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PROFITABILITY ASSESSMENT OF LOW-POWER COMBINED HEAT AND POWER SYSTEMS IN AGRICULTURE

Summary

The article assesses the profitability of investment in low-power CHP systems in an agricultural holding. This assessment pertains to three CHP units, it is units powered by a Stirling engine, equipped with a microturbine, and powered by a piston internal combustion engine. The assessment is based on the assumption that all electric power and heat generated will be used by the agricultural holding for its own purposes. For comparison, the results of calculations, including the depreciation of investment in the CHP system, were compared with the costs of purchasing electric power and heat from external providers.
***Key words**: CHP unit, economic evaluation, microturbine, piston internal combustion engine, Stirling engine*

OCENA OPŁACALNOŚCI ZASTOSOWANIA UKŁADÓW KOGENERACYJNYCH MAŁYCH MOCY W ROLNICTWIE

Streszczenie

W artykule przedstawiono ocenę opłacalności inwestycji w układy CHP małych mocy w gospodarstwie rolnym. Ocenie tej poddano trzy agregaty kogeneracyjne, tj. agregaty z silnikiem Stirlinga, z mikroturbiną oraz z tłokowym silnikiem spalinowym. Do oceny przyjęto założenie, że cała wytwarzana energia elektryczna i ciepło wykorzystywane będą na potrzeby własne gospodarstwa. Dla porównania wyniki obliczeń, w tym czas amortyzacji inwestycji w układ kogeneracyjny, zestawiono z kosztami zakupu energii elektrycznej i ciepła z zewnątrz.
***Słowa kluczowe:** agregat kogeneracyjny, ocena ekonomiczna, mikroturbina, tłokowy silnik spalinowy, silnik Stirlinga*

1. Introduction

The generation of heat and electric power in high-performance combined heat and power systems is one of the ways that enable adapting to the increasingly stringent laws and regulations concerning the emission of pollutants into the atmosphere, which determine the development of renewable energy sources and force the reduction of the consumption of fossil fuels, and thus save primary energy [5, 20].

The low-power CHP systems enable constructing heat and power plants that are very precisely tailored to the needs of even the smallest customers, as the heat and electric power produced by them are primarily supplied to local consumers, covering energy requirements of the facilities where such systems are installed. Excess of heat and electric power can be stored in specially selected batteries or, particularly in case of electric power, sold to the grid or other local consumers [2, 5]. Under such operating conditions, the ratio of electric power and useful heat produced and used on site to the amount of energy supplied together with fuel equals to 75-85%. It is also essential that such systems can be powered by liquid and gaseous local biofuels, hence the combination of low-power CHP systems with local biogas plants may significantly reduce the emission of pollutants into the atmosphere and reduce the consumption of primary fuels [5, 6].

The objective of the study was to assess the profitability of investment in low-capacity CHP systems in a standard agricultural holding.

2. Research methodology

To assess the profitability of investment in low-power CHP systems in an agricultural holding, there were employed three CHP units, it is units powered by a Stirling SD4-E engine, equipped with a Capstone C30 microturbine, and powered by a Tedom Micro T30 piston internal combustion engine. The selection was based on currently available technologies applied in low-power CHP systems, in which various types of thermal engines are used as a source of power. It was also essential to introduce innovative technologies such as microturbines [5, 7, 13] and Stirling engines [12].

A significant parameter was the power generated by the CHP systems adopted for assessment. As for piston internal combustion engines, there is no problem with power selection as - due to the popularity of their construction technology - it is easily possible to select units with power capacities ranging from a few to several hundred kW. As far as microturbines are concerned, only models with a power of 15 kW, 30 kW, 65 kW, 100 kW and 200/250 kW are available in the market [13]. A significant problem is the selection of Stirling engines, as currently the largest commercially available Stirling engine reaches the power of 55 kW, and most of the offered CHP units with these engines reach the power of 1-10 kW [12]. As a result of the analysis of CHP systems available in the market, 30 kW power systems were evaluated.

The assessment was based on the assumption that the selected CHP systems would operate in agricultural holdings with greenhouses or other types of facilities requiring large amounts of heat, with an average annual electric power consumption of 245,000 kWh_e and an average heat consumption of 525,000 kWh_{th}. It was also presumed that all electric power and heat generated would be used by the agricultural holding for its own purposes. As for any surpluses of electric power and heat, consideration could be given, for example, to their storage or supply to neighbouring agricultural holdings. At this stage, however, the resale of electric power to the grid was not taken into account, as the CHP unit was assumed to operate in the island mode [4].

