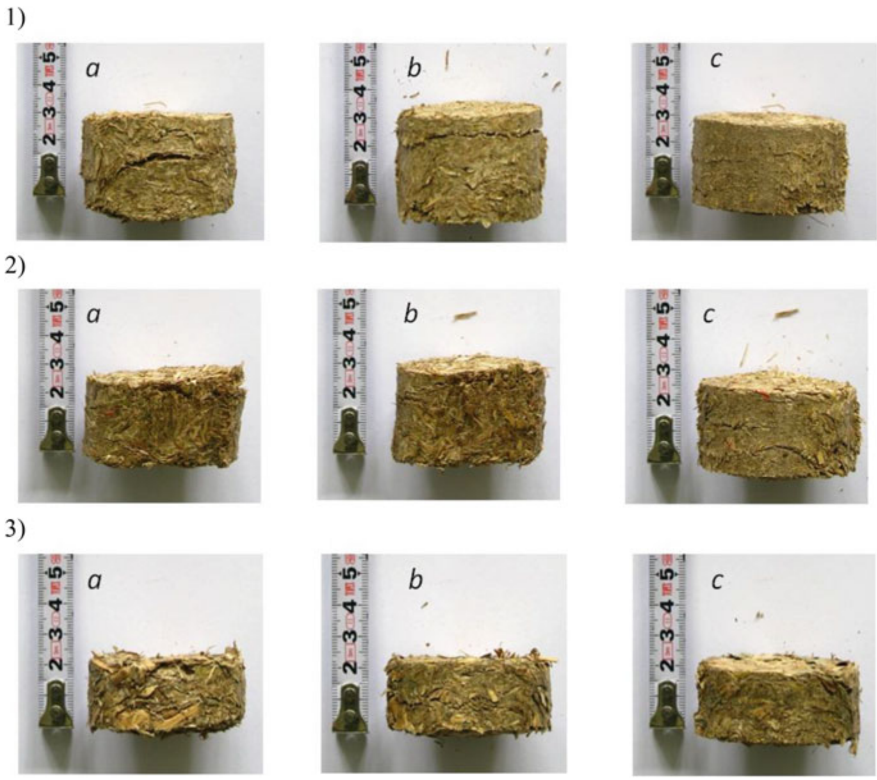


Fig. 4 View of example briquettes made of crushed material: **1** on a save with hole ⌀10 mm, **2** on a save with hole ⌀15 mm, **3** chopped raw material; compressed at working pressure: a—27 MPa, b—37 MPa, c—47 MPa

The parameter values of individual parameters are classic for energy crops and comparable to those of other researchers [10, 11].

The graph 3 shows the granulometric composition of the analyzed agglomerated raw materials. It can be seen that the distribution of individual fractions is similar. The largest group of over 40% are particles retained on a 3.2 mm sieve. Fine fractions dominated on 1.4; 1 and 0.5 mm. It can also be observed that the reduction of the sieve openings from ⌀15 to ⌀10 mm resulted in a decrease in the main fraction (8–3.2 mm) for small fractions. In the case of a sieve with 10 mm holes, the fine particle fraction was 0.5 mm (13.4%).

Figure 4 shows samples of briquettes obtained from the agglomeration of the tested raw materials using three agglomerated pressures. It can be observed that as the amount of raw material increases, the height of the briquette increases. This is due to the fact that in the case of materials with larger particles, the bulk density was lower, which resulted in less agglomeration in one agglomeration cycle. It can also

Table 2 Parameters of obtained briquettes

Sample	Working pressure (MPa)	Durability DU (%)	Specific density (kg m^{-3})
Crushed on a sieve ⌀10 (mm)	47	95.4 ± 1.3	942 ± 3
	37	92.6 ± 1.4	891 ± 8
	27	91.2 ± 1.1	822 ± 6
Crushed on a sieve ⌀15 (mm)	47	92.7 ± 1.2	928 ± 4
	37	91.3 ± 1.4	869 ± 5
	27	90.1 ± 1.3	814 ± 8
Chipped on the forage	47	89.6 ± 1.5	865 ± 6
	37	87.4 ± 1.4	789 ± 11
	27	85.3 ± 1.9	721 ± 7

be observed that the increase in pressure caused that the briquette got more regular shapes and there were no visible cracks and cavities.

Performed quality assessment tests of briquettes are presented in Table 2. It can be seen that the increase in agglomeration pressure caused an increase in the durability of obtained briquettes for all analyzed raw materials. Similar occurrence were observed at specific density. The highest density (942 kg m^{-3}) was characterized by briquettes obtained from the most crushed raw material. Density at this level compared to products used in the trade is satisfactory. Based on literature [11–13] it can be assumed that the density of over 850 kg m^{-3} is satisfactory. Considering the above mentioned criterion it should be noted that the agglomeration pressure of 27 MPa is not sufficient for each material. In the case of agglomeration of unmilled raw materials, the highest pressure is required, however, the stability of these granulates is low (below 90%) which may cause problems during longer logistic processes.

4 Summary

The research has shown that biomass from the Miscanthus plantation grown in the southern part of Ukraine is the raw material for obtaining high quality briquettes. Research has also shown that it is essential to use grinding in the technological process to obtain a high degree of milling. It seems to be sufficient for mill grinding mills with a perforation of ⌀15 mm. Reducing the size of sieve holes, e.g. up to 10 mm, can improve the quality of pellets, but it should be borne in mind that this significantly increases the energy consumption of the process.

The presented agglomeration method based on an open cell hydraulic briquette is a very accessible solution. The application of this agglomeration technique should enable the dynamic development of the solid biomass sector from biomass of the Miscanthus. The quality of the obtained briquettes, in terms of energy (calorific value > 17.5 MJ kg^{-1}) and physical properties make this product a local commodity and export commodity. Taking action to produce solid biofuels from raw materials obtained from energy plantations creates opportunities for the development of Ukraine's agricultural sector.

