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OPTIMIZATION OF ENERGY COGENERATION PROCESSES OF DISTRICT HEATING SYSTEMS BASED ON BIOGAS SOURCES – CASE STUDY OF A MUNICIPAL AREA

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Purpose: The aim of this article is to present selected research results in the field of optimization of energy cogeneration processes of heating systems based on biogas sources, in terms of the possibility of obtaining ecological and energy benefits in the municipal area.

Design/methodology/approach: The considerations are a case study, including an analysis of the choice of the optimal variant of agricultural biogas construction in the Łobez Municipality in the Zachodniopomorskie Voivodeship from the point of view of both the substrate used in biogas and the proposed technological solutions. The subject matter focuses on comparing the estimated ecological effect of biogas with different powers and choosing the optimal model solution. The research process used secondary and statistical data and the selected comparative method to calculate the carbon dioxide emission reduction factor.

Findings: The authors indicate which technology of obtaining energy should be dominant in the field of optimization of energy cogeneration processes of heating systems in Poland in areas dominated by agricultural economy.

Research limitations/implications: The presented research concerns the assessment of one of the parameters (substrate used in biogas) affecting the optimization of biogas production. Future research in this area should focus on the assessment of other factors determining the validity of the discussed solutions in relation to the adopted state policy in the field of development of renewable energy sources and agricultural economy.

Practical implications: The results of the research are the first approach to indicate the government and regional administration the type of energy that may form the basis of the future strategy of changes in the field of energy cogeneration of heating systems in municipal and agricultural areas in Poland.

Social implications: The description of the agricultural biogas model, which served as an example, can be helpful in the process of identifying benefits not only for the environment but also as an element stimulating economic and social development at the local and regional level.

Originality/value: An experimental research approach may be helpful in understanding the essence of optimization of energy congregation processes of heating systems based on biogas sources in selected areas of Poland.

Keywords: process optimization, energy management, renewable energy, cogeneration.

Category of the paper: Case study, Technical paper.

1. Introduction

There is no doubt that energy efficiency and demand management in the current era of the energy crisis will play a fundamental role in the new vision of the energy market organization in Poland (Pietrzak et al., 2021; Tucki et al.,2019). It is not without significance that coal has dominated the Polish energy raw materials market for many years, both in terms of its availability and price. This process resulted in the fact that the Polish energy system is based on practically one energy raw material (Polityka, 2009). Nevertheless, coal alone is not able to fully meet Poland's energy needs, and the lack of significant resources of oil and natural gas caused the need to import these raw materials and get a new look at the process of managing the energy transformation (Janiszewska, 2019; Krajowy 2010). The analysis of the energy structure of Poland in the years 2004-2020 (Drożdż, Mróz-Malik, Kopiczko, 2021) indicates a decrease in the share of hard coal and lignite, both in consumption and extraction, in favour of the increasing position of renewable energy sources (RES), including biogas plants. Considering that the share of natural gas and oil in energy consumption in Poland is at a relatively stable level (Central, 2022). At this stage, it should be emphasized that large amounts of waste of agricultural origin and the agri-food industry are produced in Poland (Igliński et al., 2020) An alternative to the agricultural use of organic waste is their use for energy production (Szymańska, Lewandowska, 2015; Brewery, 2020). According to the available research data (Piwowar, Dzikuć, 2016; Ignaciuk, Sulewski, 2021) – the real potential of biomass in Poland in 2020 was estimated at 600 168 TJ, including wet waste intended for biogas at the level of 72 608 TJ (Śleszyński et al., 2021). On this basis, there were postulates that the use of waste from agricultural production may significantly contribute to the improvement of the energy balance of the country, voivodship, poviat and in particular, a given municipality (Piwowar, Dzikuć, 2019).