For calculations, it was estimated that the units would be powered by high-methane natural gas, type E (GZ-50) with a calorific value of $W_d = 31\ MJ \cdot m^{-3} = 39{,}744\ kJ \cdot kg^{-1}$ (assumed gas density $\rho = 0.78\ kg \cdot m^{-3}$). The operating time of the units was considered to be equal to 7,500 hours per annum. In calculations the price for natural gas without fixed costs amounted to PLN 1.35 per m^{-3} and the purchase price of electric power amounted to PLN 0.50 per kWh_e^{-1}.

Given that CHP units generate electric power and useful heat, the cost of producing 1 kWh of useful heat was reduced by the value of electric power produced at the same time. Therefore, the economic value of 1 kWh of electric power generated by CHP units was assumed to be equal to the price for electric power purchased from the grid.

The cost of generating 1 kWh of useful heat k_{th} was calculated from the following equation (1):

$$k_{th} = \frac{\dot{V}_g \cdot price_g}{N_{th}} \quad [PLN \cdot kWh_{th}^{-1}] \qquad (1)$$

where:

$\dot{V}_g$ - gas consumption $[m^3 \cdot h^{-1}]$,

$price_g$ - price of natural gas, $[PLN \cdot m^{-3}]$,

N_{th} - thermal power, $[kW_{th}]$.

However, the cost of generating 1 kWh of useful heat less the value of simultaneously generated electric power K_{th} was calculated from the following equation (2):

$$K_{th} = k_{th} - price_e \cdot \frac{N_e}{N_{th}} \quad [PLN \cdot kWh_{th}^{-1}] \qquad (2)$$

where:

k_{th} - cost of generating 1 kWh of useful heat, $[PLN \cdot kWh_{th}^{-1}]$,

$price_e$ - price of purchasing electric power, $[PLN \cdot kWh_e^{-1}]$,

N_e - electric power, $[kW_e]$,

N_{th} - thermal power, $[kW_{th}]$.

On the other hand, the annual profit on electric power generation Z_{we} was calculated from the following equation (3):

$$Z_{we} = N_{we} \cdot price_e \quad [PLN] \qquad (3)$$

where:

N_{we} - quantity of generated electric power, $[kWh_e]$,

$price_e$ - price of purchasing electric power, $[PLN \cdot kWh_e^{-1}]$.

The Stirling engine, due to its specific operating conditions (e.g. exhaust fumes leave the combustion chamber at a temperature of about 1200°C), generates much more useful heat that can be used to heat additional greenhouses or to dry more crops or can be transferred to neighbouring agricultural holdings. The additional quantity of useful heat is about 75 kW_{th}. The profit from generating this additional heat can be estimated, considering that gas air heaters will be employed to heat additional greenhouses or to dry more crops, hence the analysis requires the use of two additional stationary air heaters with fume exhaust and a gas burner WD 30 [16] with a nominal power of 38.5 kW each and powered by propane-butane gas. In the calculations, the annual operating time of the heaters was 7,500 hours, the fuel consumption of one heater equalled to 3.3 $l \cdot h^{-1}$, and the price of propane-butane gas amounted to 2.21 $PLN \cdot l^{-1}$.

The additional annual profit on useful heat Z_{dc} was calculated from the following equation (4):

$$Z_{dc} = 2 \cdot (ZP_n \cdot price_p) \quad [PLN] \qquad (4)$$

where:

ZP_n - annual fuel consumption of one heater, $[l \cdot year^{-1}]$,

$price_p$ - price of propane-butane gas, $[PLN \cdot l^{-1}]$.

3. Assessment results

The technical data used in the analysis of CHP units are shown in Table 1, whereas the results of the calculations are shown in Table 2.

Table 1. Technical data of the analysed CHP units [14, 17, 18]

Tab. 1. Dane techniczne agregatów kogeneracyjnych poddanych analizie [14, 17, 18]

Item			Stirling SD4-E	Capstone C30	Tedom Micro T30
1	Electric power N_e	$[kW_e]$	35	30	30
2	Thermal power N_{th}	$[kW_{th}]$	140	65	61.6
3	Coefficient of association N_e/N_{th}	[-]	0.25	0.462	0.487
4	Electrical efficiency η_e	[%]	18	26	31.2
5	General performance η_o	[%]	89.2	80	95.3

Source: own study / Źródło: opracowanie własne

Table 2. Results of the calculation of annual profit on generation of electric power in the CHP system [14, 17, 18]
Tab. 2. Wyniki obliczeń rocznego zysku z wytwarzania energii elektrycznej w kogeneracji [14, 17, 18]

