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Thermodynamic and economic effectiveness of a CHP unit with piston engine fueled with gas from biomass gasification

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Abstract

This paper presents the results of a thermodynamic and economic analysis concerning the use of gas from gasification of biomass in a cogeneration system with an internal combustion piston engine, working for the needs of a district heating network, with power of 1.5 MW in biomass supplied. The data on the gas generation and purification process were taken from real experiments conducted on a research installation with a fixed bed gasifier at the Institute for Chemical Processing of Coal in Zabrze. Electricity and heat generation efficiency and electric and thermal power of the system were primarily used as indicators of the thermodynamic evaluation. The economic analysis was carried out using discount methods, taking into account the existence of support mechanisms in the form of the colorful certificates. A sensitivity analysis of evaluation indices to the change of selected characteristics was performed.

Keywords: Biomass gasification, CHP units with piston engine, Thermodynamic analysis, Economic efficiency

1. Introduction

Systems using biomass for the production of energy are included in Polish and European Union energy policy guidelines, which promote the use of renewable energy sources (RES), production of energy from local sources and development of distributed energy sources [1–5]. One of the methods of energetic use of biomass is through gasification in gas generators. The resulting combustible gas can be used for energy production in systems combined with a piston engine or gas turbine [6–10]. The use of gas in engines is justified mainly by the relatively low investment cost, high durability and high efficiencies of electricity generation. However, due to the specific properties of the fuels derived from gasification, including in particular their much lower calorific value, combustion engines designed for natural gas and working on synthesis gas often require significant modifications. The biggest problem with the use of gas from gas generator in an internal combustion engine is that it has different properties to natural gas. No less important, since raw synthesis gas contains many contaminants, it fails to meet environmental standards or the allowable levels set by engine producers and must undergo, often expensive, gas purification [11, 12]. On the other hand, such systems can use often cheaper, local sources of biomass (including waste biomass). Moreover, electricity produced in cogeneration from RES qualifies for support in the form of certificates of origin (green and violet certificates), which is an additional source of revenue.

This paper focuses on evaluating the thermodynamic and economic effectiveness of a biomass cogeneration system with power of 1.5 MW in the supplied biomass, integrated with an internal combustion gas engine, working for a district heating network.

2. Characteristics of the analyzed unit

A co-generation system with a piston engine, using gas from biomass gasification for the production of elec-

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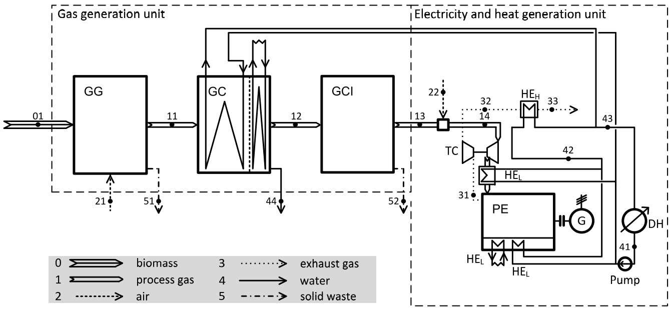

Figure 1: Schematic diagram of the integrated system cooperating with a piston engine installation; denotations: GG—gas generator, GC—gas cooler; GCI—gas cleaning installation; DH—district heating system; HE—heat exchanger (index: H—high-temperature, L—low-temperature); PE—piston engine; TC—turbo-compressor

tricity and heat, was subjected to a thermodynamic analysis. The system cooperates with a district heating (DH) network with a temperature characteristic for the heating season of 90/70°C and maximum heat demand 9 MW. Outside of the heating season water is provided with nominal parameters of 70/40°C, and the heat demand is 2 MW. In the district heating system quality governing is realized, in which instantaneous heat demand $\dot{Q}_x$ (for the instantaneous outside air temperature $t_{o,x}$) depends on the computational outside air temperature $t_{o,cal}$) and nominal heat demand $\dot{Q}_{cal}$ according to the equation (1), while the minimum heat demand in summer period is 2 MW:

$$\dot{Q}_x = \dot{Q}_{cal} \frac{20 - t_{o,x}}{20 - t_{o,cal}} \tag{1}$$

Based on data from the Institute of Chemical Processing of Coal (IChPW) a numerical model of the analyzed cogeneration system was built. The authors' own computational codes were used here as well as commercial software Aspen Plus.

