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ORIGINAL ARTICLE

Bio-SNG production — concepts and their assessment

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Abstract A major goal of today's energy policy is to establish an energy system with less greenhouse gas emissions (cf. "Renewable energy roadmap" [1]). The energetic use of biomass seems to be a very promising option to contribute to this goal: biomass can be used demand-oriented and to produce different energy carriers (e.g. power, heat and biofuels) needed within the energy system. Due to high overall efficiencies, especially the thermo-chemical conversion of solid biofuels to the natural gas substitute Bio-SNG (Synthetic Natural Gas) seems to be very promising. Therefore, it is the goal of this paper to analyse Bio-SNG production processes as a part of integrated polygeneration processes. Different Bio-SNG concepts using a gas slip stream in a gas engine or a gas turbine and process heat in an organic rankine cycle or conventional steam cycle are assessed. Based on mass and energy balances these concepts are discussed from an energetic, economic and environmental point of view. The analysis shows increasing exergetic efficiencies as well as improved economic and environmental process characteristics with increasingly integrated processes. However, the economic competitiveness still remains a bottleneck for a Bio-SNG market implementation. Therefore, two possible options to improve this competitiveness are discussed in detail.

Keywords Bio-SNG · Methanation · Biomethane · Polygeneration · Gasification · Flow sheet

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1 Introduction

The Bio-SNG process aims to convert solid biofuels (e.g. wood, straw) into an energetically useable gas with high methane content (>95 %) suitable for gas grid feed-in. The process chain can be subdivided into five main parts indicated in Fig. 1 [2].

- The biomass pretreatment primarily comprises a conditioning of the biomass' particle size and water content. The reduction of the water content minimises the exergetic losses within the gasifier [3] and allows for an improved gasification process regarding e.g. process stability. The adjustment of the fuel particle size distribution depends on the gasification technology. While fluidised-bed gasifiers require particles with a defined mass/diameter ratio, fixed-bed gasifiers work with fuel of a specific grain size and entrained-flow gasifiers use biomass powders or slurries [4].
- After this pretreatment, the conditioned biomass is gasified at temperatures up to 1,600 °C by the addition of a gasification agent (e.g. oxygen, water steam). The result is a raw gas with the main components carbon dioxide, carbon monoxide, water steam, hydrogen and — depending on the gasification conditions — certain amounts of methane [5, 6].
- To prevent catalyst poisoning and a possible blocking or damage at other plant components, impurities as particles, tars, sulphur, nitrogen and halogen compounds as well as alkalis have to be removed securely from the gas. Particles are separated from the gas by filters and cyclones. Sulphur, nitrogen and halogen compounds are removed by different absorptive or adsorptive gas cleaning steps (e.g. alkaline washing, active carbon bed, zinc oxide bed) [7].

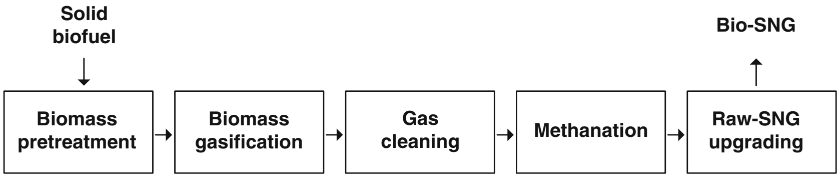


Fig. 1 Bio-SNG production pathway

- The clean gas subsequently enters the methanation process (realised either by several fixed-bed reactors [8] or by fluidised-bed reactors [9]), where carbon monoxide and hydrogen are converted into methane. If fixed-bed methanation reactors are used, in general a H_2/CO ratio of about 3 to 1 has to be adjusted by an upstream installed CO-shift reactor. If a fluidised-bed methanation is realised, at defined gas compositions no additional CO-shift reactor is required [10].
- After the methanation, the raw SNG has to be dried and (if necessary) cleaned from carbon dioxide by gas cleaning methods commonly used to purify technical gases (e.g. amine or triethyleneglycol based washing systems). Furthermore, unconverted gas components (e.g. hydrogen) have to be removed (e.g. by membranes) [7]. They are recycled to the process to maximise the overall efficiency.

However, the production pathway described above is still at demonstration stage and not available at commercial scale so far. To design plants for a commercial competitive Bio-SNG production, it is thus necessary to evaluate different concept configurations regarding energetic, economic and environmental aspects. Thereby, especially the integration of systems for the additional provision of power and heat has to be taken into account as a conceptual option to increase the process competitiveness. Hence, it is the goal of this paper to analyse different plant concepts for the polygeneration of SNG, power and heat from an energetic, economic and environmental point of view with a special focus on the influence of an increased power and heat generation.

2 Concept definition

To evaluate the energetic, economic and environmental competitiveness of possible Bio-SNG production plants, in the following 14 different plant designs are defined. These 14 concepts include seven concepts based on technology available in the short term (e.g. allothermal fluidised-bed gasification, wet gas cleaning) and seven concepts based on technological solutions probably available in the longer term (e.g. autothermal oxygen-based fluidised-bed gasification, hot gas cleaning). Both groups (i.e. concepts available in the short and the long term) comprise one concept without and six concepts with additional power production based on a gas engine, a gas turbine, a conventional steam cycle and an organic rankine cycle (ORC). Thereby, commercially available engines and turbines are the basis for an exemplary concept (slip stream) dimensioning. An overview about the 14 concepts is given in Table 1.

2.1 Short-term concepts

The seven short-term concepts are based on the demonstration plant in Güssing, Austria [11]. In this concept (Fig. 2), dried wood chips are converted into raw gas by an allothermal fluidised-twin-bed gasifier (FICFB: Fast Internally Circulating Fluidised-Bed [12]) with water steam as gasification agent. The steam is produced with waste heat from the process (e.g. from the flue gas cooling). The raw gas is dedusted in a precoated baghouse filter. Tars are removed by a washing system operating with fatty acid methyl ester produced from rape oil (i.e. rapeseed methyl ester (RME)). Additionally, sulphur compounds are separated from the gas with a combination of an active carbon and zinc oxide bed. After gas compression to 4 bar, the gas components carbon monoxide and hydrogen are catalytically converted into methane and water in a fluidised-bed methanation reactor [9]. To meet the demands of the natural gas grid (after a gas compression to 16 bar), carbon dioxide is removed from the gas leaving the methanation reactor. Therefore, an amine washing unit is used. Finally, remaining hydrogen is separated by a membrane and the gas is dried before it is fed into the natural gas grid.