References

1. Global Status Report, [Elektronnyy resurs]. http://www.unep.org/pdf/GSR2013.pdf (2013)
2. Blum, J.B., Hryhoryuk, I.P., Dmitruk, K.V., and others.: System of Biotechnology Alternative Fuels. K. Agrar Media Group, 360 p. (2014)
3. Heletuha, G.G.: Evaluation of the energy potential of biomass in Ukraine. In: Heletuha, G.G., Zhyelezna, T.A., Zhovmir, N.M., et al. (eds.) Industrial Heat. vol. 32, no. 6, pp. 58–65 (2010)
4. Sorenser, A.: Hydrolysis of Miscanthus for bioethanol production using dilute acid presoaking combined with wet explosion pretreatment and enzymatic treat-ment. Biores. Technol. **99**, 6602–6607 (2008)
5. Nalborczyk, E.: Rosliny alternatywne rolnsctwa XXI wieku I perspektywy ich wykoristania/ Zeszyty Problemowe Nauk Rolnsczych 1999, z. 468, s. 174-30
6. Miscanthus// World plants. 2011 [electronic resource]. Access: http://svit-roslyn.com/bez-rubriki/miskantus/
7. Ivanyshyn, V., Hutsol, T.: The Ukrainian agricultural groups state and agro-machinery rovision. Scientific achievements in agricultural engineering, agronomy and veterinary medicine. Monograph—Traikon. Krakov. vol. 1, pp. 1–13 (2017)
8. Blum, J.B., Heletuha, G.G., Hryhoryuk, I.P., et al. New Technologies Bioconversion: Monograph. K. Agrar Media Group, 326 p (2010)
9. New dedicated energy crops for solid biofuels. AEBIOM, FP6 FESTMAC project. www.aebiom.org/IMG/pdf/ (2008)
10. Nixon, P., Bullard, M.: Plantinge and growing of Miscanthus. Best practice guidelines. DEFRA http://adlid.everysite.co.uk/resource/000/023/838/miscanthus-guide.pdf
11. Sjaak, V.L., Jaap K.: The Handbook of Biomass Combustion and Co-firing. Earthscan (2012)
12. Mudryk, K., Fraczek, J., Slipek, Z., Francik, S., Wrobel, M.: Chosen physico-mechanical properties of cutleaf coneflower (*Rudbeckia laciniata* L.) shoots. Engineering for Rural Development Jelgava, 2013, Available at: http://tf.llu.lv/conference/proceedings2013/Papers/122_Mudryk_K.pdf
13. Wrobel, M., Frączek, J., Francik, S., Slipek, Z., Mudryk, K.: Influence of degree of fragmentation on chosen quality parameters of briquette made from biomass of cup plant *Silphium perfoliatum* L., Engineering for Rural Development Jelgava, 2013 Available at: http://tf.llu.lv/conference/proceedings2013/Papers/121_Wrobel_M.pdf

Conceptual Design of the RDF Granulation Line

Marek Wróbel, Jarosław Frączek, Krzysztof Mudryk, Marcin Jewiarz and Krzysztof Dziedzic

Abstract The paper presents a concept of a technological line for the production of granulated fuel from RDF. The main assumption of the line is the complexity of processing a raw RDF with very variable input parameters (morphological and granulometric composition, proportion and type of impurities as well as variable moisture content) to a pellet with high quality parameters (specific density, mechanical durability). Based on an analysis of the raw material characteristics and preliminary research on the RDF granulation process, design guidelines and assumptions were proposed. This allowed to develop a block diagram including all technological operations which must be used to process raw material. For each operation a technical solution was proposed which best fulfills the stated assumptions. A vacuum transport system of raw material has been proposed to reduce the amount of fly dust generated during the production process. This system is equipped with a central filter from which the dust is driven for re-granulation. Such system, reduces production of waste byproducts. As the pelletizing unit, a developed by the authors pelletizer with modified dye was proposed. Thanks to this solution, the granulation process will proceed in the temperature about 100 °C. Beside recommended moisture content and fineness of the raw material, high temperature helps ensure the predetermined quality of pellets.

M. Wróbel (✉) · J. Frączek · K. Mudryk · M. Jewiarz · K. Dziedzic
Faculty of Production and Power Engineering, University of Agriculture in Krakow,
120 Balicka Street, 30-149 Krakow, Poland
e-mail: Marek.Wrobel@ur.krakow.pl

J. Frączek
e-mail: jaroslaw.fraczek@ur.krakow.pl

K. Mudryk
e-mail: krzysztof.mudryk@ur.krakow.pl

M. Jewiarz
e-mail: marcin.jewiarz@urk.edu.pl

K. Dziedzic
e-mail: dziedzickrzysiek@poczta.fm

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_79

Keywords RDF · Agglomeration technology · Conceptual design
Fuel quality

1 Introduction

Processing and using municipal solid waste (MSW) as secondary raw material is a problem that requires an urgent and comprehensive solutions on a regional, national, European and world scale [1–4]. The current model of waste management in Poland assumes that the wastes are pre-sorted at or near place of their production. Such situation requires introduction of solutions for recovery from the waste stream with energetic potential (raw RDF), which we can obtain from municipal wastes.

The raw material can utilized by pyrolysis and obtained gas or oil can be used as source of energy [5–7]. The second way is combustion or cocombustion, intense oxidation at high temperature which has an advantage over pyrolysis that the combustion is much more efficient. Each of these processes has its advantages and disadvantages, as well as the process of indirect thermal treatment of waste in the literature called quasi pyrolysis [8].

Two fractions (oversize and undersize) are obtained during the mechanical-biological treatment (MBT) in the process of mechanical separation of various municipal waste streams, most often performed on drum screens (of varying mesh size: from od 50 to 100 mm, in Poland at least 80 mm). The undersize fraction has a significant content of organic matter and is often sent for biological treatment. The oversize fraction is most usable for energy recovery [9, 10]. Dziedzic et al. [11] have presented the results of analysis of morphological composition of mixed municipal waste and morphological composition of waste after mechanical separation on a drum screen (⌀ = 80 mm), i.e. the undersize and oversize fraction sent to produce RDF. Dominating in the municipal waste is organic matter, plastics and paper and cardboard. Plastics, paper and cardboard, and textiles have the highest share in the oversize fraction, and these are materials with high energy parameters (low ash content and high calorific value) which can be used with success as raw material for production high quality RDF based fuel.

Such type of fuel can be use in conventional power plants as an additive in co-combustion with coal. It need to be mentioned that RDF is a very cumbersome material to use, due to the fact that most of it consists of flexible material like textiles, paper, and other plastic materials with very low bulk density [12]. For this reason, it is quite hard to obtain well milled material with use of ball mill, which are most often used in power plants. It is possible when RDF has the form of pellets. Taking into account the variety of morphological, grain size distribution and physical properties of RDF, agglomeration to form of pellets its very good way to improve the physical properties of the raw material. These process aims to increase the energy density of the fuel and convert it to a form that more conventional in terms of transport, storage or dosage in thermal treatment plants.

Currently, the RDF agglomeration is carried out on equipment dedicated to pelletizing and of biomass. However, due to specific properties of RDF dedicated solutions must be proposed. The densification matrix need to be modified; its thickness should be increased and shape of densification channels should be altered which makes the material stay in the matrix longer and finally can improve the granulate quality [13–17]. Obtained pellets must be of good quality (mechanical stability, specific density). This is the reason for search for optimum parameters of the raw material and the process, and interrelations between them. The main factors are moisture content, degree of shredding, densification pressure and the process temperature [18].

In order to be able to produce RDF pellets of high quality, the designed technological line must enable complex processing of the raw material. Due to the RDF properties, this treatment must include raw material pre-fragmentation, drying (if necessary), milling agglomeration and cooling. In addition, due to the origin of the RDF, the line should be equipped with a hygienisation system and a filtration system to prevent the getting out of dust from the technological string.

2 Characterization of the Raw Material

Based on the results obtained during realization project No: GEKON2/05/268002/17/2015 (samples taken from MSW sorting plants in Tarnów, Tarnobrzeg, Włoszczowa and Kraków) the raw material for the production of granulated EkoRDF fuel was oversize fraction of municipal waste (material, after the separation of fractions that can be reused, which not passing the 80 × 80 mm mesh sieve) (Fig. 1a). This kind of raw material contains only small fragments of glass, ash or metal. The results indicate that the maximum ballast content (non-flammable material) is 30% by weight (18% on average). Studies have shown also that the use of undersize municipal waste as a raw material for the production of EkoRDF fuel should be excluded. In this case the content of ballast is too high—it is over 50%.

