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ENERGY CROPS AS LOCAL ENERGY CARRIER

ROŚLINY ENERGETYCZNE JAKO LOKALNY NOŚNIK ENERGII

Abstract: The experimental investigation of energy crops (*Miscanthus* x *giganteus, Sida hermaphrodita, Spartina pectinata, Panicum virgatum*) gasification was carried out. The influence of excess air ratio (λ) on lower heating value (*LHV*) was investigated. Downdraft fixed bed gasifier was used. For all types of biomass, the highest *LHV* value was achieved for λ = 0.18. Compositions of gases obtained during the experimental study were used for thermodynamic and economic analysis of CHP system with gas piston engine. The system quality indices and input data for economic analysis were calculated. For the economic analysis the net present values method was adopted. Given the assumptions, despite biomass type, the *NPV* indice did not reach positive values. Break even price of electricity and break even cost of fuel were calculated. The economic viability of such systems is strongly influenced by economic and legal environment. The paper includes sensitivity analysis of change of the selected parameter such as annual availability of the system, price of fuel and price of green certificates.

Keywords: biomass, gasification, cogeneration, energy crops, gas piston engine

Introduction

Energy crops are in the area of interest because of multiple ways of advantageous utilization. They can be used for biofuels (solid, liquid and gaseous) and biocomponents production. Examples of commonly used plants are *Salix* L., *Miscanthus* x *giganteus, Spartina pectinata*, *Panicum virgatum*, *Sida hermaphrodita*, *Rosa multiflora* [1].

In Poland, agro-biomass is not widely used, which becomes a reason for underdeveloped cultivation techniques, lack of methods of preventing crop diseases and other detrimental external factors. That has a great impact on the volume of production and the quality of fuel. Other factors that affect an agro-fuel production are soil fertility, quality of agricultural treatment and field preparation (*eg* number of weeds). However, the current state of the Polish agro-energy sector gives number of opportunities for relatively easy and quick progression.

Energy crops utilization can be useful in more than one field. Phytoremediation is one of the techniques used for remediation of contaminated areas. Soil contamination can be found close to landfills, heavy-metal/oil industry areas. There are energy crops which can be grown on contaminated areas and have a potential to accumulate contaminants. The reasonable method of contaminated biomass utilization is gasification [2].

Gasification is a thermo-chemical conversion of solid feedstock into a gaseous fuel. Because of the low amount of the oxidizer used in the process and the reducing atmosphere, gasification prevents sulphur and nitrogen oxides emission, also it is possible to accumulate part of the contaminants in the solid residues. Gasification is a way to utilize contaminated biomass while useful syngas is produced. Syngases are mostly low-calorific gases (depends

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on the feedstock and gasification agent) that can be used in power boilers, industrial furnaces, gas turbines or piston engines [3]. Biomass gasification gases, as a fuel that might be received from local energy sources shows a great potential as fuel for combined heat and power (CHP) plants [4]. Combined heat and electricity generation in distributed energy systems with internal combustion piston engines is a good option for local communities due to a relatively low investment cost and the high efficiency of electricity production. What is more, the market of commercial solutions for low-calorific value gases (*eg* biogas, syngas) is constantly growing [5].

In this study the experimental investigation of four types of energy crops gasification was carried out. Compositions of gases obtained during the experimental study were used for thermodynamic and economic analysis of CHP system with gas piston engine.

Feedstock and apparatus

Four types of energy crops were gasified: *Miscanthus* x *giganteus*, *Sida hermaphrodita*, *Spartina pectinata* and *Panicum virgatum*. Picture of the feedstock samples is presented in Figure 1. Main properties of the studied plants are presented in Table 1.

Table 1

Properties of the analyzed energy crops (dry basis)

	Unit	***Miscanthus* x *giganteus***	***Sida hermaphrodita***	***Panicum virgatum***	***Spartina pectinata***
C	[%]	46.6	44.8	45	45.8
H	[%]	7.16	7.4	6.9	7.28
N	[%]	0.16	0.37	0.55	0.26
S	[%]	1.35	1.4	1.43	1.45
O	[%]	44.73	46.03	46.12	45.21
Cl	[ppm]	417.4	98.3	343.4	174.4
Pb	[ppm]	35	56.84	88.96	92.66
Cd	[ppm]	1.55	5.2	1.34	1.25
Zn	[ppm]	83.28	146.5	122.4	147.7
Ash	[%]	1.36	2.6	3.23	3.24
Volatiles	[%]	75.4	78.8	78.1	77.5
Moisture	[%]	7.6	9	8.5	8
LHV_{bio}	[MJ/kg]	19.45	19	18.35	19.29

Fig. 1. Samples of gasified energy crops

The experimental study was conducted using laboratory-scale fixed-bed gasification facility. The scheme of the installation is shown in Figure 2.

