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ORIGINAL PAPER

Energy Generation Potential in Greece From Agricultural Residues and Livestock Manure by Anaerobic Digestion Technology

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Abstract Greece is an agricultural country producing a significant amount of crop residues as well as livestock manure. The use of agricultural waste as a major component of renewable energy is suitable for improving energy security. Thus, studying the energy generation potential of these wastes is important. The theoretical annual potential of agro-industrial residues (such as wheat products, industrial plants, potatoes, vegetables, olives, fruits, nuts, dairy products etc.) was estimated equal to 19,005,490 t/y, taking into consideration their annual production and their respective residue production in Greece. Accordingly, the theoretical annual potential of livestock manure, including the residues from animal husbandry in Greece (cattle, chicken, goats, pigs, sheep etc.) was estimated equal to 26,952,500 t/y. In this study, the possibility of energy production through anaerobic digestion was investigated. Taking into account the biodegradability of the residues, it was estimated that the total 45,957,990 t/y residues may produce 330,000 t/y fertilizer and 1.97×10^9 m^3/y methane. Taking advantage of the energy content of biogas by co-generation of energy and heat, 4.9–7.9 TWh/y of electrical energy and 6.9–12.8 TWh/y of thermal energy could be produced. Given the annual electrical energy consumption in Greece, about 39 % of this energy need could be replaced by electrical energy produced from agricultural residues and livestock manure. Conclusively, crop residues and livestock manure may stand as an energy source with significant contribution to the Greek energy balance.

Keywords Anaerobic digestion · Biogas · Crop residues · Electricity · Energy · Livestock manure

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Introduction

Greece is located in the east side of Mediterranean Sea, covers an area of 131,940 m^2, with a population of around 10.6 million people and is enjoying a moderate growth through the last decades [1, 2]. Social, economic and industrial development results in a continuously raising energy-consumption demand. The Greek energy sector is still largely dependent on fossil fuels, most of which are imported. Owing to the limited indigenous conventional energy sources, the country is obliged to import almost 70 % of its annual energy demand, in forms of fossil fuels like oil, coal and natural gas [1]. Domestic energy sources include lignite which accounts for around 50 % of electricity generation as well as renewable energy sources (RES) such as hydro-power, wind, solar energy and biomass. RES currently account for 13.8 % of gross final energy consumption and a national target of a 20 % share by 2020 has been set. Imported energy sources are mainly petroleum products that account for 44 % of total energy consumption and natural gas with a share of around 13 %. The main electricity supplier in Greece is Public Power Corporation (PPC). According to PPC, gross national electricity consumption in 2012 was 55 TWh, including transmission and distribution losses of 2.9 % [3].

Today the Greek energy market is undergoing fundamental reforms. New advanced energy technologies and perpetual environmental issues, requirements arising from

European and international cooperation as well as various intergovernmental agreements are factors shaping and harmonizing the institutional and legislative framework of the Greek energy market with current tendencies and perceptions. At the centre of this process lies: the liberalization of the electricity and natural gas markets, increased competitiveness, the extension and enhancement of the domestic and cross-border electricity, natural gas and oil networks, the further separation of production and supply from transmission networks, consumer choice, increased share of energy from RES, reduced share of fossil-fuel generated electricity, improved energy efficiency, energy saving and the protection of the environment [4]. It is well established that an effective measure to change the national energy map is the substitution of imported energy sources by national resources. It is clear that if it is to align with the EC Directive 2001/77/EC and reach a 20 % contribution of renewable fuels to electricity production, a large amount of energy must be supplied by exploitation of non-conventional energy sources [1].

Agro-industrial residues are the most abundant and renewable resources on earth. Accumulation of this biomass in large quantities every year results not only in the deterioration of the environment, but also in the loss of potentially valuable material which can be processed to yield a number of valuable added products, such as food, fuel, feed and a variety of chemicals. The agro-industrial residues have alternative uses or markets. As a common practice, agro-industrial residues including crop residues, forest litter, grass and animal garbage are directly burnt as fuel in the developing world. Crop residues are more widely burnt than animal waste and forest litter [5].

Greece is an agricultural country producing a significant amount of crop residues as well as livestock manure [6]. The use of agricultural waste as a major component of renewable energy is suitable for improving energy security. Thus, studying the energy generation potential of these wastes is important.

Anaerobic digestion is a biological process that produces biogas from biodegradable wastes by bacteria under no oxygen conditions. In the past two decades, anaerobic digestion has been applied as an effective technology for solving the energy shortage and environmental pollution problems of industries [7]. In general, anaerobic digestion may meet two principal goals: the production of energy from biomass and the stabilization of organic waste, giving two final products: biogas (energy fuel) and stabilized sludge—fertilizer respectively.