In the light of the preliminary studies on the granulation process, the material intended for production of RDF pellets of 8 mm diameter should be comminuted in a mill using a screen with a hole diameter of about 15 mm (Fig. 1b).

The maximum humidity of the feedstock is 40% and depends on the season and weather conditions. Most often moisture content of raw material was in range 20–30%. Raw material should be hygienized with calcium oxide added at 1% of sample weight.

Fig. 1 Raw material: **a** after delivery from RIPOK, **b** after milling (diameter of sieve 15 mm)

3 Project Assumptions

Based on the raw material analysis, preliminary agglomeration trials on the endurance machine and their verification on a pelletiser fitted with a biomass die and a modified RDF die, the following design assumptions were made:

- The pellet production process from Municipal Solid Waste should be able to process the raw material as an oversize RDF fraction. The nature of line work: continuous or batch.
- The line should be protected from dust emission and should not generate waste byproducts.
- The parameters of the technological chain must ensure the production of pellets with high quality parameters. Based on the norm requirements [19, 20], as measures of quality were assumed: mechanical durability DU at a level not less than 95%, bulk density BD at least 550 kg/m^3, solid density SD at least 1000 kg/m^3, moisture M_{max} 12%.

Accordingly, the line should consist:

- shredding-preparing unit, performing the processes of pre-shredding, drying, milling, hygienization, homogenization and stabilization of raw material,
- agglomeration unit, performing the process of pressure agglomeration of prepared raw material,
- cooling-stabilizing unit, performing of cooling the pellets and their weighing and packaging.

The entire installation must be equipped with additional, not previously mentioned devices as:

- installation of aspiration and transport of raw material and products,
- system of impurities separation (glass, stones, metal) and technology air filtration,
- platforms, ladders, rails, supports, racks and maintenance structures for comfort, high quality work and safety,
- motor and gearbox protection against overload,
- temperature measurement of the matrix directly or indirectly through product temperature measurement.

4 Concept of the Granulation Line

Based on the assumptions, a flowchart of the proposed technological process was developed (Fig. 2), which contains raw material processing units and flow direction. In addition, there are points where raw materials are fed into the line (RDF and calcium), and received impurities in the form of glass, debris and metals. Scheme includes also the system of technology air filtration, with indication of the points from which contaminated air is aspired and point where the dust is transported.

The following technical solutions are proposed for each processing step.

Storage of the raw material should to takes place in a sealed tank which cooperate with a floor conveyor with mechanical performance control.

The process of fragmentation of RDF should be conducted in two stages. In the first stage a shredder is proposed, powered by an inverter to control engine speed. Pre-shredding is aimed at homogenizing the fraction of material and its aeration, so that the drying process can proceed efficiently.

The optimal moisture content of the pelletizing material is approximately 12%. In case RDF, the moisture is mainly on the surface of the particles. Therefore, for drying RDF, one of the two drying units is proposed.

A tunnel dryer with infrared or microwaves emitters. This solution allows for intensification of the drying process, allowing the temperature of the chamber to be changed in a short time without interruption. It is recommended to use these dryers especially in the case of periodic work of the lines.

A drum dryer in which drying takes place with the use of hot air or exhaust, can be also used. An additional process intensification is possible by using baffles to force additional material movement. This type of drier is recommended for high performance continuous lines.

Separation of ferromagnetic impurities should be carried out using a magnetic separator. Other impurities like ash, debris, glass, etc. should be separated using a inertial separator. With proper airflow velocity regulation, it is possible to remove heavy contaminants from the material. Separators must remove contaminants that can damage the mill and pelletizer.

As a second stage of fragmentation, it is proposed to use a hammer mill. The fineness of the material is determined by the diameter of the screen. It is recommended that the diameter of the screen holes is about 2× the diameter of the pellet.

One of the innovative solutions used in the designed line is a hygienisation unit consisting of a calcium container and a calcium dispenser. The dispenser should be able to adjust the amount of calcium to be dosed in the range of 0.5–5% of the raw material mass. It is suggested that the stabilization and hygienisation process should be carried out in a buffer tank equipped with a continuously runs stirrer.

The raw material before granulation goes to the conditioner where it can be mixed with water or steam. The homogenizer should have a steam or water nozzle. If the material moisture is too low, it should be increased to an adequate level. It is proposed to use a homogenizer in the form of a paddle-screw conveyor which by mixing the raw material simultaneously transports it to the granulator.

To RDF pelletization is recommended using a granulator with cylindrical die which thickness should be increased (in comparison to biomass matrixes) to obtain a compression factor aprox. 10. Such a high compression factor allows rise the temperature in the working channels to 100–120 °C. This guarantee production of a high quality pellets. In the designed line it is proposed to use a die with holes of 8 mm in diameter.

Pellets after granulation must be cooled to obtain good mechanical durability. The use of a conveyor cooler co-operating with the ventilator and cyclone is proposed. This type of cooler allows simultaneously cooling pellet and separation of the loos raw material which can be pelletizing again. After cooling, pellets should be stored in a hopper from where is taken to the packing and weighing system.

The transport of the raw material up to the separation stage should be carried out by belts or screw conveyors. Separation and milling are handled by a vacuum transport system that directs the material to the cyclone. A similar system receives non-compressed material from the cooler and a central filter. The material from the cyclones passes through the dispensing cells onto a screw conveyor transporting it to the buffer tank.

All air from the vacuum transport systems should be routed to the central filter before leaving the line. It is proposed to use a bag filter equipped with an automatic filter cleaning system.

It is proposed that the entire process of pellet production technology be monitored and controlled using a multi-level touch control panel. It is recommended that all unit processes whose parameters are regulated should be represented in the form of pictograms.

Based on the proposed technical solutions, a technological layout of the projected line was developed, which is presented on Fig. 3.