The concepts with a steam or organic rankine cycle (for an additional power provision) are similar to the reference concept. However, they use surplus process heat for electrical power production instead for the provision of district heating.

The concepts with a gas engine use a gas slip stream in the engine to produce electrical power. The slip stream is separated from the main gas stream after the tar removal (i.e. tar washing system 1) at a temperature of about 40 °C. Surplus heat is provided to a steam or organic rankine cycle from different process steps and heat sources, respectively (e.g. raw gas cooling, methanation, engine flue gas cooling).

The concepts with a gas turbine use a Bio-SNG slip stream in a gas turbine. The Bio-SNG slip stream is separated from the main gas stream directly before the gas is fed

Table 1 Concept overview

Abbreviation	Gasification	Gas cleaning	Power production	Products
S1	Allothermal	Wet	–	SNG, heat
S2-SC	Allothermal	Wet	Steam cycle	SNG, power, heat
S3-ORC	Allothermal	Wet	ORC-module	SNG, power, heat
S4-GE-SC	Allothermal	Wet	Gas engine; steam cycle	SNG, power, heat
S5-GE-ORC	Allothermal	Wet	Gas engine; ORC-module	SNG, power, heat
S6-GT-SC	Allothermal	Wet	Gas turbine; steam cycle	SNG, power, heat
S7-GT-ORC	Allothermal	Wet	Gas turbine; ORC-module	SNG, power, heat
L1	Autothermal	Hot	–	SNG, heat
L2-SC	Autothermal	Hot	Steam cycle	SNG, power, heat
L3-ORC	Autothermal	Hot	ORC-module	SNG, power, heat
L4-GE-SC	Autothermal	Hot	Gas engine; steam cycle	SNG, power, heat
L5-GE-ORC	Autothermal	Hot	Gas engine; ORC-module	SNG, power, heat
L6-GT-SC	Autothermal	Hot	Gas turbine; steam cycle	SNG, power, heat
L7-GT-ORC	Autothermal	Hot	Gas turbine; ORC-module	SNG, power, heat

into the natural gas grid (with a pressure of 16 bar). Similar to the concepts with a gas engine, surplus heat is provided to a steam or organic rankine cycle, respectively.

2.2 Long-term concepts

For the long-term concepts exemplary innovative technology (e.g. pressurised fluidised-bed gasification, tar reforming) is selected which currently is in the focus of investigation and analysed in several concept studies. The seven long-term concepts (Fig. 3) use a dryer with heated air for the biomass pretreatment. After this drying process, the wood chips are directed to an autothermal gasifier through a lock hopper system using carbon dioxide as inert gas. The gasifier is a circulating fluidised bed, which works at a temperature of 950 °C, a pressure of 10 bar, SiO_2 as bed material and with an oxygen–water mixture as gasification agent. The oxygen is provided by a cryogenic air separation unit. To reduce the raw gas' tar load, a catalytic tar reformer is applied after the gasifier. In this reformer tars and 80 % [13] of the methane produced during the biomass gasification are destroyed while the gas is cooled down to