In this paper, the theoretical energy generation potential in Greece through anaerobic digestion from agricultural residues and livestock manure is estimated, taking into consideration Greek statistical data and literature records concerning production to residues ratios, residue biodegradability indices and balances' principles in anaerobic digestion.

Methodology

The methodology used for this study involved a bibliographic study according to which a wide variety of documents and records relating to residual biomasses in Greece were collected and studied in order to obtain all the background information as well as useful data to enable a further formulation of a theoretical biomass management model on agricultural and animal waste management in Greece. Residual biomass may derive from the agricultural sector, both in the form of crop residues and of animal waste (Table 1 [8]). These two categories were considered in this study.

Agro-Industrial Residues

In the European Union, agriculture is the most important land use in geographic terms occupying 40 % (130 million ha) of the total land area (323 million ha). Also Europe is one of the world's largest and most productive suppliers of food and fibre with the European Union accounting alone for 10 % of the global cereal production and 16 % of global meat production [8].

Large quantities of residues are generated every year by agriculture. Cereals, grass, sugar beet, potatoes and oilseed rape are arable crops that generate considerable amounts of residues. In aggregate, figures of the total amount of residues look very attractive if not staggering. A distinction, however, has to be made between residues remaining in the field and those generated after harvesting and during processing. Field residues occur in smaller quantities, are spread over larger areas and remain in the field; examples are stubble, straw, stalks and leaves depending on the crop and the farming practice. Crop residues play an important role on the field both protecting the soil from erosion and returning nutrients to the soil [9]. For this reason, residues removal should be evaluated in each specific case, according to local soil and climatic characteristics and to agricultural practices. In all cases, to avoid soil impoverishment, residues removal should always be accompanied by the application of the same amount of humified organic substances [9]. Biomass and harvested residues are often used for many site-specific purposes: food, fodder, feedstock, fibre, fuel and further use such as compost production. These purposes are often not mutually exclusive; for example, straw can be used as animal bedding and thereafter as fertiliser. After processing, residues can be concentrated which make their further use for compost production and soil amelioration easier [10].

Table 1 Classification of the biomass resources under study [8]

Sector	Resource	Description	Moisture content (% wet basis)	Ash content (% dry basis)
Agriculture	Agricultural residues	Dry ligno-cellulosic (e.g. straw, prunings)	30–50	2.2–17
	Livestock waste	Wet cellulosic	74–92.1	27.1–35.4
		Dry ligno-cellulosic (e.g. poultry litter)	75	17.5–28
	Energy crops	Dry ligno-cellulosic	12.5–50	0.3–8.4
		Oil seeds for methylesters	n.a.	<0.02
		Sugar/starch crops for ethanol	n.a.	<0.02

Agricultural potential for organic matter sources depends on residue production such as crop residues from annual and perennial crops and manure application. Agriculture in Europe has a high technical potential for biomass production. In particular cereal straw, which is most often returned to the soil in arable cropping systems, is of renewed interest as a potential source of bio-energy. However, the sustainability of this practice implies systematic removal of above ground biomass of cereal crops [10].

The main advantages that biomass energy utilization offers are avoiding energy dependence on conventional fossil fuel imports, strengthening employment in decentralized regions (islands and/or rural areas) and contribution to energy production targets [1]. Moreover, biomass energy utilization may be considered as "carbon neutral", since by comparing the two scenarios (crop energy utilization by anaerobic digestion and uncontrolled natural crop decomposition in soil) nearly equal carbon emissions are produced [11]. Following the above advantages of biomass utilization, there are also some disadvantages that bring difficulties to biomass energy exploitation: the big raw material volumes, difficulties in collection and transporting from remote rural areas and islands, high moisture contents by unit of produced energy (and as a result, reduced biomass heating value), the seasonal character of its production and the variety in quality even for the same biomass sample [1].

Agricultural wastes represent a primary energy source in rural areas of Greece as well and contribute to energy production, mainly with wood combustion. The main production in agricultural wastes in Greece comes from agricultural and farming activities in the fields.

The technical potential of crop residues can be estimated on the basis of cultivated area or agricultural production for each crop (usually available from national statistical offices or from Eurostat) and average product to residue ratios or residue yields derived from literature or from referenced local trials [9]. Whenever possible, parameters describe as much as possible the local conditions and agricultural practices.