The process gas generation system is based on the GazEla research installation that IChPW developed and intensively expanded in recent years. In the analysis use was also made of data from an experimental, demonstration biomass gasification installation located in the wood processing plant of Galaxia Ltd. Sp. z o.o. in Paruszowice. A detailed description of the gasification technology as well as the results of the analysis conducted on the test stand using gas generator GazEla were presented, among others, in [13–17]. A schematic diagram of the analyzed process gas, electricity and heat generation system, with marked main mass streams, are presented in Fig. 1.

The process gas generation system consists of three main components: the gas generator (GG), gas cooling installation (GC) and gas cleaning installation (GCI). The main product of the gasification and cleaning process is process gas (point 13 in Fig. 1) with parameters enabling use in piston engines integrated with the gas generation system.

Biomass of the following composition is subjected to gasification in the gas generator: moisture 31.1%, ash 2.7%, sulfur 0.03%, carbon 46.6%, hydrogen 5.75%, nitrogen 0.19%, oxygen 40.15% and with a lower heating value of 17.71 MJ/kg (analytical state). The energy efficiency of the gas generator (defined as the ratio of the chemical energy flux of the generated gas and biomass supplied to the generator) is 0.7. The gasification generates process gas with the following molar composition: (H_2)=0.095, (CH_4)=0.0149, (CO)=0.1534, (CO_2)=0.0833, (N_2)=0.4734, (H_2O)=0.1800. The lower heating value of the gas is 3.49 MJ/m_n^3 (3.14 MJ/kg). The gas exits the generator at 560°C, which excludes cleaning with commonly used technologies. Thus, the gas is cooled in a gas cooler to a temperature of approximately 40°C, before entering the gas cleaning installation. As such radical gas cooling requires that a cooling medium with a relatively low temperature be supplied to a heat exchanger, it was assumed that the gas cooler is a two-section heat exchanger. The high-temperature section uses water as a cooling medium. Gas is cooled to a temperature allowing to obtain effectiveness of 90% (methodology for determining effectiveness can be found in [18]). Heat flux obtained in this section of the heat exchanger is, thus, qualified as useful heat. The second section cools the gas to 40°C, but in this case cooling heat is not qualified as useful heat.

The gas cooled to a suitable temperature is introduced into the gas cleaning installation (GCI) operating with an efficiency of 95%. It was assumed that the purification process affects only the gas stream and not its calorific value. The cleaned gas exits the process gas generation installation and is introduced into the electricity and heat generation unit. The main element of this part is a piston engine system.

After leaving the gas cleaning installation the gas is mixed with air and introduced into the turbocharger TC, then the mixture is combusted in the engine. The high-temperature heat from the exhaust gas is used to heat water in the DH system heat exchanger HE_H. Low-temperature heat comes from the cooling of the intercooler of the turbocharger, water jacket and oil sump (HE_L). Heat (both high-temperature and low-temperature) recovered within the engine is used to heat water for the district heating network.

The division of the whole installation into two parts results in the thermodynamic characteristic quantities (such

Table 1: Results of the thermodynamic analysis of the cogeneration system

Quantity	Value
Electric power, kW	360.3
Useful stream of high-temperature heat, kW	291.8
Useful stream of low-temperature heat, kW	201.9
Useful stream of process gas cooling heat, kW	166.6
Chemical energy flux of the gaseous fuel supplied to the engine, kW	997.5
Overall efficiency of the engine	0.8562
Efficiency of electricity generation in gas engine	0.3612
Efficiency of high-temperature heat generation in gas engine	0.2926
Efficiency of low-temperature heat generation in gas engine	0.2024
Overall efficiency of the integrated installation	0.6805
Efficiency of electricity generation in the integrated installation	0.2402
Efficiency of useful heat generation in the integrated installation	0.4403

as efficiencies and heat production) being defined for the piston engine itself and for the integrated system (which includes, apart from the heat received within the engine, the heat received from process gas cooling in the gas cooler).

3. Results of the thermodynamic analysis

In the first round of calculations, the thermodynamic indicators were determined for a gas generator system with power of 1.5 MW in supplied fuel, integrated with a piston engine. The basic relationships for determining the thermodynamic characteristics were used here, of which a detailed description can be found in the literature, among others, in [13–16]. The main results of this analysis are presented in Table 1.