According to many researchers, the production of agricultural biogas is seen as one of the most forward-looking directions of energy use of biomass. It is a key objective indicated in the programme "Energy Policy of Poland until 2030" (Koryś et al., 2019) In addition, on 13 July 2010, the Council of Ministers adopted the document "Directions for the development of agricultural biogas plants in Poland in 2010-2020", which was developed by the Ministry of Economy in cooperation with the Ministry of Agriculture and Rural Development. This document emphasizes the importance of optimal conditions for the development of installations producing agricultural biogas, which are to be used for the production of electricity and heat. The legislator, among others, imposed an obligation on public sellers to purchase electricity produced from renewable energy sources, according to the average price of its sale in the previous year (Scarlat, Dallemand, Fahl, 2018). Agricultural biogas plants themselves were exempted from paying stamp duties for official activities related to the keeping by the President of the Agricultural Market Agency of a register of energy companies involved in the production of agricultural biogas with a total electrical capacity not exceeding 5 MW. It is worth noting that Biogas plants also fit into climate protection strategies, such as emission-free CO_2 energy production and contribute to the climate package objectives (Baral et al., 2018). The positive balance of greenhouse gas emissions in agricultural biogas plants is based on the fact that they produce electricity and heat from biomass, which is an undisputed renewable energy source (Masłoń et al., 2018; Wiater, Horysz, 2017). The pro-ecological product is obtained as a result of methane fermentation of a deodorant, devoid of odor, not emitting into the atmosphere, as opposed to slurry and manure, methane and harmful nitrogen compounds, which occur in its mineralised form and have valuable fertilising properties (Tufaner, Avsar, Gonüllü, 2017).

In addition, Directive 2009/28/EC (Directive, 2009) requires Member States to ensure a specific share of energy from renewable sources in gross final consumption of energy in 2020. The mandatory national overall targets consist of an assumed 20% share of energy from renewable sources in the gross final consumption of energy in the Community. For Poland, this target has been set at 15%. Recently, investors in the biomass energy market can count on a number of possibilities to obtain subsidies from the Structural Funds. For example, private enterprises, local government units, public institutions may receive grants for the construction or development of high-efficiency cogeneration units fired with biomass or biogas under the Operational Programme Infrastructure and Environment, Priority IX. Environmentally friendly energy infrastructure and energy efficiency, Action 9.1. High-efficiency power generation (Operational, 2014).

As indicated by the extensive literature on the subject, one of the greatest advantages of using renewable energy sources, including biogas, is the possibility of achieving ecological and energy synergy (Wąs et al., 2020; Bielski et al., 2021) In addition to the benefits that renewable energy brings for the environment, it is seen as an increasingly common factor stimulating economic and social development at the local and regional level (Altzas et al., 2019; Kozłowski et al., 2018). Thus, the process approach to energy cogeneration certainly requires careful analysis and research, both in the context of academic and practical considerations.

In addition, the analysis of the available literature showed that it is limited in the scope of considerations related to the energy cogeneration of heating systems based on biogas sources (Dach, Kula, Wożniak 2021; Antoni, Mazzegannd, Mathieu 2019). In particular, there is a lack of publication in relation to the analyses of individual variants of the case study (Central Europe), which are largely identified with the areas dominated by the agricultural economy.

Therefore, the presented study is an attempt to fill the gap in the literature by discussing the essence of optimization of energy congregation processes of heating systems based on biogas sources on the example of selected municipal areas.

Considering that the aim of the research is to gain extensive knowledge on the perception of the optimization of energy cogeneration processes of heating systems based on biogas sources. The article itself has many important practical implications, both political and economic. The article was organized as follows. Chapter 2 contains a description of the research method used in response to the set objective of the work. Chapter 3 describes the results of experimental studies and their interpretation. In turn, Chapter 4 discusses and presents the conclusions – pointing to their limitations in the perspective of the research conducted so far, at the same time, the future directions of research in relation to the issue of energy cogeneration of heating systems and the strategy of managing the development of renewable energy sources in municipal areas where agriculture plays a key role.

2. Materials and methods

The considerations in this article are of a case-stage nature, focussing on the assessment of the choice of the optimal variant of agricultural biogas construction in the Łobez Municipality in the Zachodniopomorskie Voivodeship from the point of view of:

- substrate used in a biogas plant,
- the proposed technological solutions, i.e. the use of two cogeneration engines with a total electrical power of 1.1 MW or the use of four cogeneration engines with a power of approx. 0.25 MW each.

In addition, the presented research aims to show the differences in the capacity of the planned biogas plant based on a comparison of the estimated ecological effect of the biogas plant. The data for the simulation was taken from the feasibility study of the investment entitled "Construction of a 1.2 MW installation for the production of electricity and heat from biogas in the town of Łobez (Studium, 2018). The choice of this destination was not accidental, but it was dictated by the desire to assess the actual project. On the other hand, the calculations in the scope of carbon savings resulting from the implementation of the investment were made on the basis of the method of calculating the carbon dioxide emission reduction factor in the 1.6.1 Operational Programme Infrastructure and Environment 2014-2020 measure. Individual data used in the research process were obtained from the reports of the Central Statistical Office and the Low-Emission Economy Plan for the Łobez Municipality (Central, 2022; Low, 2022; Energie 2022). This allowed to distinguish development trends and to indicate the dynamics of changes in individual years 2008-2020 in the structure of the heating system in the Łobez Municipality.