Agricultural production, cultivated areas and residues that characterize Greek agriculture activity, are shown in the table below (Table 2), in an annual base, along with the indices used to estimate the residues. Differences in yield and therefore in residues have been observed depending on the crop species, the climate and the cultural practices. The areas where agricultural wastes are mainly produced in vast amounts are Thessaly, East Macedonia, Peloponnesus and Crete island [1, 12]. The agricultural production and cultivated areas depicted in Table 2 are in accordance with the latest data of FAO (2012–2013). Two kinds of indices were used: an areal residue yield (kg/1000 m^2) and a residue to product ratio. In general, most of the studied crops perform high yielding potential under Greek climatic conditions. Thus, an effort was performed in order to use literature data that had derived from either Greek or Mediterranean countries. In reality, the indices mentioned above obviously fluctuate since they are influenced in each case by several parameters such as climate conditions, cultivation practices and crop management. The values presented in Table 2 may be considered as mean values.

Animal Wastes in Greece

In Greece, animals produce a substantial amount of wastes, as animal breeding activity is highly developed. The Greek livestock system constitutes of sheep, goats, cows and calves, swine and pullets breeding. Poultry farming, sheep and goats breeding represent the highest percentage of livestock industry, amounted for over 95 % of the total animals in the year 2012 (National Statistical Service) [12]. However, sheep and goats breeding are extensive and thus the produced manure is spread all over the grazing land [17, 18]. Intensive livestock consists of cattle, brood sows and poultry farming. All these animals produce a substantial amount of wastes (Fig. 1). The number of animals that were breaded in year 2013 is depicted in Table 3 according to the latest data of FAO. After a rough estimation, it is underlined that due to intensive animal farming 28,571 t of pig, cattle and poultry manures are produced daily, resulting in that way to an annual load of

Table 2 Basic agricultural wastes in Greece in annual basis

Cultivation species	Production (tn)	Residues (tn)	Type of residue	Cultivated area ($\times 10^6$ m^2)	Index		Reference
					Residue yield (kg/1000 m^2)	Residue/product	
Wheat for crop	**4,532,100**	**4,025,570**					
Wheat	1,585,600	1,675,080	Straw, husk, bran	5640	297		[13]
Barley	353,400	262,880	Straw, bran	1240	212		[13]
Oat	148,000	236,800	Straw, bran	782		1.6	[12, 14]
Rye	33,100	102,610	Straw, bran	167		3.1	[14]
Maize	2,185,000	1,362,300	Cobs, stover	1900	717		[13]
Rice	227,000	385,900	Straw, husk	292		1.7	[12]
Industrial plants	**1,201,800**	**2,329,480**					
Tobacco	24,000	24,000	Stems	157		1	[12, 14]
Cotton	475,000	997,500	Stalk, lint, hull	0		2.1	[12]
	367,000	770,700		0		2.1	
Sugarbeet	335,800	537,280	Leaves, bagasse, collar	58		1.6	[15]
Potatoes	**829,400**	**331,760**	Stems and leaves	327		0.4	[14]
Vegetables	**1,384,300**	**553,720**	Stems, foliage and leaves			0.4	[14, 15]
Tomatoes	979,600						
Eggplants	73,000						
Onions, shallots, green	23,000						
Cabbages and other brassicas	186,400						
Cauliflowers and broccoli	88,900						
Leeks, other alliaceous vegetables	33,400						
Grapes	**978,200**	493,024	Sarments	992	497		[13]
Citrus fruits	**956,100**	**1,912,200**	Pruning				
Oranges	791,600	1,617,963 ”		353		2–2.9	[12, 15]
Lemons and limes	58,600	130,092		72		2.22	[12, 15]
Tangerines, mandarins, clementines, satsumas	105,900	164,145		68		1.55	[12, 15]
Fruits	**1,239,300**	**465,696**	Pruning, peels, seed	**792**	588		[13]
Apples	251,000	79,380		135			
Pears	77,600	28,812		49			
Peaches and nectarines	760,200	259,308		441			
Apricots	90,200	37,044		63			
Cherries	60,300	61,152		104			
Nuts	**53,200**	**101,080**	Pruning, shell, stalk, leaves				
Almonds	29,000	55,100		135		1.9	[14]
Walnuts	24,200	45,980		109		1.5–1.9	[12, 14]
Olives	**2,000,000**	**5,200,000**	Pruning, olive stone	9,300		0.5–2.6	[12, 14]
Edible							
Oil producing							
Cheese	**224,560**	**3,592,960**				16 (m^3/tn)	[16]

The numbers in bold indicate the sum amounts

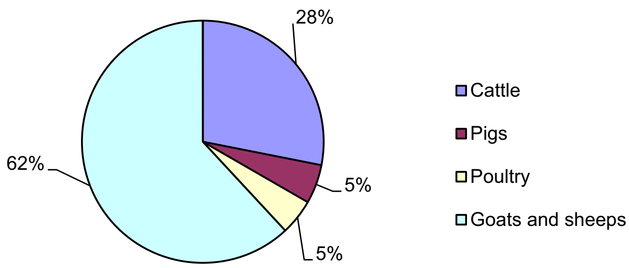

Fig. 1 Animal waste production estimation in Greece (2013)