The district heating network served by this system is characterized by considerable variability in the thermal load during the year. Therefore, in the analyses, two variants of calculation were assumed:

- Option I—calculations were carried out for the network operating during the summer season. Water is produced for the heating system with parameters 70/40°C.
- Option II—calculations were carried out for the network operating during the heating season when the DH network characteristic is 90/70°C.

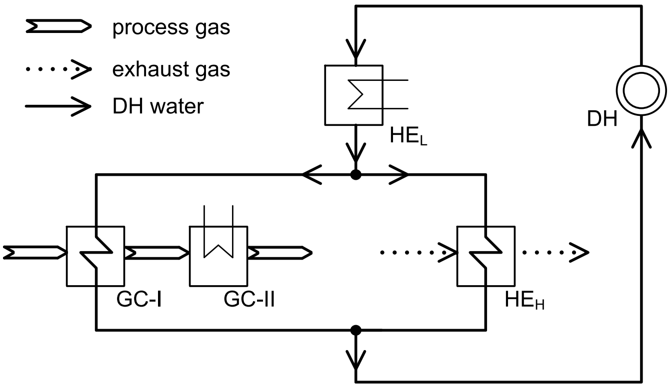

Figure 2: Schematic diagram of heating the return water from DH system

It was also assumed that the system can operate at base supply, or cover the total heat demand.

It was assumed in the analyses that water returning from the district heating network is first heated in the engine cooling system (cooling of the water jacket, oil sump and intercooler of a compressor), and then in high-temperature heat exchangers, i.e., the exhaust gas cooler and process gas cooler (Fig. 1). It was also assumed that composition and gas parameters allow for heat exchangers to be built into the system.

In the first round of calculations, a system was considered that works on the production of heat outside of the heating season. In this case, the water returning from the heating system has a temperature of 40°C. This allows for the use of low-temperature heat sources to preheat the water in the water jacket cooler and oil sump cooler (HE$_L$). Then, in order to maximize the use of cooling heat of the process gas and the exhaust gas, the stream of water is divided into two parts. The first part is directed to the first section of the heat exchanger built on the stream of the process gas (GC-I), while the second part is directed to the heat exchanger built on the exhaust gas stream from the engine (HE$_H$). It was assumed that the split of streams will be chosen in such a way as to ensure that both streams after leaving the heat exchangers have the same water temperature. Then the streams are mixed and go to the district heating network. The aim of the second section of the gas cooler (GC-II) is to cool the process gas down to the temperature required for the purification process (40°C). Heat

Table 2: Results of the analysis of the cooperation of the cogeneration system with the district heating system

Quantity	Value	
	Summer	Winter
Gas temp. at the inlet to 1^{st} section of gas cooler (SG-I), °C	560	
Heat flux received from 1^{st} section of gas cooler, kW	202.2	194.1
Gas temp. at the inlet to 2^{nd} section of gas cooler (SG-II), °C	99.5	124.2
Heat flux received from 2^{nd} section of gas cooler, kW	104.6	112.7
Temp. of the flue gas at the inlet to flue gas-water (HE$_H$) heat exchanger, °C	445.2	
Heat flux received from the flue gas in the HE$_H$, kW	296.1	
Flue gas temperature at the exit of the HE$_H$, °C	120	
Water temp. at the exit from low-temperature heat exchangers HE$_L$, °C	49	76
Water temp. at the exit of SG-I and HE$_H$, °C	70	90
District water flow, kg/s	5.2	7.6
Heat flux delivered to DH network, kW	649.4	635.7

received here is not utilized. A schematic diagram of the system is presented in Fig. 2.

In the next round of calculations, a system working for the production of heat during the heating season was considered. The analysis assumes that the system serves the district heating network, with parameters 70/90°C. For the analysis the same scheme as shown in Fig. 2 was assumed. However, it was assumed that the temperature of the return water from the plant is 70°C.

The most important results of the analyses for both variants of the system with power supplied in biomass at 1.5 MW are presented in Table 2.

4. Economic analysis

The economic analysis of the considered solution was carried out using the NPV discount method (Net Present Value) [13, 19–21]. The analysis assumes that the system produces heat at base supply (annual working time of 6000 h). Capital costs were estimated on the basis of data obtained from IChPW concerning the investment costs incurred for the demonstration installation with power in the fuel supplied at 1.5 MWt. It was assumed in the calculations that the total investment cost is 4.92 million PLN, including PLN 200,000 for the biomass supply installation, PLN 1.5 million for the biomass gasification system, PLN 300,000 for the purification and cooling installation for the synthesis gas, PLN 600,000 for piston engine assembly, PLN 600,000 for automatics and electrical engineering and approximately PLN 800,000 for other costs.