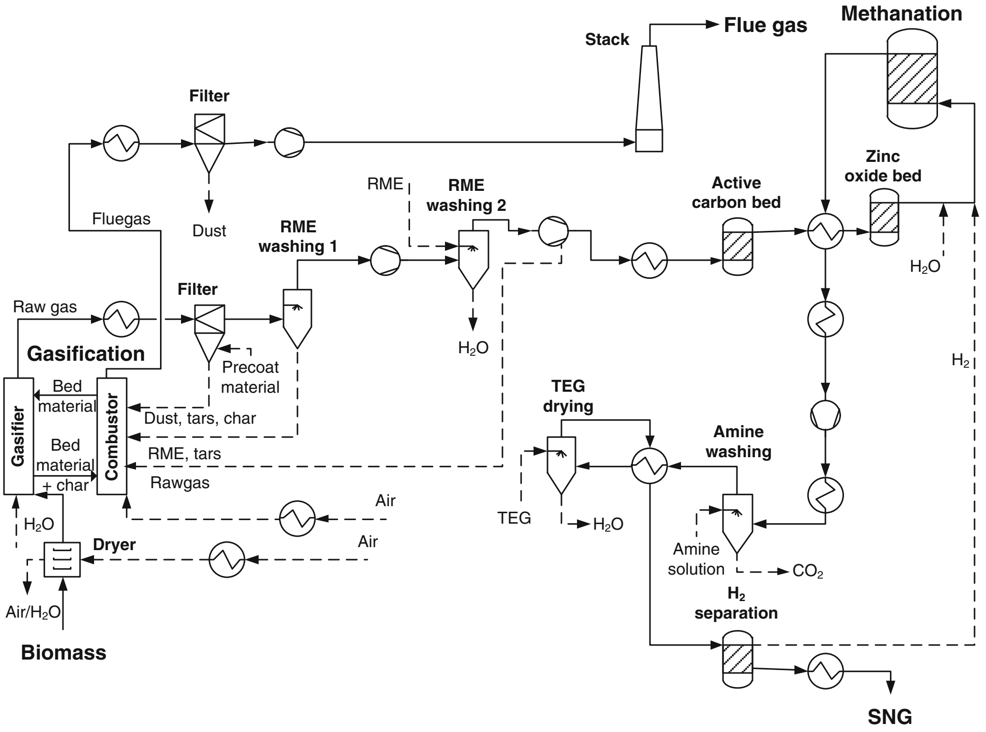


Fig. 2 Basic process setup of short-term concepts

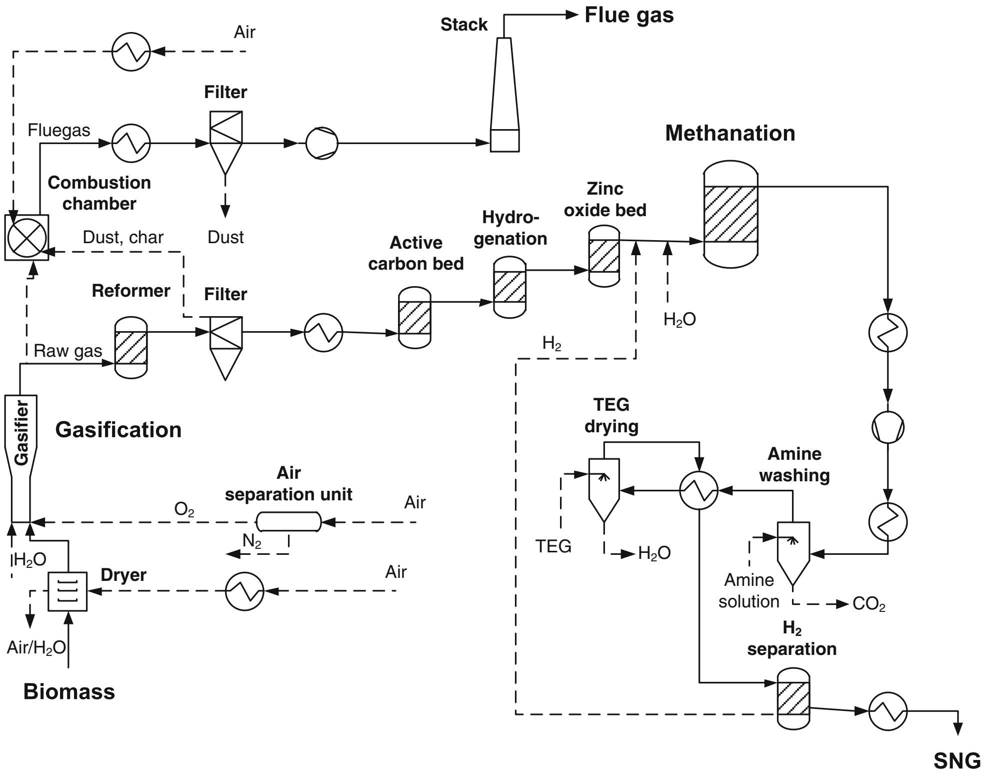


Fig. 3 Basic process setup of long-term concepts

850 °C. Heat required for the endothermic reforming reactions comes from a combustion chamber fired by unconverted char and parts of the raw gas. A ceramic filter — installed downstream the reformer — separates the char from the gas. Subsequently, the gas is cooled down to 350 °C and cleaned from sulphur compounds by an active carbon bed and a combination of hydrogenation for COS conversion and zinc oxide bed.

The following process steps correspond to the short-term concepts (Section 2.1). After the gas cleaning, water steam is added to the gas. The mixture is directed into a thermo-oil cooled fluidised-bed methanation reactor [9]. Afterwards, the gas is cooled down, compressed to 16 bar and cleaned from carbon dioxide with the help of an amine washing. To ensure a sufficient gas quality for a gas grid feed-in, the gas is dried by triethylenglycol (TEG) and the remaining hydrogen is removed by a membrane [14].

The concepts with a steam or an organic rankine cycle are similar to this concept and use surplus process heat to produce electrical power.

The concepts with a gas engine use a gas slip stream in an engine to provide electrical power. The slip stream is separated from the main gas stream after the tar reformer. Heat is provided to a steam or organic rankine cycle from different process steps and heat sources, respectively.

The concepts with a gas turbine use a Bio-SNG slip stream in a gas turbine. The Bio-SNG slip stream is separated from the main gas stream directly before the gas grid feed-in with a pressure of 16 bar. Similar to the concepts with gas engines, surplus heat is provided to a steam or organic rankine cycle respectively.

3 Concept analysis

The concepts outlined in Section 2 are analysed taking energetic, economic and environmental aspects into consideration. The boundary of this analysis includes the overall Bio-SNG production plant starting with the biomass pretreatment (drying) and ending with the raw-SNG upgrading up to gas grid feed-in quality. Methodology and frame conditions of the analysis are explained below.

3.1 Analysis of energetic aspects

To evaluate Bio-SNG plant concepts from an energetic point of view, their thermodynamic behaviour is modelled. Therefore, equations of state as well as chemical properties of relevant substances are implemented and used in (adapted) equilibrium models. Afterwards, mass, energy and exergy flows are calculated with the software package MATLAB Simulink. Exemplarily, the exergetic efficiency is determined as an energetic evaluation criterion within the further analysis.

With regard to the analysed system boundary the exergetic efficiency η_{ex} is defined based on the exergy flow of the produced SNG $\dot{E}_{SNG,\,out}$, the exergy flow of the provided electricity $\dot{E}_{el,\,out}$, the exergy flow of the produced heat $\dot{E}_{th,\,out}$, the exergy flow of the solid biofuel $\dot{E}_{bf,\,in}$, the exergy flow of the RME used for tar washing $\dot{E}_{RME,\,in}$ and the exergy flow of the electricity self-consumption $\dot{E}_{el,\,in}$. Based on this, the exergetic efficiency η_{ex} is calculated according to Eq. 1.

$$\eta_{ex} = \frac{\dot{E}_{SNG,\,out} + \dot{E}_{el,\,out} + \dot{E}_{th,\,out}}{\dot{E}_{bf,\,in} + \dot{E}_{RME,\,in} + \dot{E}_{el,\,in}} \tag{1}$$

To allow for a reasonable comparison of the 14 Bio-SNG concepts, the process modelling is realised under uniform frame conditions and assumptions (Table 2).

3.2 Analysis of economic aspects

The decision for the production of a fuel is significantly influenced by economic considerations. Thus, based on the calculated mass, energy and exergy balances (Section 3.1) the Bio-SNG production costs at plant gate C_{SNG} are determined as the ratio of the annual annuity A and annual exergy of the product SNG $\dot{E}_{SNG,out}$ (Eq. 2).

$$C_{SNG} = \frac{A}{\dot{E}_{SNG,out}} \tag{2}$$

The annuity is determined according to the methodology defined within the VDI guideline 2067 [15] and under consideration of uniform frame conditions for all 14 concepts (Table 3).

3.3 Analysis of environmental aspects

A method to assess selected environmental effects within defined borders is the life cycle assessment, which can be applied to consider different impact categories. Here the greenhouse gas (GHG) emissions G_{SNG} released during the Bio-SNG production are determined as an exemplary impact category.