10,428.500 t of manure stock. Those animal wastes spreading in Greek rural areas come mainly from medium and large-scale animal farms and are placed all over the country. Also, the fact that there are, traditionally, many small-scale animal farms in Greek rural areas must not be ignored and most of them are located in Central Macedonia (Thessaloniki, Imathia), Epirus (Ioannina), Thessaly and Attica representing a 55.6 % of the total national amount in animal wastes production [1]. The average volume of faeces and urine largely differ from one type of animal to another and mainly depend on their age and lifeweight [8, 19]. However in order to assist in the planning, design and operation of manure collection, storage, pre-treatment and utilization systems for livestock enterprises mean values have been developed by various researchers [8]. In this analysis, the coefficients presented in Table 3 were adopted. The values represent fresh faeces and urine. As was the case for agricultural residues, these coefficients are mean values.

Anaerobic Digestion as an Energy Conversion Process

The choice of the energy conversion process generally depends on the chemical and physical properties of biomass, in particular the carbon to nitrogen ratio (C:N) and the moisture content. Broadly speaking, biomass with a low moisture content (below 50–55 %) and a high C:N ratio (over 30) are suitable for thermo-chemical conversions such as combustion and gasification. On the other hand, biomass with a high moisture content (over 50–55 %) and a low C:N ratio (below 30) are suitable for bio-chemical conversions such as anaerobic digestion and fermentation [9]. Thus, bio-chemical conversions seem as an ideal choice for the treatment of the agro-industrial residues examined in this study according to Table 1

An anaerobic digester energy system promotes biogas production (which contains methane), captures and converts it to electricity and heat for on-farm use or sale to the local utility. Biogas can also be used for combined heat and power (CHP) generation. In recent years, this bioenergy conversion technology has been developing as one of the most attractive renewable energy resources especially in Northern Europe, in countries such as Germany, UK and Denmark [9, 21]. Biogas produced in anaerobic digestion primarily consists of methane which is about 50–60 % for a typical plug-flow anaerobic digester. The rest of the biogas includes carbon dioxide (40–50 %) and other trace gases such as hydrogen sulfide and nitrogen. Table 4 shows that biogas yield and biogas methane content vary depending on the kind of raw material used as input, given the same conversion technology. This variation is due to the different chemical and physical composition of the raw material; in particular to the difference of organic matter, carbohydrate, fat and protein content. High fat content, for example, provides biogas with high methane content. In addition, the composition of a specific raw material can vary markedly among sites, years etc. For instance, the time of harvesting will affect the content of various carbohydrates in ley crops, and thus affect the degradability of the crop. As to digestion technology, the gas yield is affected by digestion temperature, retention time, load, digestion technology (co-digestion; batch or continuous; one or two-phase digestion), pre-treatment of the raw materials [9, 22].

In order for the digestion to proceed, a number of conditions must be fulfilled. If there is too little nitrogen relative to the amount of carbon-containing material to be transformed, then bacterial growth will be insufficient and biogas production low. With too much nitrogen (a ratio of carbon to nitrogen atoms below around 15), “ammonia poisoning” of the bacterial cultures may occur. When the carbon–nitrogen ratio exceeds about 30, the gas production starts diminishing. Table 4 also gives carbon–nitrogen values for a number of biomass feedstocks. It is seen that mixing feedstocks can often be advantageous. For instance, straw and sawdust would have to be mixed with some low C:N material, such as livestock urine or clover/lucerne (typical secondary crops that may be grown in temperate climates after the main harvest) [24].

Table 3 Number of animals and animal waste production in Greek farms in annual basis [20]

Animal species	Number of animals	Residue/animal (tn/head)	Residues (tn)
Cattle	679,000	11.16	7,577,640
Pigs	1,077,000	1.34	1,443,180
Poultry	35,192,000	0.04	1,407,680
Goats and sheeps	13,770,000	1.2	16,524,000

Table 4 Characteristics and operational parameters of the most important agricultural feedstocks by anaerobic digestion [23]