Table 3: Results of the economic analysis for a 1.5 MW system working for a DH network

Quantity	Biomass price, PLN/GJ			
	15	20	25	30
NPV, mln PLN	2.160	0.847	-0.508	-2.031
IRR, %	11.19	8.26	4.88	0.43
NPVR, -	0.439	0.172	-0.103	-0.413

In the cash flows the fuel purchase cost is an important element. The analysis assumes that nominal unit price of biomass together with supply is 30 PLN/GJ.

On the basis of information from the Energy Regulatory Office [22] it was assumed in the calculations that the selling price of electricity is 201.36 PLN/MWh (the average selling price on a competitive market) and the selling price of useful heat 44.95 PLN/GJ. Additional financial benefits arise from obtaining certificates of origin from renewable energy sources (green certificates), for which the price was assumed at 253.31 PLN/MWh (average price of property rights of the PMOZE_A type, all transactions in 2012 [23]), and violet certificates at a price of 59.51 PLN/MWh.

Additionally, the analysis assumes that the lifetime of the system is 20 years, and the installation works 6000 hours per year. It was assumed that the investment is 50% financed from internal resources and 50% from a commercial loan with an interest rate of 6.5% and repayment period of 10 years. For calculations, the discount rate was assumed at 6.2%. Additional costs were also assumed, such as the unit cost per unit of water supply and sewage disposal (2.5 and 6 PLN/m^3, respectively), unit operating costs (2 PLN/MWh), unit costs of repair (2% of the investment cost), unit cost of the purchase of non-energy products (1.5 PLN/MWh), unit cost of using the environment (0.3 PLN/GJ$_{pg}$), unit cost of insurance (0.5% of expenditures), and unit costs of work (together 22,000 PLN/month). The exchange rate is PLN 4.185 per € 1.

For such assumptions the basic economic indicators were determined (NPV, IRR, NPVR) as a function of biomass price. These quantities are summarized in Table 3.

Fig. 3 shows the results of calculations depicting the revenue structure in a system with a capacity of 1.5 MW. The analysis shows that the sale of heat has the largest

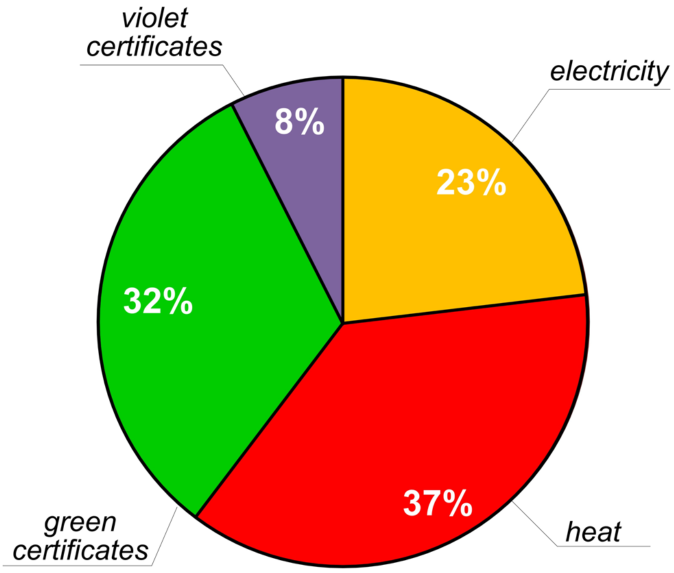

Figure 3: Revenue structure for a cogeneration unit with biomass gasification with the power of 1.5 MW in fuel supplied

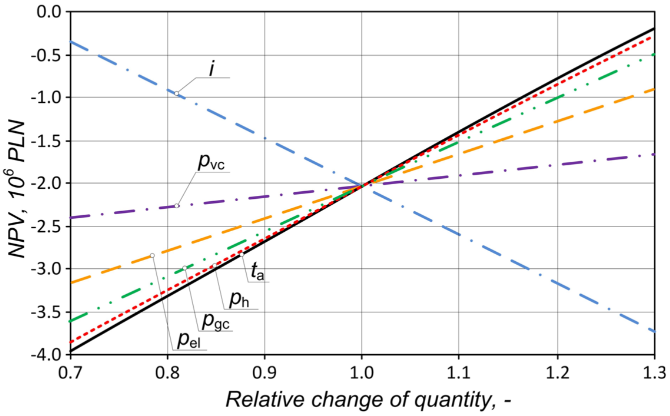

Figure 4: Influence of the selected quantities on the NPV index for biomass priced at 30 PLN/GJ

share of the revenue (37%) followed by the sale of property rights arising from green certificates (32%).