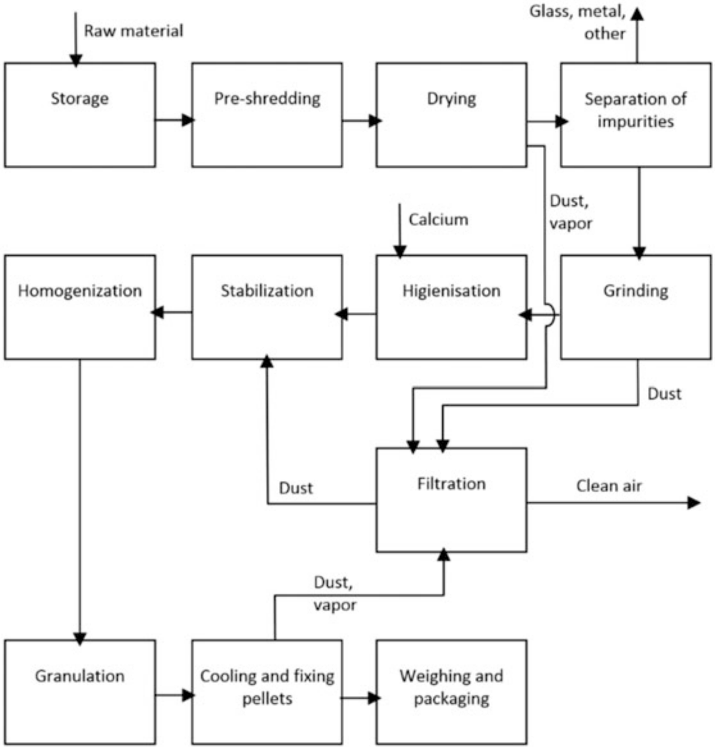


Fig. 2 Block diagram of the projected technological line

5 Summary

The presented concept of a technological line for the production of high quality RDF pellets takes into account all assumptions and in complex way allows processing of the raw materials with variable input parameters (different morphological and granulometric composition, moisture up to 40%). The proposed processing steps allow preshreding, drying and grinding of the raw material to the level required by the granulation process. The proposed separation system protects the elements of the line (mill, peletizer) from damage by metal, ash, debris, glass, etc. The innovation is a hygienisation system using calcium in a controlled amount of 0.5–5% of the weight of the raw material (laboratory studies have shown that satisfactory results are already achieved with 1% calcium addition). It is worth emphasizing that the proposed vacuum conveying system prevents the discharge of dust from the line. The air purification system allows to clean the air before leaving the line. The extracted dust returns to the granulation, this solution doesn't generate waste during the production process. The main component of the line is a granulator with installed a modified die for palletization of RDF material. The modification

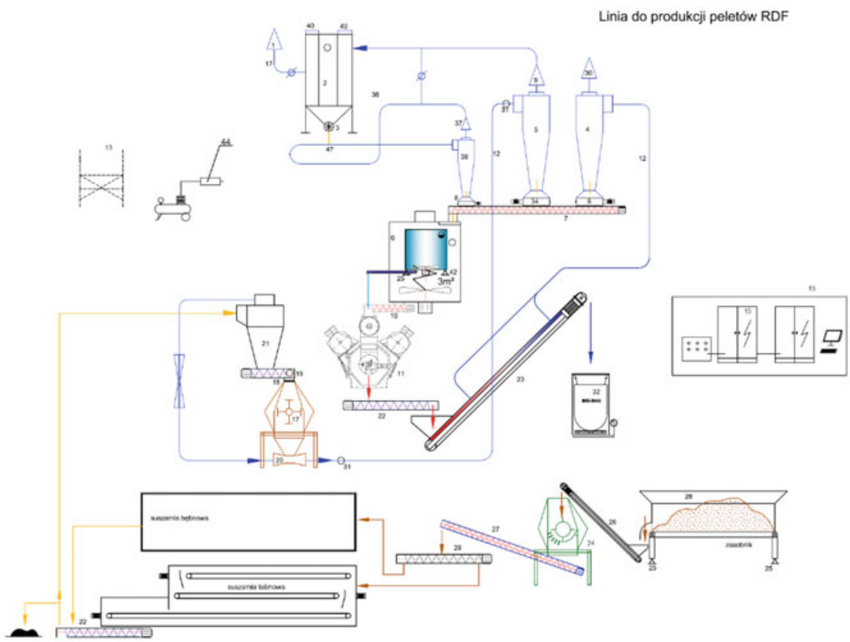


Fig. 3 Technological layout of the pellet production line from RDF

was aimed at obtaining a temperature of 100 °C during the process. This was achieved by increasing the compression factor up to 10.

Acknowledgements This research are financed by Polish Centre for Research and Development and National Fund for Environmental Protection and Water Management under the GEKON Programme—project No: GEKON2/05/268002/17/2015. “EkoRDF—an innovative manufacturing technology of alternative fuel from municipal waste for power and heating plants—a key component of the Polish waste management system”.

References

1. Gawłowski, S.: Zarządzanie pozyskanymi funduszami unijnymi w Polsce w obszarze ochrony środowiska. Annu. Set. Environ. Prot. **13**, 269–282 (2011)
2. Gawłowski, S., Gawłowska-Listowska, R., Piecuch, T.: Uwarunkowania i prognoza bezpieczeństwa energetycznego Polski na lata 2010–2110. Annu. Set. Environ. Prot. **10**, 127–176 (2012)
3. Cao, Y., Pawłowski, L.: Lubelskie doświadczenia we współspalaniu odpadów komunalnych w przemyśle cementowym. Annu. Set. Environ. Prot. **14**, 132–145 (2012)
4. Sarc, R., Lorber, K.E.: Production, quality and quality assurance of refuse derived fuels (RDFs). Waste Manag. **33**(9), 1825–1834 (2013). https://doi.org/10.1016/j.wasman.2013.05.004

5. Pająk, T.: Termiczna utylizacja odpadów komunalnych jako element współczesnej komplek- sowej gospodarki odpadami. Przegląd Komunalny **3**(78), 17–41 (1998)
6. Piecuch, T., Dąbrowski, T., Piekarski, J., Dąbrowski, J.: Energetyczne wykorzystanie odpadów przemysłu chemii organicznej. Kwartalnik Gaz Rosji **2**, 74–77 (2007)
7. Zechner, V., Guziurek, M., Fecko, P.: Application of brown coal pyrolytic oils in black coal slurry flotation mineral resources management. Gospodarka Surowcami Mineralnymi, IGSMiE PAN **29**(2), 51–67 (2013)
8. Piecuch, T., Dąbek, L., Juraszka, B.: Spalanie i piroliza odpadów oraz ochrona powietrza przed szkodliwymi składnikami spalin. Podręcznik Politechniki Koszalińskiej, Koszalin (2002)
9. Dębicka, M., Żygadło, M., Latosińska, J.: Investigations of bio-drying process of municipal solid waste. Ecol. Chem. Eng. A **20**(12), 1461–1470 (2013). https://doi.org/10.2428/ecea.2013.20(12)132
10. Jędrczak, A., Szpadt, R.: Określenie metodyki badań składu sitowego, morfolgicznego i chemicznego odpadów komunalnych. NFOŚiGW, Kamieniec Wrocławski, Zielona Góra (2006). (in polish)
11. Dziedzic, K., Łapczyńska-Kordon, B., Malinowski, M., Niemiec, M., Sikora, J.: Impact of aerobic biostabilisation and biodrying process of municipal solid waste on minimisation of waste deposited in landfills. Chem. Process. Eng. **36**(4), 381–394 (2015). https://doi.org/10.1515/cpe-2015-0027
12. Pedersen, M.N., Jensen, P.A., Hjuler, K., Nielsen, M., Dam-Johansen, K.: Agglomeration and deposition behavior of solid recovered fuel. Energy Fuels **30**(10), 7858–7866 (2016). https://doi.org/10.1021/acs.energyfuels.6b00839
13. Singh, R.N., Bhoi, P.R., Patel, S.R.: Modification of commercial briquetting machine to produce 35 mm diameter briquettes suitable for gasification and combustion. Renew. Energy **32**, 474–479 (2007)
14. Matus, M., Krizan, P.: Influence of structural parameters in compacting process on quality of biomass pressing. Aplimat J. Appl. Math. **3**(3), 87–96 (2010). ISSN:1337-6365
15. Gulley, B.W., Williamson, G.J., Carmichael, R.Q., Cooke, D.F., Taylor, R.: U.S. Patent No. 4,561,860. Washington, DC: U.S. Patent and Trademark Office (1995). https://www.google.com/patents/US4561860
16. Li, Y., Liu, H., Zhang, O.: High-pressure compaction of municipal solid waste to form densified fuel. Fuel. Process. Technol. **74**(2), 81–91 (2001). doi:https://doi.org/10.1016/S0378-3820(01)00218-1
17. Marsh, R., Griffiths, A.J., Williams, K.P., Wilcox, S.J.: Physical and thermal properties of extruded refuse derived fuel. Fuel Process. Technol. **88**(7), 701–706 (2007). https://doi.org/10.1016/j.fuproc.2007.01.015
18. Kersa, J., Kulua, P., Šoošb, L., Aruniita, A., Laurmaa, V., Kaskc, Ü.: Determination of physical, mechanical and burning characteristics of polymeric waste material briquettes. Estonian J. Eng. **16**(4), 307–316 (2010). doi:https://doi.org/10.3176/eng.2010.4.06
19. PN-EN ISO 17225-2:2014-07: Solid Biofuels—Fuel Specifications and Classes—Part 2: Graded Wood Pellets
20. PN-EN ISO 17225–6:2014-08: Solid Biofuels—Fuel Specifications and Classes—Part 6: Graded Non-woody Pellets