The greenhouse gas emissions caused by the analysed Bio-SNG production plants refer to the defined system

Table 2 Frame conditions of process modelling

		Short-term concepts	Long-term concepts
Mass flows			
Mass flow solid biofuel	kg/s	4.49	4.49
Mass flow RME	kg/h	66.59	–
Mass flow oxygen (gasification agent)	kg/h	–	3,794.7
Mass flow carbon dioxide (inert gas)	kg/h	–	1,901.2
Drying parameters			
Drying temperature	°C	95	95
Biofuel water content before dryer	%	40	40
Biofuel water content after dryer	%	20	20
Gasification parameters			
Pressure gasification reactor	bar	1	16
Temperature gasification reactor	°C	850	950
Ratio H_2O/biofuel (dry)		0.50	0.27
Pressure combustion chamber	bar	1	–
Temperature combustion chamber	°C	930	–
Lambda combustion chamber		1.15	–
Raw gas content CH_4	% vol.	7.62	7.41
Raw gas content CO	% vol.	16.50	27.09
Raw gas content CO_2	% vol.	17.13	22.34
Raw gas content H_2	% vol.	31.91	18.38
Raw gas content H_2O	% vol.	22.09	24.46
Raw gas content C_2H_4	% vol.	3.09	0
Raw gas content $C_{10}H_8$, NH_3, H_2S, COS	% vol.	1.66	0.32
Methanation parameters			
Pressure methanation	bar	4	16
Temperature methanation	°C	300	300

Table 3 Frame conditions of Bio-SNG production costs calculations

Capital-related costs		
Total amount of investment (I_0)	*M* €	70
Observation period	*a*	20
Average rate of interest	%/*a*	8.0
Annual overhaul costs	% of I_0	2.0
Average inflation rate	%/*a*	0
Consumption-related costs		
Full load hours	*h*/*a*	7,500
Biomass provision costs (dry)	€/*t*	70
Disposal costs waste water	€/*t*	2
Disposal costs ash	€/*t*	150
Electricity tariff	€/kWh	0.10
Average inflation rate	%/*a*	0
Operation-related costs		
Manpower demand	Employees	16
Annual personal costs	€/(employee *a*)	50,000
Annual service costs	% of I_0	3.0
Average inflation rate	%/*a*	0
Other costs		
Annual insurance costs	% of I_0	1.0
Annual administration costs	% of I_0	0.5
Annual unexpected costs	% of I_0	1.0
Average inflation rate	%/*a*	0
Revenues for by-products		
Compensation for heat	€/kWh	0.03
Compensation for electricity	€/kWh	0.10
Average inflation rate	%/*a*	0

boundary. This boundary starts with the feedstock at plant gate (no pre-chains are taken into consideration) and ends with the Bio-SNG gas grid injection. The greenhouse gas emissions comprise the emissions related to auxiliary agents G_{AA}, residues G_R and auxiliary energy G_{AE}. The emissions are allocated to the different products (SNG, power, heat) by their exergy content (Eq. 3).

$$G_{SNG} = \frac{G_{AA} + G_R + G_{AE}}{\dot{E}_{SNG,\,out}} \frac{\dot{E}_{SNG,\,aus}}{\dot{E}_{SNG,out} + \dot{E}_{el,\,out} + \dot{E}_{th,\,out}} \quad (3)$$

4 Results

Below the results of the energetic, economic and environmental concept analysis (Section 3) are discussed in detail.

4.1 Results of the energetic analysis

The investigated short-term concepts show exergetic efficiencies between 44.3 and 64.5 % (Fig. 4). Compared to the concept without electricity production (S1) characterised by an exergetic efficiency of 62.9 %, a maximum efficiency increase of 1.6 % (absolute) is possible by integrating power production units.

Due to the exergetic losses related to the (internal) combustion process converting gas to electrical power and heat, the concepts using a gas slip stream for power generation (S4-GE-SC, S5-GE-ORC, S6-GT-SC, S7-GT-ORC; see Table 1) — either with a turbine or an engine — lead to the lowest efficiencies: 44.3 to 46.4 % for the gas turbine concepts and 58.8 to 59.9 % for the gas engine concepts.

The concept with steam cycle (S2-SC) achieves the highest efficiency of 64.5 % as process heat — used for district heating at low temperature in the concept without electricity production (S1) — is used to provide electrical power. The concept with an ORC module (S3-ORC) is characterised by a slightly lower efficiency than the steam cycle concept because the stability of the thermo oil used within the ORC module restricts its maximum steam temperature (according to Carnot the efficiency of a steam cycle ideally depends on the steam temperature resp. the useable temperature difference). Thus, if no heat consumer is available close to the Bio-SNG plant, the integration of a steam cycle provides an opportunity to use high temperature process heat in a reasonable way for polygeneration purposes and efficiency enhancement.

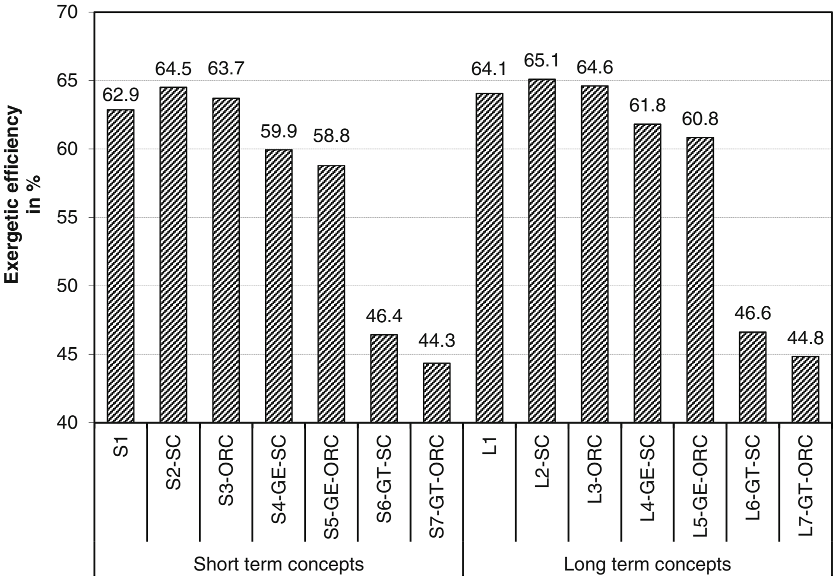
The long-term concepts analysed here show exergetic efficiencies between 44.8 and 65.1 % (Fig. 4). The concept without electricity production (L1) is characterised by an exergetic efficiency of 64.1 %. Hence, regarding the investigated concepts a maximum increase of the efficiency of 1.0 % (absolute) is possible.