Feedstock	Total solids TS (%)	Volatile solids (% if TS)	C:N ratio	Biogas yield (m^3/kg VS)	Retention time (days)	CH_4 content (%)	Unwanted substances	Inhibiting substances	Frequent problems
Pig slurry	3–8	70–80	3–10	0.25–0.50	20–40	70–80	Wood shavings, bristles, H_2O, sand, cords, straw	Antibiotics, disinfectants	Scum layers, sediments
Cow slurry	5–12	75–85	6–20	0.20–0.30	20–30	55–75	Bristles, soil, H_2O, NH_4^+, straw, wood	Antibiotics, disinfectants	Scum layers, poor biogas yield
Chicken slurry	10–30	70–80	3–10	0.35–0.60	>30	60–80	NH_4^+, grit, sand, feathers	Antibiotics, disinfectants	NH4 + - inhibition, scum layers
Whey	1–5	80-95	n.a.	0.80–0.95	3–10	60–80	Transpiration impurities		pH-reduction
Fermented slops	1–5	80–95	4–10	0.35–0.55	3–10	55–75	Undegradable fruit remains		High acid concentration, VFA-inhibition
Leaves	80	90	30–80	0.10–0.30	8–20	n.a.	Soil	Pesticides	
Wood shavings	80	95	511	n.a.	n.a.	n.a.	Unwanted material		Mechanical problems
Straw	70	90	90	0.35–0.45	10–50	n.a.	Sand, grit		Scum layers, poor digestion
Wood wastes	60–70	99.6	723	n.a.	n.a.	n.a.	Unwanted material		Poor anaerobic digestion
Garden wastes	60–70	90	100–150	0.20–0.50	8–30	n.a.	Soil, cellulosic components	Pesticides	Poor degradation of cellulosic components
Grass	20–25	90	12–25	0.55	10	n.a.	Grit	Pesticides	pH-reduction
Grass silage	15–25	90	10–25	0.56	10	n.a.	Grit		pH-reduction
Fruit wastes	15–20	75	35	0.25–0.50	8–20	n.a.	Undegradable fruit remains, grit	Pesticides	pH-reduction
Food remains	10	80	n.a.	0.50–0.60	10–20	70–80	Bones, plastic material	Disinfectants	Sediments, mechanical problems

Biogas production by anaerobic digestion of biomass may help in partially replacing fossil-fuel-derived energy and thereby in reducing environmental impact by providing a clean and diffused fuel from renewable feedstock. In some EU countries, such as Italy, Austria and Germany, substrate supply is often achieved by dedicated energy crops, such as cereals and maize [25, 26]. However, an energy crop requires a high expenditure in terms of arable land, energy (irrigation, machines, transport) and environmental resources (groundwater).Residual biomasses, such as agro-industrial by-products and residues, animal manures and source-separated organic wastes represent the spatially diffused sources of the substrate for its anaerobic biotransformation to biogas. Biogas is rich in methane (CH_4) which can be used in internal combustion engines either, for electricity generation, or burn directly for cooking, and space and water heating [25].

Generally in Greece, the anaerobic digestion technology is used mainly as a waste treatment method but not accompanied with biogas and energy production (at least not in a wide extent at the moment). The wastes disposal (e.g. manure) created so far only a few problems compared to what happened to the other EU Member States (e.g. West Europe). Thus, the implementation of biogas schemes for reduction of water and soil pollution was not so imperative in Greece until now. With available waste streams and infrastructure in place the conditions for biogas plants in Greece is an option. Options for sitting of facilities are numerous as they can be centralised or distributed as required [18]. In 2007, 15 biogas plants were in operation in Greece. In total the electricity produced in a year was calculated to amount for 174247.64 MWh_e while the heating energy was 717.40 TJ. The majority of biogas plants (8 of 15) used the sewage sludge of Municipal

Wastewater Treatment plants, 4 were agro-industries and in the rest 3 the biogas was collected from pipes established in landfills. The biggest part of the generated energy was produced in the region of the Greek capital due to the operation of MWWT of Psyttalia and Landfill of Ano Liosia, which treat the liquid and solid municipal wastes of Athens, Greece, respectively [12, 18].

Taking into consideration the physico-chemical characteristics of crop residues and livestock manure and the feasibility of anaerobic digestion application, the latter was evaluated as a potential energy conversion process for the case study of Greece.

Results and Discussion

Greek Agro-Industrial Residues Estimation

From the data presented above in Section "Agro-Industrial Residues", it was estimated that the total agro-industrial residues amount up to 19,005,490 t/y. Their classification is presented more colourfully in Fig. 2.

The availability of these types of residues for energy purposes is restricted by several technical, environmental or economic factors that are difficult to be quantified. According to Dalianis and Panoutsou [8, 27] from the total agricultural residues produced in EU, 48 % are being exploited in non-energy (e.g. animal feeding) or traditional energy applications and a further 40–45 % of the unexploited quantity cannot be exploited for various technical and/or economical reasons [8]. Moreover, agricultural residues have to be collected and transported to the conversion plant. Since the bulk density of agricultural residues is generally low, transport costs can be relevant and need to be carefully assessed [9].