Agglomeration of Ash-Based Fertilizer Mixtures from Biomass Combustion and Digestate

Krzysztof Mudryk, Jarosław Frączek, Marek Wróbel, Marcin Jewiarz and Krzysztof Dziedzic

Abstract The production of fertilizers based on high quality waste materials is a highly important problem in environmental protection, mainly due to the protection of natural mineral resources. In addition, the combination of organic and mineral raw materials makes these fertilizers innovative in the fertilizer economy. As the research material unique mixtures of mineral and organic substances mixture were used. The main components were ash from biomass combustion power plant in the Połaniec and the digestate from a biogas plant located in Piekoszów. Sulfur and phosphorite were used as components to enhance the fertilizer value of the tested prototype blends (variant A). There were also blends supplemented with urea (variant B) to add nitrogen to composition. During the tests the energy consumption of the granulation process was determined and the quality of the obtained granules was determined by specifying envelope density, bulk density and mechanical durability.

Keywords Fertilizer granules · Agglomeration techniques · Quality features Density

1 Introduction

Waste generated in different processing technologies often have characteristics that predispose them to further use. In particular, mineral or organic waste products are very often characterized by the characteristics of fertilizer raw materials.

The main type of ash management was their storage, without distinction of origin, in landfills. As a result, the beneficial properties of the ashes from the combustion of biomass were irretrievably lost. Utilization of fly ash from biomass combustion reduces the amount of this material in landfills—this gives economi-

K. Mudryk (✉) · J. Frączek · M. Wróbel · M. Jewiarz · K. Dziedzic
Faculty of Production and Power Engineering, University of Agriculture in Krakow, ul. Balicka 116 b, 30-149 Krakow, Poland
e-mail: Krzysztof.Mudryk@ur.krakow.pl

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_80

cally (reducing transport and storage costs) and ecological (reducing the amount of waste entering the environment) benefits [1, 2]. Since the beginning of 2013, the “Green Block” of the Połaniec Power has been produced a by-product in the form of fly ash generated from 100% biomass combustion. Processing of this type of waste is new due to previous absence of biomass burning in Poland. Hitherto, the biomass as a fertilizer was used on a small scale, mainly at home (e.g. in home gardens), as an alternative to mineral fertilizers.

In Poland, the use of digestate mass for fertilizer purposes has been very small. This was related to the existing existence of legal barriers (which have been abolished) that treat post-fermentation waste as waste—In order to transfer the fermented pulp to third parties, it was necessary to obtain a permit issued by the competent Ministry of Agriculture, this was a big hindrance for biogas owners. Without such permission, the biogas plant could use its fertilizer only in the fields to which it has a legal title.

Obecnie popiół ze spalania biomasy w tzw. Currently, the ashes from burning biomass in the so—The Green Power Blocks (ZBE) in the power industry are deposited in a separate landfill [3–5], because of that properties are irretrievably lost (washed out) and the ash contributes to environmental pollution (dusting, leaching from the landfill). The “ash management” through its storage is:

- inefficient—Ash from biomass combustion is characterized by composition other than ash from coal, its characterized by a composition similar to the chemical composition of plants such as grain, grass, wood, burned in green blocks. Naturally, micro and macroelements contained in ashes should be returned to the soil, what is not happening now, which on a global scale causes slow soil erosion, as a result, fertilizers are used to improve soil properties. The specific objective is to put the elements back into the soil in practice.
- non-ecological—technology development contributes to not only new solutions but also generates new waste.
- In cases where they are not adequately managed into the environment, a new pollutant load is introduced, inter alia, by creating new landfills.
- The lack of use of biomass-derived ashes not only results in the loss of potential benefits, but also increases the environmental burden by creating a new landfill,
- which generates dust and leachate that are introduced into the environment, during improper storage of the landfill,
- costly—The cost of maintenance of the ash/landfill incinerator includes the cost of transportation to the landfill, the cost of maintaining the heap dump, the cost of reclamation. The specific goal is to reduce this cost in the production of electricity.

Similarly, the case is presented with a fermentation that has not been efficiently and effectively used as a fertilizer until now. Its storage is also non-organic because organic ingredients are not used in fertilization, they are closed in landfills.

The results of the initial laboratory tests (on a small number of samples) showed that the fly ash contained:

SiO_2 (56%), Ca (19%), Al (7.8%), P (5.3%), K (4%), Fe (2.7%), Mg (2.5%), S (1.8%), Mn (0.5%), whereas bottom ash was characterized by: SiO_2 (89.45%), Ca (5.4%), P (1.5%), Al (0.9%), K (0.9%), Mg (0.7%), Fe (0.6%), S (0.3%), Mn (0.2%). The research carried out on the post-fermentation showed that it contains about 2.08% of the minerals and the following components: P (54.4%), Ca (14.1%), K (10.1%), Mg (7.3%), S (6.3%), Fe (1.8%). The pH value was set for fly ash 12.24, for bottom ash 11.54 and for post-fermentation 7.71.

Studies have shown that both ash and post-ferment have valuable nutrients, moreover, it was noted that the ingredients contained in the above substances are complementary, thus confirming the assumption of the use of both substances for the production of fertilizer [6–8]. The main purpose of this paper was to present the results of research work to verify classical agglomeration techniques for the compaction of ash-based raw materials mixtures and post-fermentation with the addition of raw materials in the fertilizer aspect.