Item			Stirling SD4-E	Capstone C30	Tedom Micro T30
1	Gas consumption G_e	[$kg \cdot h^{-1}$]	17.61	10.45	8.72
2	Gas consumption V_g	[$m^3 \cdot h^{-1}$]	22.58	13.40	11.18
3	Unit gas consumption g_e	[$kg \cdot kWh^{-1}$]	0.503	0.348	0.291
4	Quantity of generated useful heat N_{wth}	[kWh_{th}]	1,050,000	487,500	487,500
5	Cost of generating 1 kWh of useful heat k_{th}	[$PLN \cdot kWh_{th}^{-1}$]	0.218	0.278	0.245
6	Cost of generating 1 kWh of useful heat K_{th} less the value of simultaneously generated electric power	[$PLN \cdot kWh_{th}^{-1}$]	0.093	0.048	0.002
7	Quantity of generated electric power N_{we}	[kWh_e]	262,500	225,000	225,000
8	Annual profit on electric power generation Z_{we}	[PLN]	131,250	112,500	112,500
9	Additional profit on useful heat Z_{dc}	[PLN]	109,395	-	-
10	Total annual profit	[PLN]	240,645	112,500	112,500

Source: own study / Źródło: opracowanie własne

Table 3. Approximate costs of purchasing and operating CHP units
Tab. 3. Orientacyjne koszty zakupu i eksploatacji układów kogeneracyjnych

Item			Stirling SD4-E	Capstone C30	Tedom Micro T30
1	Costs of purchasing CHP units	[PLN]	840,000	290,000	215,000
2	Costs of purchasing the exhaust fume-water heat exchanger	[PLN]	-	85,000	-
3	Period of operation	[$PLNyear^{-1}$]	30,000	30,000	35,000
4	Costs of purchasing and constructing the system	[PLN]	100,000	100,000	100,000
5	Total costs	[PLN]	970,000	505,000	350,000

Source: own study / Źródło: opracowanie własne

Table 4. Estimated depreciation time of investment in the CHP system
Tab. 4. Szacunkowy czas amortyzacji inwestycji w układ kogeneracyjny

Item			Stirling SD4-E	Capstone C30	Tedom Micro T30
1	Investment costs	[PLN]	970,000	505,000	350,000
2	Annual profit on electric power generation	[PLN]	131,250	112,500	112,500
3	Annual profit on electric power generation with additional profit on usable heat	[PLN]	240,645	-	-
4	Estimated depreciation time without additional profit on heat	[years]	7.39	4.49	3.11
5	Estimated depreciation time with additional profit on heat	[years]	4.03	-	-

Source: own study / Źródło: opracowanie własne

The purchase costs of the CHP unit powered by a Stirling SD4-E engine were assumed on the basis of the offer presented by the company Stirling DK, the purchase costs of the CHP unit equipped with a Capstone C30 microturbine based on information obtained from the Training and Research Centre for Renewable Energy in Ostoja that is part of the West Pomeranian University of Technology in Szczecin [6], whereas the purchase costs of CHP unit powered by a Tedom Micro T30 piston internal combustion engine were calculated on the basis of available reference books [18].

The microturbine requires an additional purchase of an exhaust fume-water recovery heat exchanger which was included in the purchase costs [6].

The annual operating costs that include, among others, the costs of materials, spare parts and maintenance work, may vary in various years of operating the CHP units and they depend on the number of operating hours. Considering the annual operating time of 7,500 hours, a full inspection will be carried out each year [6], so the annual operating costs may amount to PLN 30,000. In the analysis, operating costs will be the same for all three CHP units, but in reality they may differ as e.g. in case of the piston internal combustion engine, these costs may be greater due to the need to replace oil and filters.

The costs of purchasing and constructing the system that include, *inter alia*, hot water storage tanks, set of electric power batteries, circulation pumps, hot water pumps, pipelines, fittings, measuring sensors and the operation and adjustment system, were calculated on the basis of information obtained at the Training and Research Centre for Renewable Energy in Ostoja that is part of the West Pomeranian University of Technology in Szczecin, where the CHP system with the Capstone C30 microturbine is operated, and these costs amount to PLN 100,000.

The total costs including the costs of purchasing the CHP units, operating costs and costs of constructing the system are shown in Table 3.

The estimated depreciation time, excluding costs of system purchase costs, summarised in Table 4 can be determined by taking into account the purchase cost of the entire system and the calculated annual profit on electric power generation.

For comparison, the costs of purchasing electric power and heat from external providers were calculated. The useful heat was assumed to be generated by a two-speed condensing boiler with a capacity of 30 kW that consumes 3.2 $m^3 \cdot h^{-1}$ of natural gas [19], while the remaining heat required to heat greenhouses or dry crops would be generated by gas-fired air heaters with a nominal capacity of 38.5 kW each, consuming 3.3 $l \cdot h^{-1}$ of propane-butane gas each [16]. In the first variant one heater is employed, while in the second one three air heaters are used due to additional heat generated in the Stirling engine. The calculation results are shown in Table 5, while Table 6 presents the annual profit from purchasing gaseous fuel for CHP units in comparison with the costs of purchasing electric power and heat from external providers.