Unfortunately, there is no organized practice in agricultural waste management in Greece until today, even if the country's potential towards it is very promising. The most common management practice in Greece is still burning in field and as a result uncontrolled fires spread and atmosphere pollution is seasonally appearing. There are also some agricultural industries that, usually after private initiative and with the help of public taxation intensives, burn their agricultural residues to produce mainly heat, and then recycle it for utilization in their production activities. According to the National Center of Renewable Energy Sources, estimation of the total amount of agricultural residues' annual exploitation in Greece reaches the amount of 5.5 million tons in field crops [1]. Industries, that exploit energetic potential of their residues are mainly cotton ginning factories that use the produced heat in order to dry cotton and to heat their space, olive kernel oil factories that burn the olive cake to heat their closed spaces, drying processes and provide heat for greenhouse cultivations, wood industries that burn the sawdust for the same reasons, fruit kernel factories that provide themselves part of their necessary production heat supply, rice mills, etc. [1].

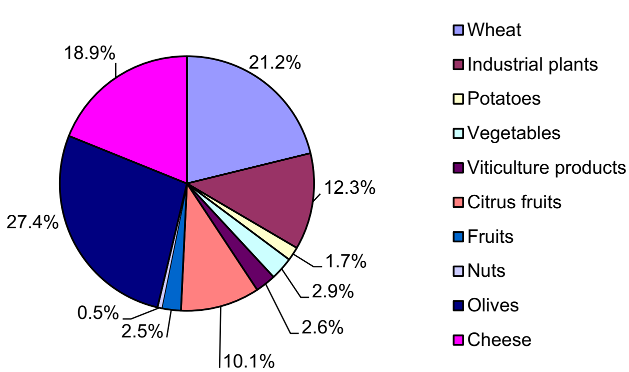

Fig. 2 Basic agricultural wastes in Greece (t/yr)

Estimation of Animal Wastes in Greece

From the data presented in Table 3, it was estimated that the total livestock manure amounts up to 26,952,500 t/y.

Animal manures are usually stocked in rural areas, especially outside medium- and large-scale animal farms, and create significant environmental problems like underground water pollution, gas and odour emissions, vector attraction and general visual pollution. What farm owners used to do as exploitation of animal manures, until recently, was to sell them as a fertilizer or simply spread onto agricultural and/or arable land, while in some rural areas, they still combust them for heat production [1].

According to the EU Regulation (1/5/2003), stricter conditions on safe collection, transport, storage, handling, processing, use and disposal of animal by-products are imposed. It is, additionally, known that animal manure and waste contain large amount of pathogen organisms, and is a source of problems like odour emissions, wastewater pollution and vector attraction. As a result, they should be treated with special care as an obligation against public health protection and general environmental protection [1]. Hence, huge amounts of wastes remain unexploited and their potential for energy production reasons could be, now on, under consideration.

Total Energy Potential by Using Anaerobic Digestion

In a typical steady state mass balance for anaerobic digestion, the influent carbon is equal to the sum of output carbon, carbon in biogas and carbon in the biomass produced. In order to estimate the potential of biogas and methane production from agricultural residues and livestock manure, the literature data of Table 4 as well as the residues quantity estimation (Tables 2 and 3) were used. In Table 5, moderate assumptions based on literature data (Table 4) were made for the parameters: %TS, %VS, Biogas yield and %CH_4. Taking all this information under consideration, the potential biogas and methane production was calculated (Table 5).

The total annual residues production in Greece amounts to 45,957,990 t/y taking into consideration the estimations for the annual production of agro-industrial residues and livestock manure. Although exploitation of residues for energy production through anaerobic digestion process would be feasible only in cases of medium–large scale units, for the purpose of this study the number of medium and small scale units was also taken into consideration.

In general, biogas is an energy carrier which can be used for several energy applications. This includes electricity generation, heat production, CHP production and transport applications. Biogas upgrading to natural gas quality (biomethane) is also possible. The most suitable system which should be implemented after biogas production from anaerobic digestion of agricultural residues and livestock manure is a CHP plant operating with combustion engines. The CHP production technology is a well known, robust technology for the utilisation of electricity and heat. CHP generation from biogas is considered a very efficient utilisation of biogas for energy production. Before CHP conversion, biogas is drained and dried. A CHP system's efficiency depends on the technology used to generate the electricity and thermal energy, the system design, and how much of the thermal energy is used by the site. Therefore, every CHP system will have a different, site-specific efficiency once installed. However, for biogas the most commonly installed CHP (gas turbine, natural gas turbine and micro-turbine) tend to offer fairly standard ranges of achievable efficiency such as 75–90 % [28].