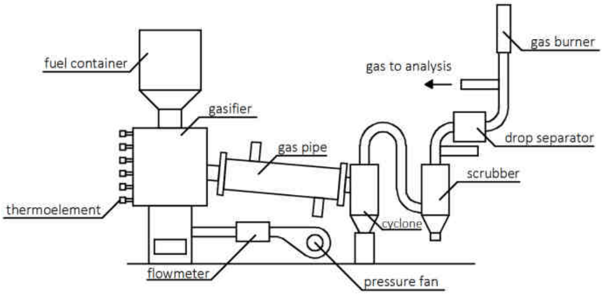

Fig. 2. Scheme of the gasification installation

The main part of the system is a fixed-bed gasifier with the maximum weight of the feedstock of 5 kg. The gasified material was fed into the reactor form the fuel container above. Gasification agent (air) was fed from the bottom by pressure fan. Air flowmeter allows to set the desirable air excess ratio in the gasifier. Produced gas passes basic gas cleaning equipment and the sample to analysis is taken. The internal temperature profile in the reactor is measured by six thermoelements located along the vertical axis of the reactor.

There are four main zones in the reactor: drying zone (water is evaporated), pyrolysis zone (thermal decomposition to volatiles and solid char), reduction zone (where main combustible gas components are produced) and combustion zone (where part of the biomass is combusted to generate heat for endothermic reactions).

Gasification process was carried out for six air excess ratios: 0.12, 0.14, 0.16, 0.18, 0.23, 0.27.

Results of experimental investigation

Figure 3 shows the dependence of lower heating values (*LHV*) on air excess ratio in reactor during the gasification. Gas with the highest *LHV*, 3.68 MJ/m^3_n, was produced using *Miscanthus* x *giganteus*. It can be seen that for particular type of biomass there is a certain range of the lower heating value of the syngas that can be obtained in the gasification process. Also, there is an optimal air excess ratio for studied energy crops gasification (the highest *LHV*). It is caused by the best thermal conditions for endothermic reactions that result in CO, CH_4 and H_2.

The lower heating value depends on the amount of combustible gases in the syngas. The main combustible gas in the syngases is carbon oxide. Figure 4 shows molar fraction of the main components of the gases for the optimum air excess ratio $\lambda = 0.18$, but the relation between the amount of particular compounds was similar for the air ratios used in the experiment. Also, minor differences in the gas compositions are related to minor differences in biomass composition. Analyzing this figure it can be confirmed that the gas with the highest *LHV* consists of the highest amount of CO and CH_4.

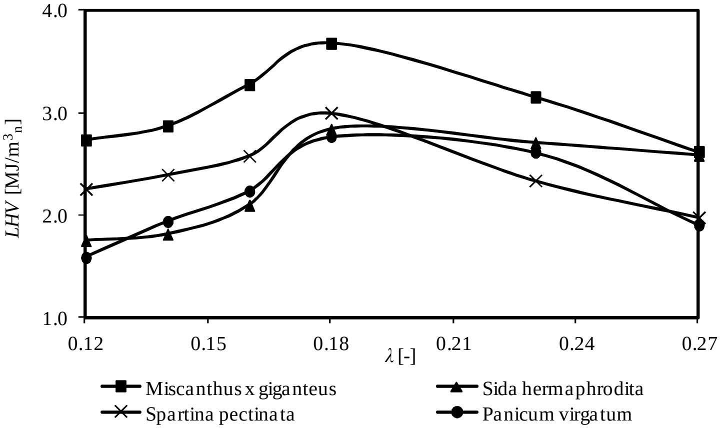

Fig. 3. Dependence on the lower heating value as a function of air excess ratio

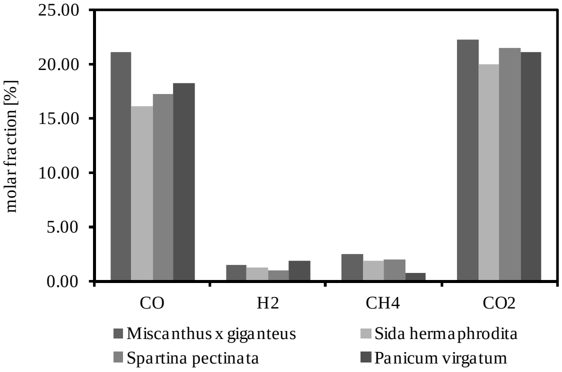

Fig. 4. Molar fraction of main components of produced gas (λ = 0.18) for all types of energy crops