2 Methodology

Verification testing of the pelleting process was carried out on the MGL 200 pelletizing line with a capacity of up to 100 kg/h by Kovo Novak, a roller compactor and a disc granulator from GitTech.

The installation is equipped with a pelletizing unit with a driven disk array. The material in the hopper, equipped with a stirrer, is taken by a screw conveyor, at the outlet of which the dosage adjustment system of material is located. The excess material returns gravity to the tank, while the fixed dose of material—also gravitationally—it is fed to a horizontal conveyor which transports it to the pelleting

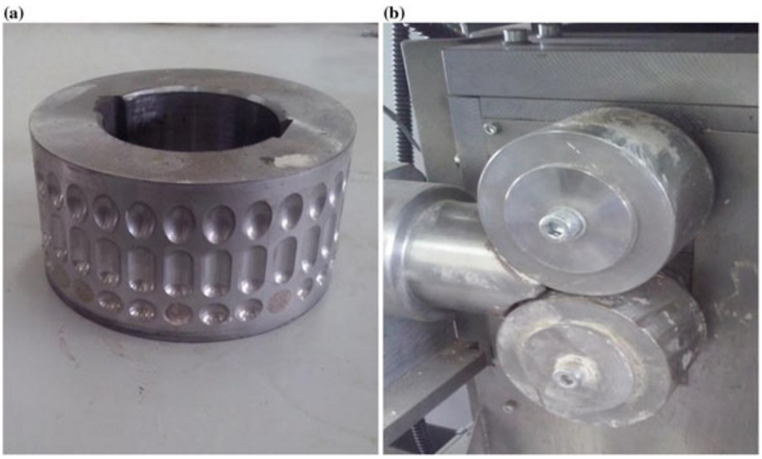


Fig. 1 GiyTech compact roller compactors; **a** with cut-out pastilles; **b** smooth

chamber. The material falls between the pressing rolls and the die surface, where it is pressed into the pressing channels and compacted into a pellet. The knife placed under the die cuts off the finished granulate, which goes to the cooler where its conditioning and sifting of the non-compressed material takes place. Whereas the impurities are transported back to the material tank by the conveyor. In addition, the line is equipped with extractor, which is designed to remove dust and water vapor from the ironing chamber and the cooler. Line control is controlled by the control panel. During the granulation tests a matrix with the geometry of the thickening channels used for pelletizing biomass with a 6 mm channel diameter was used.

The next device on which the research was carried out was a cylindrical compactor consists of basic executive modules which are: 1—material tank with stirrer, 2—screw feeder material, 3—compact roller assembly Parameters of operation and control of executive modules are realized by control panel—4. The compactor can compact the material between the pair of smooth rollers or between rollers with cut shapes of the resulting pellets (Fig. 1).

The last agglomeration system was a GitTech disc granulator (Fig. 2) which consists of such executive modules as: 1—Vibrating material dispenser, 2—spray nozzles granulate material 3—plate on which the granulation process takes place Parameters of operation and control of the actuators are realized by means of the control panel—4. The material dispensed by the feeder (the granulator has the ability to regulate the amount of material being dispensed) falls on the lower edge of the pelletizer which is set at an angle to the horizontal (adjusting the inclination

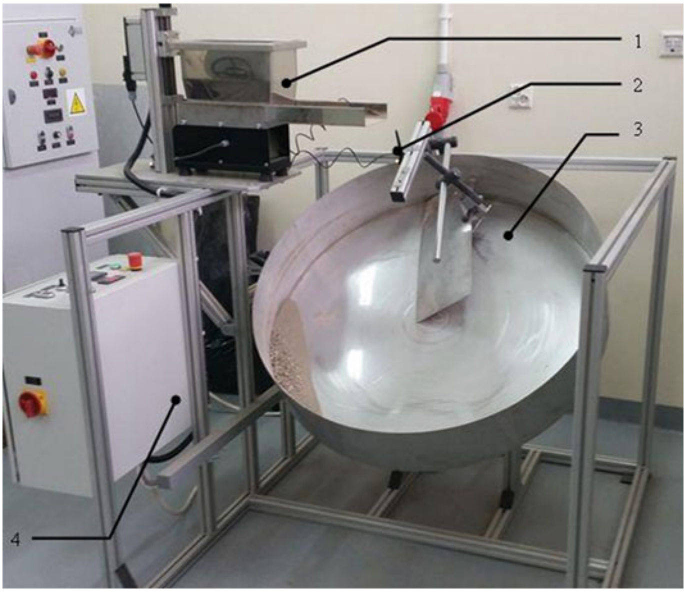


Fig. 2 GitTech Disc Granulator; 1 vibrating material dispenser, 2 spray nozzles granulate material, 3 the plate on which the granulation process takes place, 4 control panel

of the plate is possible in the range of 20–60°). The rotational movement of the plate and its tilt cause the material to be circumferentially raised on the surface of the plate and reaching the maximum point (depending on the angle of inclination and turntable speed and material parameters) rolls to the lower edge of the plate. The liquid that is sprayed onto the surface of the rolling material causes the granulation process to be initiated. The granulation runs continuously and the granules that reach the diameters are continuously received from the granulator.

During the agglomeration of the sample, energy expenditure was measured on the weight of the obtained granulate. The LUMEL ND1 network parameter analyzer was used to measure the energy expenditure. n order to record actual energy expenditure, the measurement started when the operating parameters of the machine (engine speed) stabilized. First, in order to determine the energy consumption to overcome the resistances of its own granulators, the measurement was carried out at no load. The next step is to measure the gross energy intensity of the process, on the basis of which the net energy consumption of the process was subtracted after subtracting the energy of the machine's own resistance. The obtained granulates were subjected to qualitative assessment. The study is illustrated in the diagram shown in Fig. 3.

The research was conducted on selected fertilizer mixtures. Test blends were selected to cover the entire quantitative variability of their constituents, i.e. maximum and minimum post-fermented content, no and 5% urea, maximum sulfur and phosphate content. Taking into account these guidelines for the study was adopted mixtures with the codes: A1, A7, A9 i B1, B7, B9 (Table 1).

Material for making granules as a mixture of the raw materials tested was prepared in a special ribbon mixer to achieve homogeneous mass. The mass fraction of compound fertilizers was calculated as the dry matter content of the components.

The humidity of the test samples was 15%, and the agglomerations of the mixture with the humidity of 18% were also compared. However, the obtained quality parameters of the obtained granulates (mechanical durability DU = 66.3% and dry density BD = 548.7 kg/m^3) were confirmed. Preliminary studies show that this level of moisture does not allow for obtaining high quality granules.

The resulting granules were subjected to a qualitative assessment including: mechanical durability DU, bulk density BD, Brazilian test and specific density ρ.

The bulk density of the obtained granulates was determined according to the procedure described in PN-EN 15103: 2010. A container of known mass, fill with granules from a height of 200–300 mm. The filled container is dropped about 150 mm from the height of the wooden base, the material must be refilled and the excess remaining above the edge of the tank is scraped off. Then weigh the container with the material and bulk density (BDar) in Mar. A normalized container with volume V = 0.005 m^3 need to be used for the tests.