Similar to the short-term concepts, long-term concepts with internal combustion processes — converting gas to electrical power and heat such as gas engines and gas turbines (L4-GE-SC, L5-GE-ORC, L6-GT-SC, L7-GT-ORC; see Table 1) — show high exergetic losses and comparatively low exergetic efficiencies: 44.8 to 46.6 % for the gas turbine concepts and 60.8 to 61.8 % for the gas engine concepts.

Again, the concept with a steam cycle (L2-SC) leads to the highest exergetic efficiency of 65.1 %. This process allows to use high temperature process heat (e.g. from the methanation or reformer combustion chamber) in an efficient way. Gas is not converted by internal combustion processes, which are not preferable from an exergetic point of view, and there are no severe temperature restrictions for the steam superheating.

In comparison to the short-term concepts, the long-term concepts show higher exergetic efficiencies in average. This is caused by the basic concept design. While the short-term concepts rely on established gas cleaning technology at low temperatures, the long-term concepts use innovative hot gas cleaning and pressurised gasification. Both measures result in exergetic advantages: the hot gas cleaning saves exergy

Fig. 4 Results of the energetic concept analysis (for abbreviations see Table 1)



for reheating the gas before the methanation process and the pressurised gasification leads to electricity savings regarding the gas compression. However, due to the necessary gas cooling for the low temperature gas cleaning of the short-term concepts, these concepts are characterised by a higher amount of process heat usable in a steam cycle. Thus, these concepts show a slightly higher optimisation potential by integrating a steam cycle into the process compared to the long-term concepts.

4.2 Results of the economic analysis

The Bio-SNG production costs of the analysed short-term concepts are between 0.09 and 0.17 €/kWh SNG (Fig. 5). Thereby, the total amount of investment has a high impact on the production costs (about 40 % of the costs are related to the investment). In comparison to the short-term concept without electricity production (S1), which produces Bio-SNG for 0.093 €/kWh, a specific cost reduction of 0.002 €/kWh is possible by producing electrical power.

The assessment of the economic results shows interrelations similar to the exergetic analysis: Concepts with a gas turbine or a gas engine (S4-GE-SC, S5-GE-ORC, S6-GT-SC, S7-GT-ORC; see Table 1) lead to the highest gas production costs; the costs vary between 0.10 and 0.17 €/kWh SNG. Reasons for this are additional investments for an engine and a turbine. Furthermore, low conversion efficiencies from gas to electricity lead to a lower annual electricity than SNG production rate (i.e. in kWh/a). Therefore, lower revenues for electricity than for SNG (if it would not be converted to electrical power) can be achieved.

Concepts that use process heat to provide electrical energy achieve the lowest Bio-SNG production costs of 0.09 €/kWh (S2-SC). Thereby, the concept using a single steam cycle for power generation (S2-SC) is characterised by slightly lower costs compared to the concept with an ORC module (S3-ORC). A higher electrical efficiency — caused by a higher steam temperature — is the reason.

The Bio-SNG production costs of the long-term concepts are between 0.089 and 0.163 €/kWh (Fig. 5). Therefore, in relation to 0.089 €/kWh for the concept without power generation (L1), concepts producing electrical power show no cost reduction potential.

Due to additional investments, the concepts with an integrated gas turbine and gas engine (L4-GE-SC, L5-GE-ORC, L6-GT-SC, L7-GT-ORC; see Table 1) even show higher production costs than the concept without power production: 0.096 to 0.097 €/kWh SNG for concepts with a gas engine and 0.160 to 0.163 €/kWh SNG for concepts with a gas turbine.

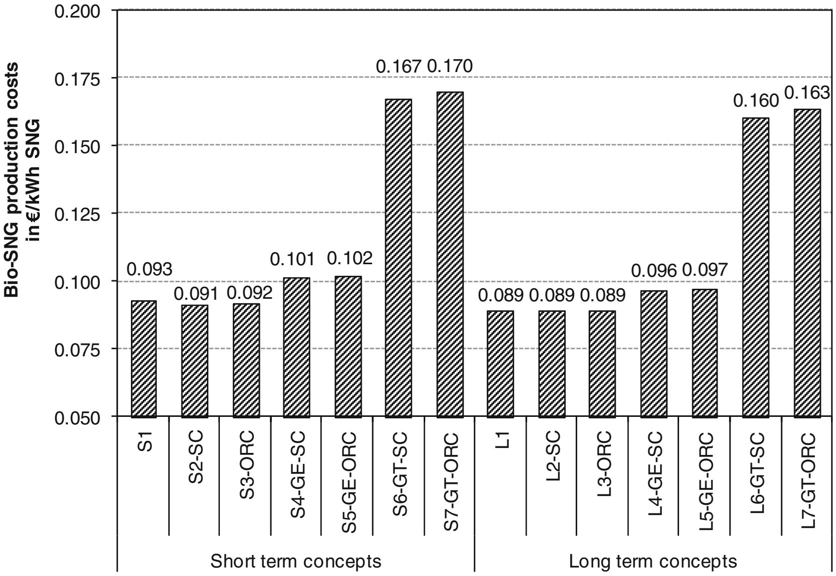
As the amount of process heat available for power generation is comparatively small (the process is designed with hot gas cleaning), there is no cost benefit neither by using a steam cycle (L2-SC) nor by using an ORC module (L3-ORC). The assumptions of this work lead to Bio-SNG production costs of 0.089 €/kWh for both concepts.

In comparison to the short-term concepts, the long-term concepts achieve lower Bio-SNG production costs in average. However, due to the small amount of process heat the possibility to reduce the costs by the integration of power production units is limited.

4.3 Results of the environmental analysis

The greenhouse gas emissions related to the Bio-SNG production of the short-term concepts investigated here comprise a range between 17.0 and 24.4 $g_{CO2\text{-}eq}$/MJ SNG

Fig. 5 Results of the economic concept analysis (for abbreviations see Table 1)