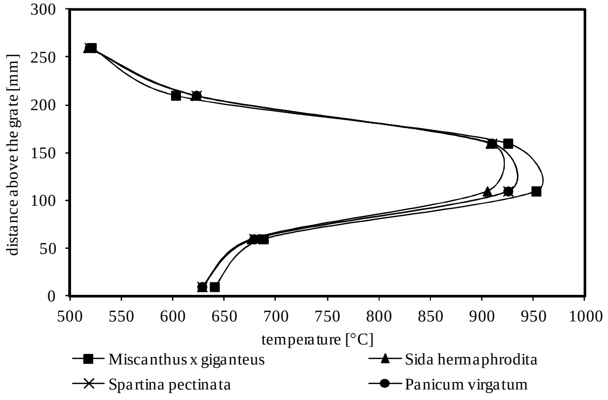

Fig. 5. Temperature profiles for λ = 0.18

Temperature in the gasifier is an important parameter, which allows to define where the particular zones of gasifier are. Figure 5 shows the temperature profile in the reactor (λ = 0.18). Despite the biomass type, the highest temperature is about 110 mm above the grate where the oxidation zone is located. This zone generates heat for the drying, devolatilization and endothermic gasification reactions.

Energetic analysis of the CHP system with gas piston engine

Calculations of CHP unit were based on the gas compositions delivered by the experimental investigation. Gas compositions with the highest *LHV* for each type of biomass were used.

Most manufacturers of gas piston engines for CHP systems does not provide detailed information about engines parameters fuelled with alternative fuels *eg* low-calorific value gases. Common way is to use the indicators describing the relative change in the engine parameters. For the purpose of the analysis, the indicators were adopted following [5] and defined by equations (1) and (2). The indicators are ratios of the parameter with alternative fuel to the parameter with nominal fuel. The indicator of the relative change in the electricity generation efficiency was defined as:

$$c_\eta = \frac{\eta_{el}}{\eta_{el}^*} \tag{1}$$

The indicator of the relative change in exhaust gas temperature was defined as:

$$c_{T_{sp}} = \frac{T_{sp}}{T_{sp}^*} \tag{2}$$

The superscript “*” refers to the values of characteristics of the engine operating at nominal conditions.

For the calculations the following values of the indicators was assumed: c_η = 0.909, $c_{T_{sp}}$ = 0.979 [5].

The database of the engines available on the Polish market (with electric power under 2.2 MW) was created. The transition functions that allow to estimate the electricity generation efficiency and the exhaust gas temperature as a function of nominal electric power were made. The functions are described by the equations:

$$T_{sp}^* = 618.07 \cdot {N_{el}^*}^{-0.043} \tag{3}$$

$$\eta_{el}^* = 0.2967 \cdot {N_{el}^*}^{0.0468} \tag{4}$$

For all types of syngases, thermal efficiency of the engine was calculated. The thermal efficiency describes the potential of generating useful heat. Heat produced within gas piston engine can be classified into two groups: high- and low-temperature heat. Low-temperature heat is obtained from the engine body and intercooler of the turbocharger. High-temperature heat is generated in the heat exchanger powered with exhaust gases. It was assumed that the efficiency of low-temperature heat generation is the same as with the nominal fuel.

To determine the high-temperature generation efficiency, it is necessary to calculate the amount of heat obtained from the heat-exchanger which is expressed by the following formula:

$$\dot{Q}_h = \dot{m}_{sp} \cdot \eta_{he} \cdot (h_{32} - h_{33}) \tag{5}$$

The efficiency of the heat exchanger (η_{he}) in equation (5) was assumed at 98%. Calculations of the enthalpy for semi-deal gas at points 32 and 33 require the knowledge of the exhaust gas composition and its temperature. Exhaust gas temperature was calculated using equations (2) and (3). Exhaust gas composition comes from stoichiometric calculations wherein the following assumptions were made: combustion is complete, air excess ratio is $\lambda = 1.5$ and the fuel is syngas with the highest *LHV* for each type of biomass. Temperature of the exhaust gas leaving the heat exchanger was assumed at 120°C.