An engine based CHP power plant produces 35 % electricity and 65 % heat. An important issue for the energy and economic efficiency of a biogas CHP plant is the utilisation of the produced heat. Usually, a part of the heat is used for heating the digesters (process heating) and approximately 2/3 of all produced energy can be used for external needs. Biogas heat can be used by industry processes, agricultural activities or for space heating.

Thus, anaerobic digestion of the whole amount of residues could result in the production of 3.34×10^9 m^3/y biogas and 1.97×10^9 m^3/y methane. Given that:

- the Lower Heating Value (LHV) of methane is 10 kWh/m^3 [29],
- the overall efficiency of the co-generation of electrical and thermal energy is 75–90 % [28, 30] and
- the overall electricity efficiency equals to 25–40 % [30],

the total amount of electricity and thermal energy produced may be estimated. The total energy content of the biogas produced may be estimated by multiplying the LHV of methane by the total amount of available methane. The latter reflects the total quantity of energy input in the CHP system. Since the overall efficiencies of electricity production and of co-generation are 25–40 and 75–90 % respectively, it was estimated that 4.9–7.9 TWh/y of electricity and 6.9–12.8 TWh/y of thermal energy may be produced by the utilization of biogas. One of the most important benefits of anaerobic digestion is that apart from

Table 5 Estimation of biogas and methane production after anaerobic digestion of agricultural residues and livestock manure

Species	Residues (tn)	%TS	%VS	Biogas yield (m^3/kg VS)	%CH_4	VS (tn)	Biogas (m^3)	CH_4 (m^3)
Wheat for crop	4,025,570	70	90	0.4	55	2,536,109	1,014,443,640	557,944,002
Industrial plants	2,329,480	80	90	0.2	55	1,677,226	335,445,120	184,494,816
Potatoes	331,760	80	90	0.2	55	238,867	47,773,440	26,275,392
Vegetables	553,720	80	90	0.2	55	398,678	79,735,680	43,854,624
Viticulture products	493,024	17	75	0.37	55	62,861	23,258,407	12,792,124
Citrus fruits	1,912,200	17	75	0.37	55	243,806	90,208,035	49,614,419
Fruits	465,696	17	75	0.37	55	59,376	21,969,209	12,083,065
Nuts	101,080	80	90	0.2	55	72,778	14,555,520	8,005,536
Olives	5,200,000	80	90	0.2	55	3,744,000	748,800,000	411,840,000
Cheese	3,592,960	10	90	1	70	323,366	323,366,400	226,356,480
Cattle	7,577,640	9	80	0.25	65	545,590	136,397,520	88,658,388
Pigs	1,443,180	5	75	0.37	75	54,119	20,024,123	15,018,092
Poultry	1,407,680	20	75	0.5	70	211,152	105,576,000	73,903,200
Goats and sheeps	16,524,000	3	87	0.87	70	431,276	375,210,468	262,647,328

the energy produced, the excess of anaerobic stabilized sludge could be used as a soil conditioner. The amount of soil conditioner that may be produced by anaerobic digestion of agro-industrial residues results from the excess biological sludge produced during digestion. Thus, assuming an average anaerobic digestion efficiency 55–70 % and a biomass production coefficient Y = 0.05 [31], about 330,000 t/y ± 17 % (in terms of VS) of soil conditioner were estimated that could be produced. In the latter estimation, the data of Table 5 regarding VS were taken into account.

Figure 3 graphically illustrates a rough balance of the exploitation of residues through anaerobic digestion and co-generation of energy.

According to the aforementioned balance, 4.9–7.9 TWh of electricity could be produced, amount that corresponds to 9–14 % of the gross national electricity consumption in Greece (55 TWh in 2012). The thermal energy on the other hand, could only be used in situ either for the thermal needs of anaerobic digesters or for neighboring activities.

Economic Aspects

Agricultural and animal waste management practice is very important for generating income and employment and could turn to be an economic way of energy production. Low-cost by-products of agriculture and animal breeding activity could enhance rural economies and keep them alive. This possibility seems to be more attractive when biomass is exploited under careful planning and in combination with a well-established energy production technology. But economic opportunities are viable and could play an important role, only under thoroughly inspected waste management practice and national motivation. With the rising fossil fuel prices, biomass conversion in energy will cost less in future and its utilization will contribute to money saving and environmental protection [1, 32].