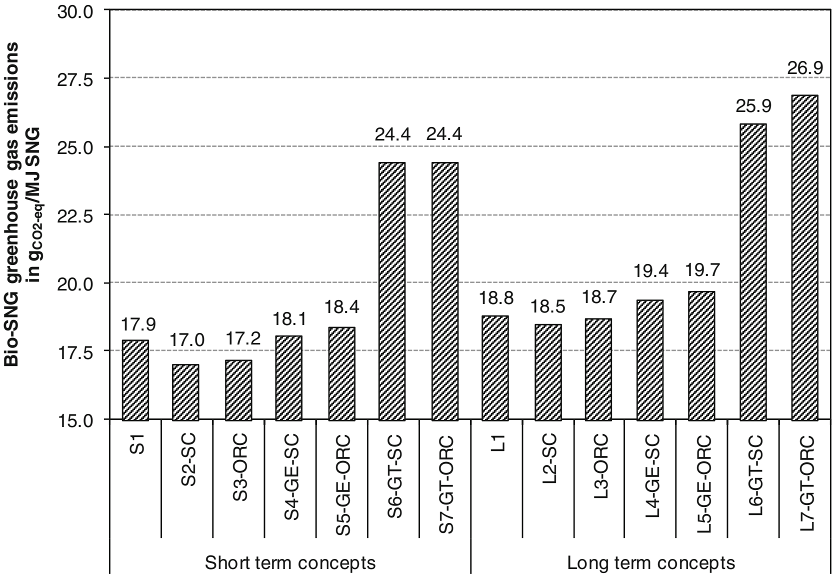
(Fig. 6). Thereby, the electricity consumption of the plants has a significant impact on the emissions (share of more than 80 % of the overall emissions). The concept without power generation (S1) is characterised by greenhouse gas emissions of 17.9 $g_{CO2\text{-}eq}$/MJ SNG. By integrating power generation units the GHG emissions can be reduced by 0.9 $g_{CO2\text{-}eq}$/MJ SNG.

These results are in accordance to the results of the analysis of the exergetic efficiencies and of the gas production costs. Concepts with a gas turbine or a gas engine (S4-GE-SC, S5-GE-ORC, S6-GT-SC, S7-GT-ORC; see Table 1) show the highest greenhouse gas emissions. The reason is the reduction of the main product Bio-SNG, which is the reference base for the greenhouse gas emission calculations: The amount of Bio-SNG is reduced by converting it into electrical power and positive effects of this measure (e.g. a lower electricity consumption of the plant) are overcompensated.

Minimal greenhouse gas emissions of 17.0 $g_{CO2\text{-}eq}$/MJ SNG are achieved by the concept with steam cycle (S2-SC). This concept does not reduce the Bio-SNG production but the energy self-consumption (i.e. electrical power produced by the steam cycle is used to satisfy the electricity self-consumption). As less electricity is produced, the concept with an ORC module (S3-ORC) achieves slightly higher greenhouse gas emissions than the concept with a steam cycle.

The calculations of the analysed long-term concepts show greenhouse gas emissions between 18.5 and 26.9 $g_{CO2\text{-}eq}$/MJ SNG (Fig. 6). Thus, the emissions of the concept without power generation (L1) can be decreased by 0.3 $g_{CO2\text{-}eq}$/MJ SNG by alternative concepts.

Fig. 6 Results of the environmental concept analysis (for abbreviations see Table 1)



Concepts with a gas engine (L4-GE-SC, L5-GE-ORC) lead to emissions between 19.4 and 19.7 $g_{CO2\text{-}eq}$/MJ SNG. Concepts with a gas turbine (L6-GT-SC, L7-GT-ORC) achieve emissions between 25.9 and 26.9 $g_{CO2\text{-}eq}$/MJ SNG. An explanation for this is a significant reduction of the main product Bio-SNG by producing electrical power from it.

Among the analysed long-term concepts, those with a single steam cycle (L2-SC) or an ORC module (L3-ORC) achieve the lowest greenhouse gas emissions of 18.8 and 18.7 $g_{CO2\text{-}eq}$/MJ SNG, respectively. These concepts use process heat, which is used for district heating in the concept without power generation (L1), and convert this heat into electricity — a product with a higher exergy than district heat. According to Eq. 3 reduced specific greenhouse gas emissions are the consequence.

A comparison between short- and long-term concepts reveals higher greenhouse gas emissions for the long-term concepts (average). The reason is a higher electricity consumption of these concepts due to an air separation unit used to supply oxygen to the autothermal gasification.

5 Conclusions

The results show high overall exergetic efficiencies of approximately 65 % for Bio-SNG processes, which use process heat in a steam cycle for power generation and without using a gas slip stream for power generation in gas engines or gas turbines. In comparison, Fischer–Tropsch Diesel production processes show overall efficiencies between 40 and 60 % [16].

Also the environmental analysis shows promising results. Compared to other options Bio-SNG shows relative low greenhouse gas emissions: regarding a corresponding system boundary comprising the biofuel production plant in the "Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources" default values for biodiesel and bioethanol of 18 to 49 $g_{CO2\text{-}eq}$/MJ and 19 to 45 $g_{CO2\text{-}eq}$/MJ, respectively, can be found [17].

The economic analysis identifies minimal Bio-SNG production costs of 0.089 €/kWh SNG. In comparison to current natural gas trading prices (between 0.02 and 0.03 €/kWh [18]) the Bio-SNG production costs are far away from economic competitiveness if subsidies and/or other administrative measures are not taken into consideration.

Thus, to implement Bio-SNG on the commercial energy markets without political support, the economic competitiveness has to be improved significantly. This competitiveness is directly related to the Bio-SNG production costs. Additionally, it depends on the potential risk of investment (linked to high capital-related costs). Therefore, exemplary two options promising to improve the economic competitiveness are discussed in the following.

- Electricity production by using a gas slip stream in gas engines or gas turbines at peak load times to benefit by higher revenues for electricity than for SNG (shown for the short-term concepts in Fig. 7).
- Combination of raw-SNG upgrading and biogas upgrading to reduce the specific investment of the Bio-SNG plant (shown in Fig. 8).

The option to use gas engines or gas turbines to produce electricity at peak load times with a gas slip stream is only reasonable, if the revenues achieved by the sold electricity are higher than the revenues achieved by the sale of SNG that could be produced from the gas slip stream (if no electricity is produced). Therefore, besides low investments for the gas engines, low SNG trading prices and high electricity prices are required to create an economic benefit by this option. Taking an average run of electricity hours at the European Energy Exchange (EEX), a heat sale of 7,500 h per year, and 7,500 full load hours of the Bio-SNG plant into account (Fig. 7), electricity production is only reasonable if the SNG trading price is below 0.02 €/kWh. For a heat sale less than 4,000 h per year, electricity production is only reasonable for SNG trading prices less than 0.01 €/kWh. Hence, considering a current natural gas trading price between 0.02 and 0.03 €/kWh, the option to use gas engines to produce electricity at peak load times with a gas slip stream is not appropriate to improve the economic competitiveness of Bio-SNG production processes.