For the annual biomass consumption the gasification efficiency was needed. Cold gasification efficiency was defined as follows:

$$\eta_{CGE} = \frac{\dot{E}ch_{LCVG}}{\dot{E}ch_b} = \frac{\dot{m}_{LCVG} \cdot LHV_{LCVG}}{\dot{m}_{bio} \cdot LHV_{bio}} \tag{6}$$

Assuming the cold gasification efficiency at 60%, the mass stream of used biomass was calculated.

The overall performance of the CHP system integrated with biomass gasification is characterized by several indices:

- Energy Utilization Factor *EUF*:

$$EUF = \frac{N_{el} + Q}{E_{ch_b}} \tag{7}$$

- Cogeneration index σ:

$$\sigma = \frac{N_{el}}{Q} \tag{8}$$

- Primary Energy Saving index *PES*:

$$PES = \left(1 - \frac{1}{\frac{\eta_{qe}}{\eta_{refe}} + \frac{\eta_{qc}}{\eta_{refc}}}\right) \cdot 100\% \tag{9}$$

- Energy Replacement Index *ERI* [6]:

$$ERI = \frac{EUF - \eta_{el}}{\eta_{Ek}} + \frac{\eta_{el}}{\eta_{el,ref}} \tag{10}$$

According to the methodology described earlier, thermodynamic analysis for CHP unit with electric power N_{el} = 500 kW and electricity generation efficiency η_{el} = 38% was made. Results of the analysis are presented in Table 2.

Table 2

The results of energetic analysis for CHP system integrated with biomass gasification

Quantity	**Unit**	***Miscanthus* x *giganteus***	***Sida hermaphrodita***	***Spartina pectinata***	***Panicum virgatum***
Q	[kW]	658	711	697	711
η_q	[%]	0.5	0.54	0.53	0.54
LHV_g	[MJ/m^3_n]	3.679	2.838	3.000	2.769
LHV_{bio}	[MJ/kg]	19.45	19	19.29	18.35
EUF	[%]	53	55	55	55
PES	[%]	42	43	43	43
ERI	[GJ/GJ$_{bio}$]	0.84	0.91	0.89	0.91
σ	[-]	0.76	0.70	0.72	0.70

The results of calculations match the data available in the literature [4, 7]. Systems fuelled with gases obtained from *Sida hermaphrodita* and *Panicum virgatum* present the highest value of thermal efficiency (54%) what effects in the highest value of the *ERI* = 0.91 GJ/GJ$_{bio}$. The *EUF* and *PES* index are similar for most energy crops, the only exception is system fuelled with *Miscanthus* x *giganteus* syngas, with the indices lower by 2 and 1 percentage point respectively. The same system presents the highest value of cogeneration index $\sigma = 0.76$.

Methodology of economic efficiency analysis

One of the commonly used indicators of economic efficiency is a Net Present Value (*NPV*) described by the following formula [8]:

$$NPV = \sum_{t=0}^{t=n} \frac{CF_t}{(1+r)^t} \tag{11}$$

The *NPV* depends on the net cash flow (CF_t), the discount rate (r) and the number of working years (n). The net cash flow can be determined as:

$$CF_t = \left[-J + S - \left(K_{op} + P_d + K_{obr}\right) + A + L\right]_t \tag{12}$$

where J is the investment cost, S is the value of sold production (electricity and heat), K_{op} is the operating cost, P_d is the income tax, K_{obr} is the change of working capital (not considered in this work), A is the amortization, L is the salvage value of the company [10].

Using the *NPV* as an indicator of economic efficiency allows to calculate a Break Even Point [8], which, for the purpose of this analysis can be defined as the minimum price of the electricity (k_{el}^{BE}) or the maximum price of the biomass (k_{bio}^{BE}), from the condition:

$$NPV = 0 \tag{13}$$

Investment cost formulas were adopted from [7]. Total investment cost of the installation consists of the gasification system (gasifier with the gas cleaning unit) cost and the CHP system cost. Unit investment cost of the gasification system, expressed in €/kW, can be estimated using following equation:

$$i_{GU} = -59.72 \ln(\dot{E}_{ch_b}) + 895.95 \tag{14}$$

and the unit CHP system cost, expressed in €/kW$_{el}$, can be described by the equation:

$$i_E = -144.80 \ln(N_{el}^*) + 1802.87 \tag{15}$$

The unit cost of biomass was assumed to be 246 PLN/Mg which can also be expressed in PLN for gigajoule of chemical energy: *Miscanthus* x *giganteus* 12.65, *Sida hermaphrodita* 12.95, *Spartina pectinata* 12.75, *Panicum virgatum* 13.41. The delivery cost for 100 km transportation distance was assumed to be 20 €.