3. Results

3.1. Assessment of the district heating system in the analysed municipality – case study

The Łobez is an urban-rural municipality in the Zachodniopomorskie Voivodeship, located in the eastern part of the Łobez county on the Rega River. The area of the municipality is 228 km^2, of which the area of the town of Łobez is 11.72 km^2, while the area of rural areas is 216.25 km^2. The seat of the municipality is the town of Łobez, which includes 21 village councils. The municipality has an agricultural and industrial character. Forest areas cover an area of 37%, while agricultural land covers 56%. The main branch of the economy is agri-food processing. Small and medium-sized farms are predominant in the municipality. The average size of the farm is 20 ha. Agriculture is mainly based on the cultivation of cereals, to a lesser extent on the cultivation of potatoes.

Thermal energy in the Łobez municipality comes from (Low, 2022):

- gas network (individual heating, network heating from the boiler room),
- local boiler rooms fired with fuel other than gas,
- individual heating using fuel other than gas.

Table 1.
Structure of heat generation in the Łobez Municipality

Specification	Amount of primary energy consumed	
	MWh	**%**
By type of heating		
Individual heating	122 219.21	64.29%
district heating	67 895.94	35.71%
Total	190 115.15	100.0%
By type of recipient		
Population	138 883.08	73.05%
Public buildings	4 375.96	2.30%
Companies	46 856.10	24.65%
Total	190 115.15	100.0%
By fuel used		
Gas	23 465.74	12.34%
Coal	118 836.86	62.51%
Heating oil	3 176.21	1.67%
Wood	44 469.21	23.39%
Electrical power	167.13	0.09%
Total	190 115.15	100,0%

Source: own elaboration based on the Low Carbon Economy Plan for the Łobez Municipality.

The analysis of the data presented in Table 1 indicates that individual heating dominates in the Łobez Municipality 64.29%. The next position is occupied by the heating network. On the other hand, the fuel used to generate heat in 62.51% is coal, in 23.39% wood and in 12.34% gas.

Table 2.
Structure of heat generation in the Łobez Municipality

Specification	Households	
	PCS	%
Gas network, including:	2 348	47.95%
Individual heating	1 359	27.76%
mains heating (local boiler rooms)	989	20.19%
Other individual heating, including:	2 548	52.05%
coal (dominant fuel)	1 620	33.09%
wood (dominant fuel)	839	17.14%
Heating oil	30	0.61%
Electrical power	59	1.21%
Total	**4896**	**100.0%**

Source: own elaboration based on the Low Carbon Economy Plan for the Łobez Municipality.

The data presented in Table 2 show that 47.95% of households use the gas network existing in the Łobez Municipality, including 27.76% individual customers and 20% network customers. It should be emphasized that the main supplier of gas to the municipality is Polskie Górnictwo Naftowe i Gazownictwo S.A., using the gas network located mainly in the town of Łobez. On the other hand, individual customers in the municipality outside the urban area use traditional fuels such as coal or wood in the heat production process.

Table 3.
Comparison of the parameters of the gas network in the Łobez Municipality

Gas network	Unit	2008	2020
Total length of active network	Metre	53615	61003
Length of active transmission network	Metre	18637	18637
Length of active distribution network	Metre	34978	42366
Active connections to residential and non-residential buildings	pc.	1325	1386
Gas Recipients	Household	2458	2597
Gas consumption for heating of dwellings	thousand m^3	1291.8	1485.0
Total gas consumption by residents	thousand m^3	1530.4	1512.2
Population using the gas network	Person	5829	7424

Source: own elaboration based on the Central Statistical Office data.

The comparison of data from selected years in Table 3 indicates a noticeable increase in the population using the gas network despite the lack of expansion of the length of the active transmission network itself. In addition, a noticeable trend is the increase in gas consumption in the process of heating apartments, which, according to the authors, is one of the basic premises for the implementation of optimization of energy cogeneration processes of heating systems based on biogas sources.

3.2. Evaluation of the choice of the optimal option for the construction of agricultural biogas in the Łobez Municipality

For the purpose of selecting the optimal variant, one of the parameters, i.e. substrate used in biogas, was analyzed:

- option I covers agricultural products as a primary substrate,
- option II includes sewage sludge as the primary substrate.