The option to combine the raw-SNG upgrading with biogas upgrading to reduce the specific investment of the Bio-SNG plant is schematically shown in Fig. 8. As biogas upgrading to biomethane and raw-SNG upgrading are based on the same process steps (gas compression, carbon dioxide removal, gas drying), this option leads to different economic and technical advantages. Firstly, the specific investment costs of the Bio-SNG production can be reduced due to higher gas throughputs by the use of gas produced with commercially available and inexpensive biogas technology. Secondly, process heat can be used to heat the biogas fermenter and the overall process is more flexible with regard to its biofuel (biogas production and raw-SNG production are based on different biomass resources). However, the integration of biogas and SNG upgrading leads to new technical tasks related e.g. to the different grades of purity of biogas and raw-SNG or the different plant scales of biogas and SNG concepts, which have to be forced.

Hence, the integration of biogas upgrading with raw-SNG upgrading might help to reduce the Bio-SNG production costs. Nevertheless, due to the huge difference between the natural gas trading prices and the Bio-SNG production costs this option is no measure to overcome this economic gap in total.

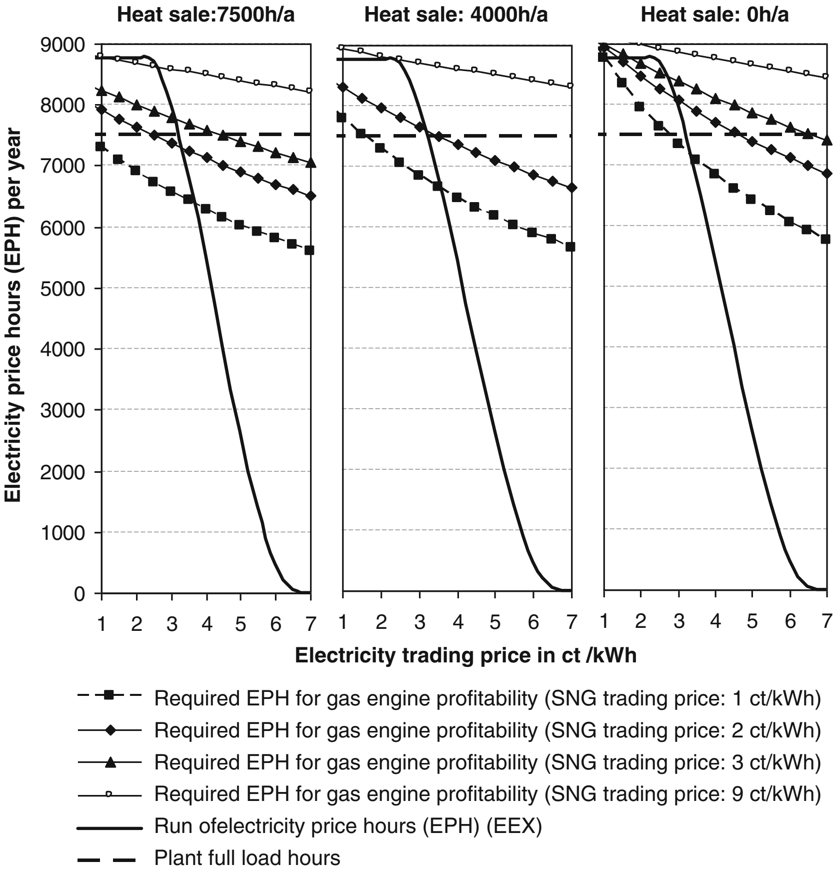


Fig. 7 Required electricity price hours (*EPH*) for gas engine profitability at peak load times for three different rates of heat sale per year (short-term concept with gas engines)

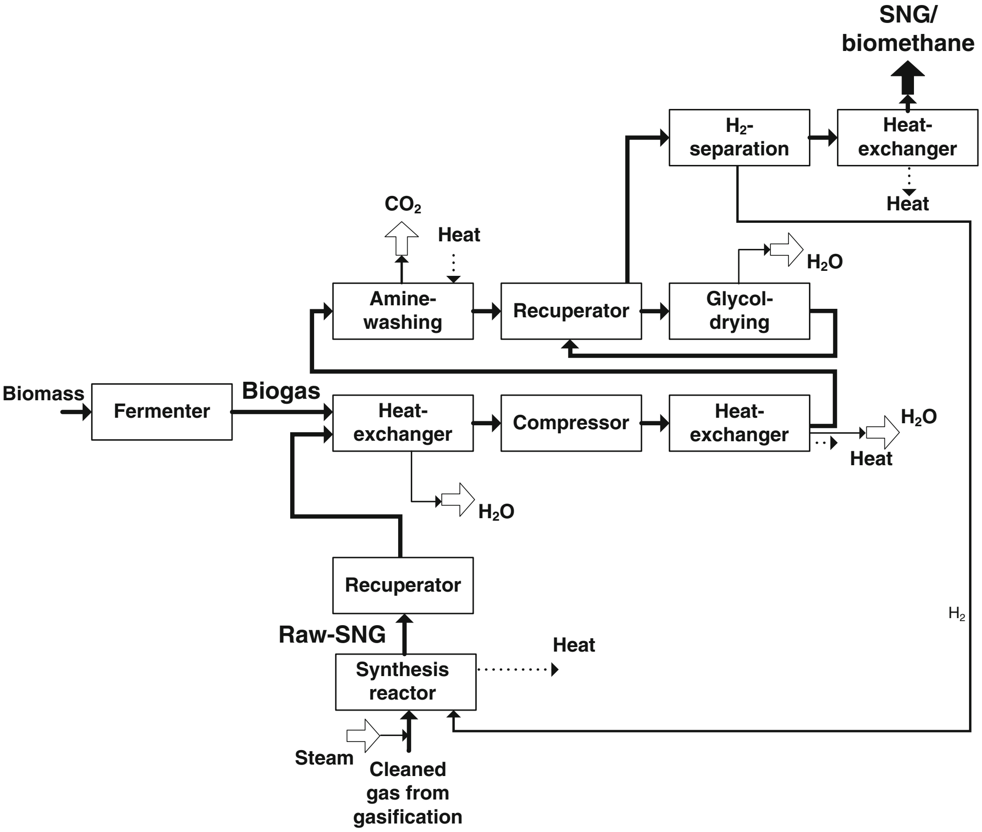


Fig. 8 Combination of biogas and raw-SNG upgrading

6 Summary

It is the goal of this investigation to analyse 14 different short- and long-term Bio-SNG provision concepts (Table 1) without and with an electricity generation according to selected technical, economic and environmental aspects. The results can be summarised as follows.