Table 3

Fuel annual consumption for all energy crops

Quantity	**Unit**	***Miscanthus* x *giganteus***	***Sida hermaphrodita***	***Spartina pectinata***	***Panicum virgatum***
Syngas annual consumption	[m^3]	7,725,000	10,014,000	9,474,000	10,264,000
Biomass annual consumption	[Mg]	2,435	2,493	2,456	2,581

Table 3 shows the biomass annual consumption, Table 4 shows selected assumptions for economic analysis of all types of studied biomass.

Table 4

Selected assumptions for the economic analysis

Specification	Unit	Value
Annual working time	[h]	6,000
Exploitation time	[years]	15
Construction time	[years]	1
Share of own resources	[%]	35
Share of commercial credit	[%]	65
Commercial credit rate	[%]	6
Payback time of the commercial credit	[years]	7
Income tax rate	[%]	19
Discount rate "*r*"	[%]	5
Depreciation rate	[%]	6.67
Investment cost	[PLN]	5,776,000
Gasification system	[€/kW$_{bio}$]	436
CHP system	[€/kW$_{el}$]	903
Exchange rate	[PLN/€]	4.1
Number of employees	[pers.]	2
Monthly salary including related cost	[PLN/pers./m]	4,000
Cost of using the CHP system (% of the investment cost)	[%]	1
Unit cost of repair (% of the investment cost)	[%]	2
Unit cost of water	[PLN/GJ]	0.13
Unit cost of sewage treatment	[PLN/GJ]	0.02
Unit price of the sale of useful heat	[PLN/GJ]	30
Unit price of the sale of electricity	[PLN/MWh]	160
Green certificate price	[PLN/MWh]	114
Yellow certificate price	[PLN/MWh]	115

Results of economic efficiency analysis

According to methodology described earlier the economic analysis of the CHP system with gas piston engine integrated with biomass gasification was made. Figure 6 shows the values of the Net Present Value for all systems fuelled with all types of produced gas which did not reach positive values. Given the assumptions, the smallest loss after fifteen years of operation was achieved for the installation fuelled with *Spartina pectinata*. However, there is an important element which may strongly influence these calculations. In this work, the gas cleaning unit was considered as a part of the gasification system and the investment cost was calculated with the unit cost method. Systems have different annual gas consumptions which may strongly influence the investment and operating costs of the gas purification installation.

Results of the Break Even Point calculations are presented in Tables 5 and 6. Break even price of electricity represents the minimum price of the product that prevents the investment from being unprofitable (which relates also to the break even price of biomass as the maximum price of fuel).

The economic viability of such systems is strongly influenced by economic and legal environment. The sensitivity analysis of selected parameters on the break even price of electricity was carried out. The following parameters were selected for the analysis: annual operating time of the system (τ), price of the fuel (K_{bio}), price of the green certificates (K_{cert}). The parameters varied in the range of –20 to +20% relative to the values assumed in previous calculations. Results of the sensitivity analysis are presented in Figure 7. Figure 7 was drawn for *Spartina pectinata* but the same dependencies were noticed for the remaining energy crops.

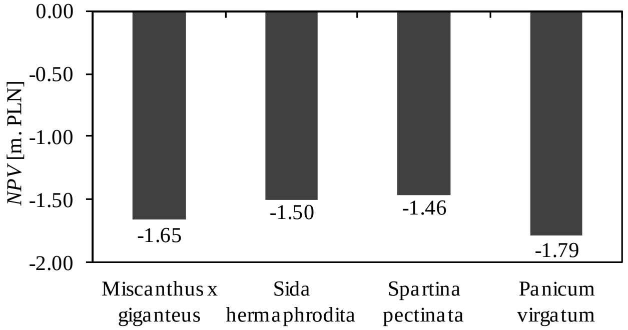

Fig. 6. The values of the *NPV* indicator for studied cases

Table 5

Break even price of electricity

Quantity	Unit	***Miscanthus* x *giganteus***	***Sida hermaphrodita***	***Spartina pectinata***	***Panicum virgatum***
k_{el}^{BE}	[PLN/MWh]	221.82	216.22	214.83	226.88