Mechanical durability of DU granules is a measure of its resistance to shocks and/or abrasions arising from transport, handling, and other distribution and storage processes. The measurement was made at the benchmark for determining the

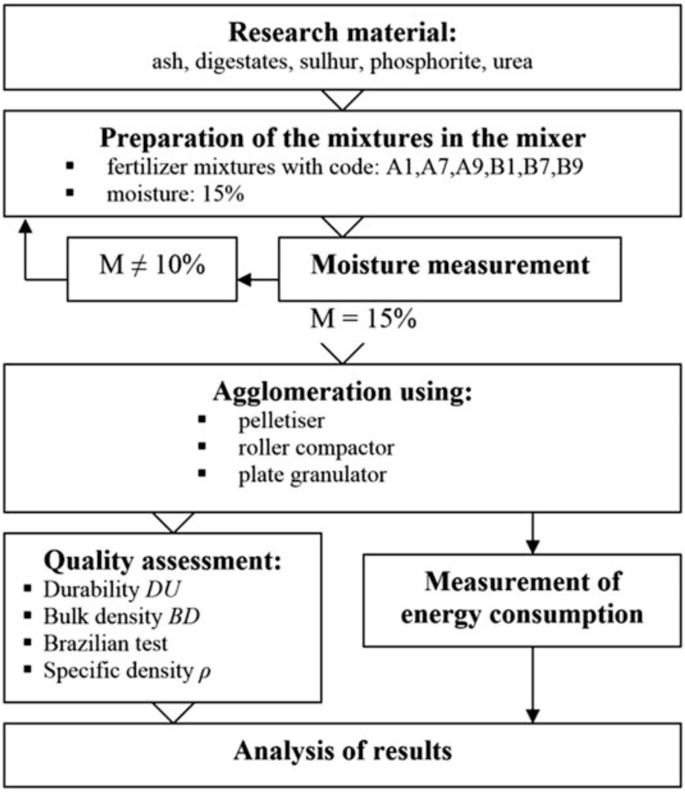


Fig. 3 Study design

Table 1 Percentage of mass of prototype components of fertilizer mixes based on biomass ash (PO) and post-fermented (PF) fertilizers plus additives

Components	Shares of mix components (%)					
	A1	A7	A9	B1	B7	B9
PO	75	25	25	70	25	25
PF	25	75	55	25	70	50
MC	0	0	0	5	5	5
S	0	0	5	0	0	5
F	0	0	15	0	0	15
Sum	100	100	100	100	100	100

Legend: *PO* ash, *PF* post-fermentation, *MC* urea, *S* elemental sulfur, *F* phosphorite

durability of granulates according to PN-EN 15210: 2010. Accurately weighed, to 0.1 g, a sample of 500 ± 10 g granules was placed in the tester chamber.

At the end of the test, the granulate was screened through an orifice sieve with a hole diameter of about 2/3 of the diameter of the granules tested. Sample sieving was done to remove fine fractions that broke away from the granulate during the test. The material remaining on the sieve was weighed on a laboratory scale to the nearest 0.1 g and the DU durability (mechanical durability) was shown as the mean.

The specific density of the analyzed granulates was determined using the Geosubject 1360 Geosynthetics Pencil from Micromeritics. The device measures the volume of the sample placed in the measuring chamber using a powder of particle size below 250 μm. The use of powder instead of liquid eliminates the wetting of the test material (soaking), which allows for testing of materials with high absorbency.

The research on the process of producing granulated fertilizer on a roller compactor dedicated to the thickening of dusty mineral materials has shown that the sample with A1 code, the sample containing the highest proportion of mineral fraction (75% ash) is compacted, but the durability of the obtained agglomerate is very low. The research was conducted at three moisture levels of material i.e. 10, 15 and 18%. The material was compacted between a pair of co-operating smooth rolls. Figure 4 shows an example of an agglomerate obtained as an irregular sheet of compressed 2–4 mm thick material. An attempt was also made to agglomerate between a pair of walks of which one was a smooth roller and the other had cavities to mold the protuberances on the surface of the agglomerate (Fig. 4).

The result of the stability test of the obtained granules is shown in Table 2. Unfortunately, none of the produced granulates has a satisfactory level of durability for which a DU rating of at least 90% is considered. The best result (DU = 34%) obtained a moisture content of 15%, which may be indicative of the moisture level at which further tests should be carried out, but additional proglomerating factors such as binder additions or agglomerated temperature increase should be considered. Despite the completion of this phase of research, such attempts are planned and will be undertaken.

Fig. 4 Granulate A1 obtained from cylindrical compactor; from the left with smooth rollers, then using a smooth roll cooperating with a roll with recesses

Table 2 Result of the stability test of sample granules with code A1 obtained on a roller compact

Equipment	Repeating	Humidity M (%)	Durability DU (%)	Average DU (%)
Compactor—smooth rolls	1	10	20.45	20.24
	2	10	20.03	
	1	15	33.89	34.02
	2	15	34.16	
	1	18	24.96	24.41
	2	18	23.86	
Compactor—smooth roller and recesses	1	15	27.84	27.40
	2	15	26.95	

Fig. 5 Granule sample A1 code obtained on a disk granulator

A similar situation occurred with the pellet granulator for granulation of mineral materials. And in this case, it is possible to produce granules with an elliptical or sphere-like shape (Fig. 5), but their stability, as in the previous case, oscillates at an unacceptable level. They can not be considered as a permanent granules (DU = 23%). In this case, further research will also be carried out to introduce additional binders into the granulation process.

In both cases the low stability of the obtained granules can be attributed to the content of the biomass fraction in the form of a post-fermentation. In the case of a compactor, the post-fermenting resilience causes the thickener to expand after passing through the thickening rolls, as a result of which the microcapsules form in the pane of granules, the resulting structure is weakened and the binding between the ash particles is too weak to give the granulate sufficient shelf life. A similar

Table 3 Quality of granulation pellet A1

Apparatus type	Wilgotność M (%)	Trwałość średnia DU (%)
Compactor—smooth cylinders	10	20.24
Compactor—smooth cylinders	15	34.02
Compactor—smooth cylinders	18	24.41
Compactor—smooth and dimpleted cylinders	15	27.40
Disk granulator	15	23.09

Maximum ash content of all samples (75%)

Table 4 Energy consumption A1

Equipment	Help without load (W)	E gross (Wh/kg)	E net (Wh/kg)	Humidity (%)	Comments
Plate granulator	157,183	39,916	1785	15	Material moisturized in the granulation process—final moisture content 24%
Compactor	464,283	19,858	5349	10	
Compactor	464,283	21,094	3325	15	
Compactor	464,283	18,536	2980	18	
Compactor	464,283	15,248	2933	15	Smooth roller + cylinder with recesses

Maximum share of ash (75%)

situation may be the case with granules obtained on a disk granulator. Granules in most cases arise as a result of pouring the particles of ash into the ash resulting in granules having a very soft and resilient center surrounded by a layer of ash mixed with the particles of the post-fermentation. This structure is too weak to resist the destructive forces acting on the colliding granules during the stability test. The increase in binding force between ash and post-ferment molecules could have improved the stability of the resulting granules (Tables 3 and 4).