Figures 4 and 5 show the results of the sensitivity analysis for the system, reflecting the influence of a change in the price of electricity (p_{el}), price of heat (p_h), price of green certificates (p_{gc}), price of violet certificates (p_{vc}), investment costs (i) and annual operating time (t_a) on the NPV index. Changes of nominal values were considered in the ranges ±30%, for different prices of fuel, i.e., 30 PLN/GJ and 20 PLN/GJ.

The analysis shows that for the adopted assumptions and biomass prices at the level of 30 PLN/GJ it would be very difficult to obtain profitability for the analyzed system. With cheaper biomass (20 PLN/GJ) economic indicators reach positive values over a wide range of changes.

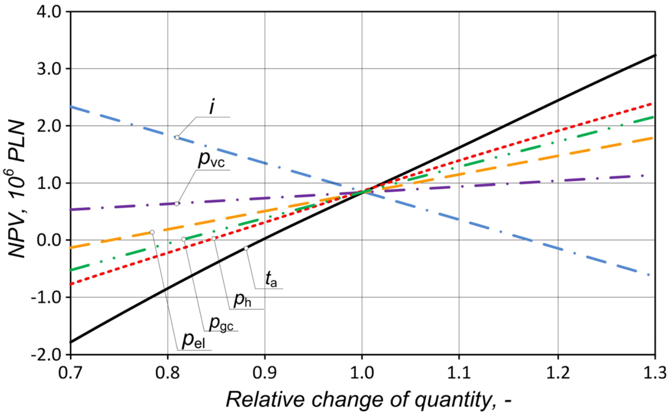

Figure 5: Influence of the selected quantities on the NPV index for biomass priced at 20 PLN/GJ

Impacting the profitability of the investment most are: annual operation time, investment costs and the sale price of heat. It can be expected that with the commercialization of the technology, unit investments in the system will decrease and disposability will increase, which will significantly improve the economic indicators. Obtaining cheaper biomass (including waste biomass) is of crucial importance. The analyses show that if biomass can be purchased 7 PLN/GJ cheaper than nominally assumed price (30 PLN/GJ), the performance indicators reach positive values.

5. Summary and conclusions

The analyses presented in this paper concerned the possibility and profitability of using gas from biomass gasification in the system for generation of electricity and heat using a piston engine. The system with a capacity of 1.5 MW in supplied biomass operates for the needs of the district heating network, while the electricity generated in the system is sold to the grid. For the purpose of the work a mathematical model of the system under consideration was constructed, enabling a thermodynamic analysis to be performed. The results of the thermodynamic analysis formed the basis for the profitability assessment.

The thermodynamic analysis showed that the cogeneration system under consideration is characterized by the overall efficiency of the installation integrated with a gas generator which is 68.05% (overall efficiency of the engine itself: 85.62%), which results in the generation of electricity with the efficiency of 24.02% (36.12% in the engine). Thus, the system with the power output at 1.5 MW in biomass can cover about one third of the heat demand for district heating network in the summer and about 15% of the heat demand during winter (heating season).

The results of the economic analysis show that the systems using gas from biomass gasification can be characterized by positive economic indicators (NPV, IRR, NPVR). It should be noted, however, that it is very important here to adopt, among others, proper assumptions regarding the unit investments on such systems. No less important is the possibility of obtaining cheaper biomass and keeping the installation operating for as long as possible during the year.

The sensitivity analysis shows primarily the importance of the effect of changes in the investment costs and the prices of color certificates on the profitability of the investment. Studies show that, in the absence of a support mechanism in the form of certificates of origin, it will be difficult to get positive values for the economic indicators. Systems with a piston engine (which from a technical point of view seems the most rational way of using low-calorific gas from biomass gasification) can be used for the production of electricity in distributed systems, based on local sources of waste (thus, cheap) biomass. In such a case, they would be characterized by positive values of NPV indicators.

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