4. Discussion on results

The analysis of the results obtained from the evaluation of the profitability of the investment in low-power CHP systems in the agricultural holding proved that the application of those systems to generate heat and electric power results in substantial savings, and the investment costs may be returned as early as the first years of the operation of this type of systems.

The development of innovative energy conversion systems, including CHP systems, will be all the more intense as methods for estimating energy and economic results at the stage of planning such an investment are more effective. With the accurate data on expected fuel consumption, the expected amount of generated electric power and heat, as well as costs and operating revenues, it is possible to evaluate their profitability and reduce their investment risk [6]. Therefore, investments in CHP systems should be preceded by an analysis of demand for electric power and useful heat of the facility being supplied. Not only are the values of annual energy demand important, but also analyses of daily, weekly or monthly electric power and thermal power profiles and forecasts of future demand for these forms of energy should be performed [6, 15]. The analyses may be based on other methods, e.g. the net present value discount rate method, similarly to the publication [10] where this method was employed to determine indicators of economic assessment of road lighting in a rural commune, or the publication [9] that employed this method to carry out a comparative analysis of various hot water preparation systems,

Table 5. Costs of purchasing electric power and heat from external providers
Tab. 5. Koszty zakupu energii elektrycznej i ciepła z zewnątrz

Item			Variant 1:	Variant 2:
1	Cost of generating usable heat (two-speed condensing boiler)	[PLN]	32,400.00	32,400.00
2	Cost of generating heat to heat greenhouses (air heaters)	[PLN]	54,697.50	164,092.50
3	Cost of purchasing electric power	[PLN]	122,500.00	122,500.00
4	Total costs	[PLN·year^{-1}]	209,597.50	318,992.50

Source: own study / Źródło: opracowanie własne

Table 6. Annual profit from purchasing gaseous fuel for CHP units in comparison with the costs of purchasing electric power and heat from external providers
Tab. 6. Roczny zysk przy zakupie paliwa gazowego dla agregatów kogeneracyjnych w porównaniu z kosztami zakupu energii elektrycznej i ciepła z zewnątrz

Item			Stirling SD4-E	Capstone C30	Tedom Micro T30
1	Costs of purchasing gaseous fuel	[PLN]	228,591.35	135,649.04	113,192.31
2	Cost of purchasing electric power and heat from external providers - Variant 1	[PLN]	-	209,597.50	209,597.50
3	Cost of purchasing electric power and heat from external providers - Variant 2	[PLN]	318,992.50	-	-
5	Annual profit (saving)	[PLN]	90,401.15	73,948.46	96,405.19

Source: own study / Źródło: opracowanie własne or the publication [6] where this method was adopted to evaluate the cost-effectiveness of specific strategies of the operation of the CHP system equipped with a microturbine. Furthermore, it should be taken into account that low-power CHP systems may be powered by almost any fuel but the most optimal is to use natural gas or biofuels. Therefore, it is important to cooperate with local biogas plants [1, 3] that can produce biogas for such CHP systems. It should also be considered that there are other renewable energy sources such as wind turbines, photovoltaic panels [11] or other more complex systems [8] that can cooperate with the CHP system applied in the agricultural holding.

5. Summary

The results of evaluating the profitability of investment in low-power CHP systems in the agricultural holding prove that it is worth investing in this type of systems.

1. The application of CHP systems significantly reduces the costs of generating 1 kWh of useful heat, as due to the simultaneous generation of heat and electric power these costs are reduced by the value of the generated electric power (Table 2).
2. The cost of the system with the CHP unit powered by the Stirling engine is about twice that of the system equipped with the microturbine, and about three times that of the system powered by the piston internal combustion engine (Table 3). However, the additional heat generated by the CHP unit powered by the Stirling engine can be considered its advantage as, taking into account the annual profit from generating electric power with additional profit on useful heat, the investment in the CHP unit powered by the Stirling engine will pay for itself at the same time as the investment in the CHP unit equipped with the microturbine (Table 4). Obviously, due to the lowest costs, the investment in the CHP unit powered by the piston internal combustion engine will pay for itself as quickly as possible.
3. Considering the costs of purchasing electric power and heat from external sources (Table 5), it can be noted that the investment in the CHP systems for the generation of heat and electric power for agricultural holdings is cost effective in comparison with the purchase of electric power from external sources and the generation of useful heat, separately (Table 6). The highest annual profit is generated by the CHP unit powered by the piston internal combustion engine, but for the remaining systems this profit is slightly lower by about 6% for the CHP system powered by the Stirling engine (additional heat) and by around 23% for the CHP system equipped with the microturbine, respectively.

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