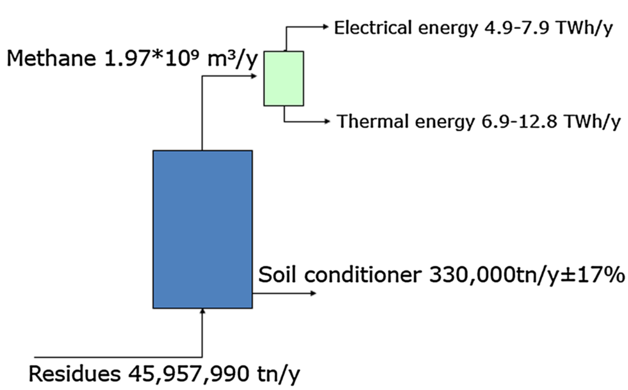

Fig. 3 Graphical representation of the utilization of residues

The lack of appropriate mechanization for biomass residue collection, the competitive markets (e.g. animal food industries), the big raw biomass volumes that must be transported, the lack of knowledge and inexistence in applicability of waste management are some of the factors that at the moment dominate in biomass negative exploitation for energy production reasons. Currently there is no organized practice in agricultural and animal wastes management in Greece, and as a result their exploitation is still set aside due mainly to economic reasons and lack of incentives for their efficient utilization, something that should not set aside the fact that biomass remains one of the cheapest fuel sources [1].

So, in order to render the calculations more realistic, the cost factor has to be taken into consideration. Taking into account the residue transportation costs as well as the fixed and operational costs (anaerobic digestion and co-generation), the cost per kWh of electrical energy produced was estimated in relation to the installed power capacity of operating plants necessary to treat the whole amount of residues [33]. The transportation cost was estimated considering the operating anaerobic plants evenly distributed in the Greek territory. The period of time required to recoup the investment was assumed 10 years. Figure 4 shows a rough cost estimation of the electricity produced through anaerobic digestion.

As it can be seen the cost gets lower as the number of plants increases and their installed power capacity decreases. The limiting value of the cost is 0.09€/kWh for 250 operating plants of 10 MW capacity. The selling price of electricity to the national energy network according to current Greek legislation is 0.20–0.22€/kWh [34]. Thus, the energy production by anaerobic digestion of residues could be also feasible from an economic point of view.

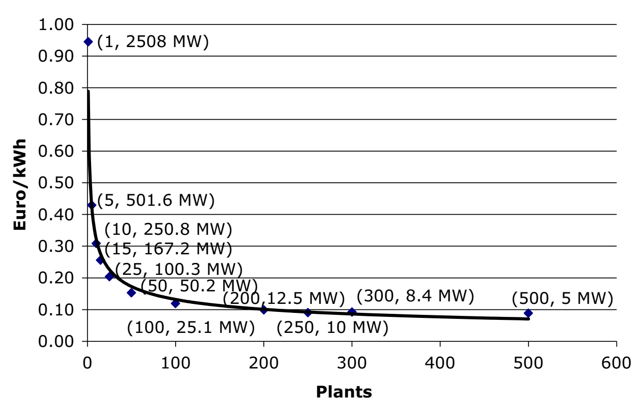

Fig. 4 Cost estimation of the electricity produced through anaerobic digestion in relation to the number of operating plants and their installed power capacity necessary to treat the whole amount of residues

Conclusions

Agricultural and animal wastes are able to contribute in a clean and safe renewable energy production and support country's socioeconomic development. Under sustainable conditions of exploitation, biomass could be a very promising alternative to fossil fuels. Some of the benefits that agricultural and animal waste treatment could offer are abatement in CO_2, NO_X, and SO_X emissions, preventing from phenomena like acid rain, smoke fog, and contribute to country's commitments in environmental protection. It is known that air pollution results in serious health problems and damages, thinns the ozone layer and leads to a climate change, but biomass conversion gases contribute positively to air pollution prevention and help in exhaust gas reduction.

Under this assumption, it is clear that Greece has a great opportunity to exploit its huge biomass stock, and specifically agricultural and animal wastes. Diverse topography and climate are very important factors for country's energy autonomy and are of strategic importance. Under the recently set national commitments on EU legislations over environmental protection, alignment with Kyoto protocol emissions abatement and climate change protection, Greece could viably exploit its RES, under an environmental friendly and economic viable way.

In this context, it was estimated that the total annual residues production in Greece amounts to 45,957,990 t/y taking into consideration the annual production of agro-industrial residues (41 %) and livestock manure (59 %). Studying the scenario of anaerobic treatment of these residues, it came up that 4.9–7.9 TWh of electricity could be produced, amount that corresponds to 9–14 % of the gross national electricity consumption in Greece.

To sum up, the need to explore new forms of energy in Greece is an imperative given the increasing energy demand and the need to find alternatives to fossil fuels as the world moves towards green fuels. Crop residues and livestock manure have a potential to contribute significantly to the energy map in Greece.

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