In the case of KovoNovak pelletizer, the greatest differences occurred in the case of destructive stresses σc. The lowest values occurred for sample A1 and the highest (more than double) for A9 (Fig. 6; Tables 5 and 6).

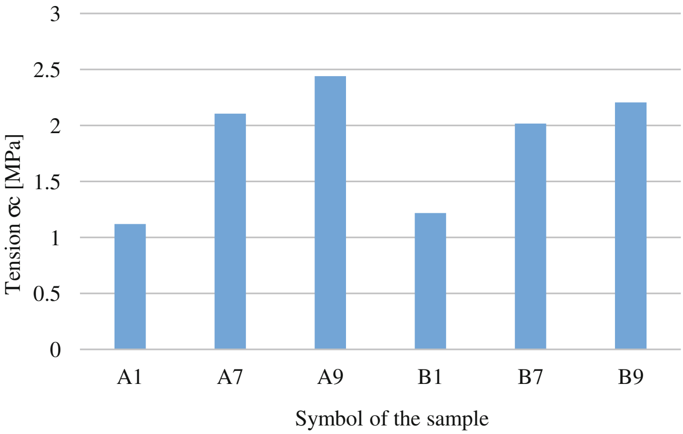


Fig. 6 Shear stress for pellets obtained on pelletiser KovoNovak

Table 5 Quality pellets obtained on pelletizers KovoNovak

Sample designation	Humidity M (%)	Durability DU_{ar} (%)	Bulk density BD_{ar} (kg m^{-3})	Bulk density BD_d (kg m^{-3})	Specific density ρ_{ar} (g cm^{-3})
A1	18	66.27	669.13	548.68	1195
A1	15	92.09	890.36	756.81	1636
A7	15	96.76	708.36	602.11	1279
A9	15	97.17	725.13	616.33	1311
B1	15	91.30	882.73	750.32	1607
B7	15	93.65	716.12	608.63	1299
B9	15	96.48	720.13	612.11	1317

Table 6 Pellet energy consumption on the pelletizer KovoNovak

	Power without load (W)	Gross energy consumption (Wh/kg)	Net energy consumption (Wh/kg)
A1	2626.9	51.39	36.60
A7	2626.9	54.48	38.43
A9	2626.9	112.22	63.88
B1	2626.9	50.88	36.23
B7	2626.9	52.92	38.77
B9	2626.9	108.85	61.96

Humidity 15%

3 Summary

Conducted studies of agglomeration of selected fly ash based mixtures and digestate showed that not all classical granulation methods are suitable for industrial scale. The three agglomerative techniques which were analyzed showed significant differences both in the quality of the obtained granules as well as in the parameters of expulsion. Plate granulation tests are characterized by very low energy consumption, but the quality of the granules obtained, inter alia by mechanical durability, was very low and did not exceed 35%. Rotating turntable-based pelletizing technology seems to be a very prospective solution, but it will be necessary to use suitable binders. In the case of compact cylinders, the quality of the obtained granules (compacted sheets) in the durability test was very similar to that of the disc method. Only the energy consumption of this process was almost twice as high (3.325 Wh kg) as compared to the pre-exposed. The biggest hope can be put into the pelleting method. The quality of the obtained granules was very high both mechanical strength (over-90%) as well as specific density (1–1.6 g cm^{-3}). The energy intensity of granulation in this method was greatest and ranged from 36 to 61Wh kg^{-1}. It is planned to conduct further experiments allowing for minimizing energy expenditure, decreasing, among other things, the degree of compression of the molding mater. The optimization will allow for optimal parameters, taking into account the minimization of energy expenditure and the maintenance of high quality.

Research was funded by the National Centre for Research and Development and the National Fund for Environment Protection as a part of GEKON program—project no. GEKON1/05/214543/38/2015 “Proecology production of organic and mineral fertilizers based on waste: by-products of combustion and biogasification of biomass”.

References

1. Lemański, J.: Ekologiczne aspekty zagospodarowania popiołów z elektrociepłowni, Poznań, 17–18 październik 1995
2. Meller, E., Bilenda, E.: Wpływ popiołów ze spalania biomasy na właściwości fizykochemiczne gleb lekkich. POLITYKA ENERGETYCZNA, Tom 15 Zeszyt 3 (2012). ISSN 1429-6675
3. Schiemenz, K., Eichler-Löbermann, B.: Biomass ashes and their phosphorus fertilizing effect on different crops. Nutr. Cycl. Agroecosyst. **87**(3), 471–48 (2010)
4. Ots, K., Tilk, M., Aguraijuja, K.: The effect of oil shale ash and mixtures of wood ash and oil shale ash on the above- and belowground biomass formation of Silver birch and Scots pine seedlings on a cutaway peatland. Ecol. Eng. Sept 2017. doi:https://doi.org/10.1016/j.ecoleng.2017.09.002
5. Zapałowska, A., Puchalski, C., Hury, G., Makarewicz, A.: Influence of fertilization with the use of biomass ash and sewage sludge on the chemical composition of Jerusalem artichoke used for energy-related purposes. J. Ecol. Eng. **18**(5), 235–245 (2017). https://doi.org/10.12911/22998993/76214

6. Baryga, A., Połeć, B., Małczak, E.: Technological value of raw materials from sugar beet growing area fertilized with digestate from sugar beet pulp biogas plant. Plant Soil Environ. **63**, 207–212 (2017)
7. Chen, R., Blagodatskaya, E., Senbayram, M., Blagodatsky, S., Myachina, O., Dittert, K., Kuzyakov, Y.: Decomposition of biogas residues in soil and their effects on microbial growth kinetics and enzyme activities. Biomass Bioenerg. **45**, 221–229 (2012). https://doi.org/10.1016/j.biombioe.2012.06.014
8. Lošák, T., Zatloukalová, A., Szostková, M., Hlušek, J., Fryč Vítěz, T.: Comparison of the effectiveness of digestate and mineral fertilisers on yields and quality of kohlrabi (*Brassica oleracea*, L.). Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, **59**, 117–122 (2011). doi:https://doi.org/10.11118/actaun201159030117

Erratum to: The Financial Efficiency of Biogas Stations in Poland

Serhiy Zabolotnyy and Mariia Melnyk

Erratum to:
Chapter "The Financial Efficiency of Biogas Stations in Poland" in: K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy, https://doi.org/10.1007/978-3-319-72371-6_9

The original version of the book was inadvertently published with incorrect author name "Melnyk Mariia", which has been now corrected to read as "Mariia Melnyk" in chapter "The Financial Efficiency of Biogas Stations in Poland". The erratum chapter and the book have been updated with the change.

The updated online version of this chapter can be found at
https://doi.org/10.1007/978-3-319-72371-6_9

K. Mudryk and S. Werle (eds.), *Renewable Energy Sources: Engineering, Technology, Innovation*, Springer Proceedings in Energy,
https://doi.org/10.1007/978-3-319-72371-6_81