The purpose of the simulation was to determine the operational risk in the scope of availability, quality and costs of obtaining substrates. A comparison of the two options is presented in the table 4.

Table 4.
Strategic options for the construction of a biogas plant from the point of view of the substrate used

Option I	Option II
basic substrate: potato wiping, plant substrates (maize silage and other green biomass), and animal faeces – high availability, high biogas yield from agro-food industry waste low acquisition cost, ease of transport (location near the agri-food processing plant), certainty of substrate parameters that have a direct impact on the course of methane fermentation.	basic substrate: sewage sludge, lower biogas yield, increase in acquisition costs - the need to cooperate with the Municipal Services Enterprise in Łobez, greater complexity of the transport procedure, due to administrative and legal constraints - special vehicles, lower intensity of biogas production from sewage sludge and longer time of processes in fermenters.

Source: own study based on the data of the investment feasibility study.

At this stage of consideration, it should be mentioned that the appropriate selection of substrates has an impact on the intensity of biogas production and the speed of processes occurring in fermenters. One of the key postulates in the area of logistics process management is the availability of the substrate, and thus the distance of its source from the location to which it must be delivered, in this case the place of storage of the substrate. It is assumed that for economic reasons this distance should not exceed 5 km (Theuerl, Klnag, Prochnow, 2019). Considering that covering transport costs over longer distances may be economically unjustified. In addition, it may require the use of specialised means of transport. Considering the above, when analyzing the available data, the authors postulate that the more favorable variant of the project implementation is variant I based on agricultural products as the basic substract.

The next stage of the research focused on analyzes in the scope of differences in the planned agricultural biogas power:

- option I – 1.1 MW biogas plant,
- option II – 0.5 MW biogas plant.

The authors assumed that increasing the capacity of an agricultural biogas plant would lead to a positive ecological effect, i.e. a direct increase in the produced energy without the use of conventional sources and an increase in emissions of pollutants into the environment.

Table 5.
Comparison of the estimated ecological effect of biogas plants of different power

Biogas plant capacity [MW]	Potential energy production in a biogas plant per year [MWh]	Average CO_2 emissions with 1MWh of conventional energy production [t]	Emission limitation CO_2 [t]
1.1	1012	0.81	8514.7
0.5	4380	0.81	3547.8

Source: own study based on the methodology of calculating the carbon dioxide emission reduction factor.

The analysis of the presented simulations based on the selected method of calculating the carbon dioxide emission reduction factor shows a higher ecological effect of an agricultural biogas plant with a maximum capacity of 1.1 MW. The estimated effect will be about twice as high as that achieved in a biogas plant with a maximum capacity of 0.5 MW. Therefore, option I, i.e. a 1.1 MW biogas plant, was adopted for further research for the simulation.

At the final stage, the following variants of technological solutions were analyzed:

- option I – use of two cogeneration engines with a total electrical power of 1.1 MW,
- option II – the use of four cogeneration engines with a power of approx. 0.25 MW each.

Table 6.
Variants of technological solutions

Option I	Option II
option I – use of two cogeneration engines with a total electrical power of 1.1 MW. The cogeneration unit will consist of two cogeneration units (2 pcs of cogeneration units), with a total electrical capacity of 1.1 MW. They will be installed in a sound absorbing enclosure, placed in two containers, with a built-up area of up to 50 m^2 each and a height of up to 4 m. This solution is more beneficial as it reduces the risk of complete cessation of operation of the biogas plant in the event of a failure.	option II – use of four cogeneration engines with a total electrical power of approx. 0.25 MW each. The cogeneration unit will consist of four cogeneration units (4 pcs of cogeneration units), with a total electrical capacity of approx. 0.25 MW each. They will be installed in a sound absorbing enclosure, placed in four containers, with a built-up area of up to 50 m^2 each and a height of up to 4 m. The solution increases the risk of failure and cessation of operation of the biogas plant. This option may generate higher operating and maintenance costs compared to Option I.

Source: own study based on the data of the investment feasibility study.

Based on the above variant analysis of technological solutions, the authors postulate that the more favorable variant of the project implementation is Option I based on the use of two cogeneration engines with a total electrical power of 1.1 MW.