Table 6

Break even cost of biomass

Quantity	Unit	***Miscanthus* x *giganteus***	***Sida hermaphrodita***	***Spartina pectinata***	***Panicum virgatum***
k_{bio}^{BE}	[PLN/GJ]	9.12	9.74	9.63	9.59

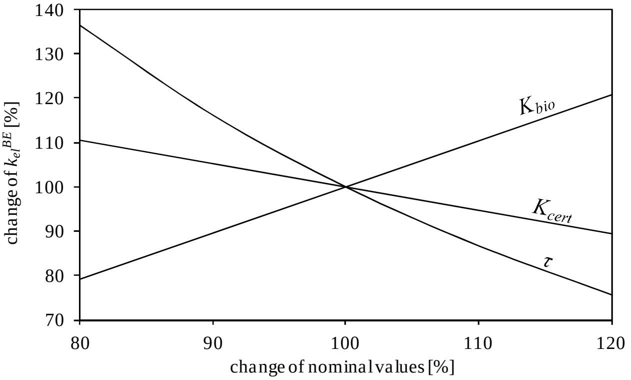

Fig. 7. Results of the sensitivity analysis for the CHP unit fueled with the *Spartina pectinata* syngas

The analysis shows that the most influential factor is annual working time. It was assumed that the installation operates 6,000 hours a year because of the limited availability of an innovative technology. Break even price of electricity decreased by 24.4 percentage points when the operating time was extended to 7,200 hours. Change of the price the biomass influenced the change of k_{el}^{BE} in the range of ±20.8%. Change of the price of the green certificates caused the change of k_{el}^{BE} in the range of ±10.6%.

Conclusions

Utilization of energy crops gasification gas as a fuel for CHP system with gas piston engine analysis was carried out. The influence of air excess ratio on the lower heating value was investigated. The results shows there are optimal conditions of the gasification process - in this case the amount of the gasification agent. For all types of biomass, the maximum value of the *LHV* was achieved for $\lambda = 0.18$. The theoretical part of the work consists of the energetic effectiveness indices calculations of the CHP unit and its economic analysis. The thermodynamic calculations were focused on determining the streams of electricity and useful heat produced in the system and the annual consumption of the biomass. These quantities allow to carry out the economic analysis. None of the presented system reach the positive value of the *NPV*. However, it was assumed that the systems operate 6,000 hours per year as the CHP unit integrated with biomass gasification is an innovative technology and it is not validated in many real facilities. The sensitivity analysis shows that annual operating time is very important factor of changing the values of economic indices. The advantage of the energy crops utilization is the phytoremediation process. The environmental aspects of such technology may provide support mechanisms that will have strong impact on the economic effectiveness.

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Abstrakt: Przeprowadzono badania eksperymentalne wieloletnich roślin energetycznych (miskanta olbrzymiego, ślazowca pensylwańskiego, spartyny preriowej, prosa rózgowatego) oraz określono wpływ stosunku nadmiaru powietrza w reaktorze na wartość opałową gazu palnego. Wykorzystano reaktor dolnociągowy ze złożem stałym. Najwyższą wartość opałową gazu uzyskano dla λ = 0,18 niezależnie od rodzaju biomasy. Składy otrzymanych gazów posłużyły do obliczeń termodynamicznych i ekonomicznych układu kogeneracyjnego z gazowym silnikiem tłokowym. Wyznaczono wskaźniki efektywności energetycznej układu CHP oraz szereg danych wejściowych do analizy ekonomicznej. Rachunek ekonomiczny przeprowadzono w oparciu o metodę wartości zaktualizowanej netto. Dla założeń przyjętych w obliczeniach dla układów zasilanych wieloletnimi roślinami energetycznymi nie uzyskano dodatnich wartości wskaźnika *NPV*. Wyznaczono graniczne ceny sprzedaży energii elektrycznej oraz graniczne ceny pozyskania biomasy z warunku *NPV* = 0. Efektywność ekonomiczna instalacji zasilanych biomasą silnie zależy od otoczenia ekonomiczno-prawnego, dlatego przeprowadzono analizy wrażliwości granicznej ceny sprzedaży energii elektrycznej ze względu na czas pracy instalacji, koszt pozyskania paliwa oraz cenę zielonych certyfikatów.

Słowa kluczowe: biomasa, zgazowanie, kogeneracja, rośliny energetyczne, gazowy silnik tłokowy