- The exergetic analysis shows high exergetic losses by converting gas or SNG to electrical power in a gas engine or a gas turbine. However, the use of process heat for power generation in a steam cycle or ORC module instead of the provision of district heat leads to an increase of the exergetic efficiency. This increase is higher for short-term concepts than for long-term concepts as short-term concepts with low temperature gas cleaning are characterised by a higher amount of available process heat.
- The optimisation potential identified by the economic analysis is low. Additional investments for the steam cycle, the ORC module, the gas engine or the gas turbine are the main reasons. Furthermore, low gas-to-electricity conversion efficiencies are related to low revenues for the sale of electrical power. Therefore, the use of a gas engine or a gas turbine even leads to higher Bio-SNG production costs than achieved by the concept without power production unit.
- The environmental analysis exemplarily carried out for greenhouse gas emissions shows similar results as the exergetic analysis. Due to a low efficiency, the use of a gas engine or a gas turbine is not promising to minimise the greenhouse gas emissions. But, with a steam cycle or ORC module the greenhouse gas emissions can be reduced. Due to the electricity consumption of the air separation unit, the long-term concepts are characterised by higher emissions than the short-term concepts.
- By comparing all investigated concepts it becomes obvious, that the energetic, economic and environmental competitiveness of Bio-SNG concepts can be increased if process heat is used to produce electrical power in a steam cycle or an ORC module. By the conversion of a gas slip stream in a turbine or an engine, the competitiveness of the Bio-SNG production decreases.
- Due to the availability of high-temperature process heat (e.g. from methanation and raw gas cooling), the application of a steam cycle is more reasonable than of an ORC-module, where — due to technical constraints — the steam temperature is limited. The competitiveness of Bio-SNG production can be increased in the most efficient way, if process heat is used in a steam cycle to produce power and heat. In addition, concepts using process heat for power generation are more flexible regarding possible plant sites as the attendance of a heat consumer is not necessary.
- The relatively high Bio-SNG provision costs hinder a fast Bio-SNG market implementation. Therefore two options, which might contribute to improve the economic competitiveness, are discussed.
  - Considering a natural gas trading price between 0.02 and 0.03 €/kWh (and the assumptions of this work), the option to use gas engines to produce electricity at peak load times with a gas slip stream is not appropriate to improve the economic competitiveness of Bio-SNG production processes.
  - Biogas upgrading together with raw-SNG upgrading might lead to economic synergy effects: Technical equipment (investments) can be reduced due to similar gas cleaning steps of biogas and Bio-SNG upgrading. Economy of scale can be achieved by higher gas throughputs (SNG and biogas). Nevertheless, this measure is not sufficient to make Bio-SNG competitive in the natural gas market.

References

1. Commission of the European communities (Ed.) (2007) Communication from the commission to the council and the European parliament — Renewable energy roadmap — Renewable energies in the 21st century: building a more sustainable future; COM (2006) 848; Brussels
2. Rönsch S (2011) Optimierung und Bewertung von Anlagen zur Erzeugung von Methan, Strom und Wärme aus biogenen Festbrennstoffen, Dissertation, DBFZ Report Nr. 5; Leipzig
3. Bolhàr-Nordenkampf M, Hofbauer H (2004) Biomass gasification combined cycle thermodynamic optimisation using integrated drying. Proceedings of ASME Turbo Expo 2004 — Power for Land, Sea, and Air; Vienna
4. Kaltschmitt M, Hartmann H, Hofbauer H (eds) (2009) Energie aus Biomasse — Grundlagen, Techniken und Verfahren. Springer, Berlin
5. Knoef H (Ed.) (2005) Handbook biomass gasification. BTG biomass technology group BV, Enschede
6. Higman C, van der Burgt M (2003) Gasification. Gulf Professional, Burlington
7. Kohl AL, Nielsen RB (eds) (1997) Gas purification. Gulf, Houston
8. Höhlein B (1983) Methanisierung von Synthesegasen im gekühlten Reaktor, Zentralbibliothek der Kernforschungsanlage Jülich; Jülich
9. Seemann M (2006) Methanation of biosyngas in a fluidized bed reactor — development of a one step synthesis process, featuring simultaneous methanation, watergas shift and low temperature tar reforming, Dissertation; Zurich
10. Rönsch S, Ortwein A (2011) Methanisierung von Synthesegasen — Grundlagen und Verfahrensentwicklungen. Chemie Ingenieur Technik 83:1200–1208
11. Rehling B, Hofbauer H, Rauch R, Aichernig C (2011) BioSNG — process simulation and comparison with first results from a 1-MW demonstration plant. Biomass Convers Biorefinery 1:111–119
12. Hofbauer H, Rauch R, Loeffler G, Kaiser S, Fercher E, Tremmel H (2002) Six years experience with the FICFB-gasification process. 12th European Conference and Technology Exhibition on Biomass for Energy; Amsterdam

13. Fürnsinn S (2008) Outwitting the dilemma of scale — cost and energy efficient scale-down of the Fischer-Tropsch fuel production from biomass, VDM Verlag Dr Müller Aktiengesellschaft & Co. KG, Saarbrücken
14. Rehling B, Hofbauer H, Rauch R, Tremmel H, Aichernig C, Schildhauer T, Biollaz S, Ulrich D, Schaub M (2009) Bio-SNG — first results of the 1 MW pilot and demonstration unit at Güssing; International Conference on Polygeneration Strategies 2009; Wien
15. Verein Deutscher Ingenieure (ed) (1996) VDI 2067, Betriebswirtschaftliche Berechnungen für Investitionsgüter und Anlagen, VDI-Gesellschaft Technische Gebäudeausrüstung. Beuth Verlag GmbH, Berlin
16. Volkswagen AG et al (2008) Renewable fuels for advanced powertrains, Final report, www.renew-fuel.com
17. Commission of the European communities (2008) Proposal for a directive of the European parliament and of the council on the promotion of the use of energy from renewable sources, COM (2008) 19; Brussels
18. Bundesamt für Wirtschaft und Ausfuhrkontrolle (BAFA): EnergieINFO 2009, http://www.bafa.de/bafa/de/energie/erdgas/energieinfo/2011/januar.html, State: 15.12.2011