4. Discussion and Conclusions

In the face of the ongoing energy crisis, the transition process will certainly be delayed. This does not change the fact that managing the optimisation of energy cogeneration processes may prove crucial for the successful implementation of renewable energy projects. Observations of market reality indicate that agricultural biogas and agricultural biogas plants are among the fastest growing segments of renewable energy in Europe (Johnson, Boersma, 2013). The dynamic development of agricultural biogas has been possible for several years thanks to the priority given to energy from renewable sources by European Union legislation (Petersen, Snapp, 2013). Therefore, the process of managing the development of biomass energy in Poland becomes important for the entire energy sector. The role of biogas is increasingly recognized also by local authorities (Ribeiro, Rode, 2019). According to many researchers, it is an opportunity for economically neglected regions that have a high potential for biomass of agricultural origin (Zhang, Qiu, 2018; Lauer, Leprich, Thrän, 2020). In the authors' opinion, proper management of the biomass energy development process will not only affect the satisfaction of energy needs, but may also lead to the professional activation of the population and development of rural areas through, among others, the dynamization of small and medium-sized entrepreneurship, increase in employment, increase in tax revenues (Lipiński, Lipiński, Kowalkowski, 2018). In addition, the functioning of agricultural biogas supports local development, based on endogenous resources, especially in rural areas, which require support (Mamica, Mazur-Bubak, Wróbel-Rotter, 2022). The United Kingdom is an example of the transition to a low-carbon economy and the possibility of achieving the above-mentioned benefits. As one of the first countries in the world, it has adopted long-term legally binding emission reduction targets CO_2 under the Climate Change Act 2008. Many of the companies that make up the UK's 'national' energy system are substantially integrated into regional and local economies, including the development of biogas energy in rural areas (Liu, Wang, Cardinal, 2022) . Available research confirms the current belief that climate change, energy security and the depletion of conventional oil reserves will change the established patterns and the scale of energy supply, its distribution and consumption (Tomaszewski, 2022; Niemczyk et al., 2022). On this basis, the authors put forward the thesis that all positive phenomena resulting from the adoption of the right strategy in the field of energy transformation can be based on the optimization of energy cogeneration processes of heating systems based on biogas sources.

The presented research results showed that the implementation variant of the project consisting in the construction of a 1.1 MW biogas plant, whose the main substrate will be agricultural products, is also the most environmentally optimal. The production of electricity within the biogas plant reduces the demand for energy from coal and natural gas combustion, i.e. fossil raw materials. This allows to reduce the extraction of these raw materials and use them primarily in obtaining electricity and heat. Thus, the ecological effect of an agricultural biogas plant with a maximum capacity of 1.1 MW will be about twice as high as that achieved in a biogas plant with a maximum capacity of 0.5 MW. On this basis, the authors conclude that the positive impact on the environment, especially on climate and air, will be more noticeable in the case of biogas plants with higher power. A positive impact on the environment is of additional importance due to the proximity of the Natura 2000 site "The Regi River Basin" and on local environmental conditions, in particular air quality. The creation of the investment in the planned place will bring an additional source of energy in the municipality, at the same time not reducing the air quality. The industrial character of the area, the direct exit onto the provincial road and the proper management of logistics and transport of raw materials will result in the lack of negative aspects felt by the local community due to the functioning of the biogas plant.

The presented research focused on the assessment of the choice of the optimal option for the construction of agricultural biogas in the Łobez Municipality in the field of optimization of energy cogeneration processes of heating systems based on biogas sources. Against the background of academic considerations, it is necessary to answer the question whether the model itself and the conclusions from the research can be implemented in other regions of Poland, where agricultural economy plays a key role? According to the researchers, the implementation of this category of projects should be individual. Duplication of common assumptions and diagrams is not advisable, as different destinations are based on different initial assumptions. It does not change the state of affairs that in any case, starting from the planning stage, through construction and operation, a process approach may prove to be crucial for success, which is a dynamic approach so desired in the case of this category of investment.

The presented research concerns the assessment of one of the parameters (substrate used in biogas) affecting the optimization of biogas production. A much broader analysis will certainly be needed in the near future, in particular regarding the interdisciplinary approach to the implementation of this category of investment. Moreover, future research in this area should focus on the assessment of other factors determining the validity of the discussed solutions in relation to the adopted state policy in the field of development of renewable energy sources and agricultural economy in the rural area.

To sum up, the presented research on the optimization of energy cogeneration processes of heating systems based on biogas sources - the municipal area does not fully exhaust the essence of the issue. They are only an incentive for further research in this matter. Therefore, such analyses will be the subject of future work to determine and identify the key factors for the implementation of an ambitious energy cogeneration plan for municipal areas where farming plays a predominant role.

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