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ENERGETIC AND ECONOMIC EFFICIENCY OF AGRICULTURAL BIOGAS PLANT WORKING WITH DIFFERENT SUBSTRATES

Summary

Ensuring the profitability of working biogas plants is a key factor for the development of biogas market. Apart from the price obtained for sold electricity, the substrates are the most important factor, particularly the ratio of their acquisition cost to methane efficiency. Thus, the objective of this paper was energy and economic analysis of the typical biogas plant with a capacity of 1 MWe working in new, favorable market situation (higher prices for blue certificates and in auction system) and using different biomass and waste substrates. After biogas efficiency tests and economic calculations of 4 different agricultural and waste substrates (maize silage, beet pulp, refood and chicken manure) it has been stated that the chicken manure was the most energy effective, just after maize silage. However chicken manure is 5 times cheaper. However, refood is the most profitable substrate for biogas plant working in both variants (certificates and auctions), and slightly less favorable - chicken manure. It is related to the best price - methane efficiency ratio, since the adoption of refood for biogas plants receives payment in the amount of 20 PLN per ton. In vast majority of analyzed substrates, investment in agricultural biogas plant is now becoming a very profitable venture, because annual profit before tax fluctuated in the range of 1-4 million PLN.
***Key words**: biogas, substrates, energetic and economic efficiency*

EFEKTYWNOŚĆ ENERGETYCZNA I EKONOMICZNA BIOGAZOWNI ROLNICZEJ ZASILANEJ RÓŻNYMI WARIANTAMI SUBSTRATÓW

Streszczenie

Najważniejszym czynnikiem dla rozwoju rynku biogazowego jest zapewnienie opłacalności pracy biogazowni. Poza ceną uzyskaną za sprzedawaną energię elektryczną, najważniejszym czynnikiem są substraty, a zwłaszcza stosunek ich kosztu pozyskania do wydajności metanowej. Stąd celem niniejszej pracy była analiza energetyczna i ekonomiczna typowej biogazowni o mocy 1 MWe pracującej w nowej, korzystnej sytuacji rynkowej (wyższe ceny za błękitne certyfikaty oraz w systemie aukcyjnym) i wykorzystujące różne substraty biomasowe i odpadowe. Po przeprowadzeniu badań i obliczeń dla 4 różnych substratów rolniczych i odpadowych (kiszonka z kukurydzy, wysłodki buraczane, refood i obornik kurzy) stwierdzono, że najbardziej efektywny energetycznie był obornik kurzy obok kiszonki z kukurydzy. Obornik kurzy jest jednak 5 razy tańszy w pozyskaniu. Z kolei najbardziej opłacalnym substratem dla biogazowni rolniczej pracującej w obu wariantach (certyfikatów jak i aukcji) jest refood, nieco mniej korzystnym obornik kurzy. Wynika to z najkorzystniejszego stosunku ceny do wydajności metanowej bowiem za przyjęcie refood do biogazowni otrzymuje się dopłatę w wysokości 20 zł za tonę. W zdecydowanej większości analizowanych substratów inwestycja w biogazownię rolniczą staje się obecnie bardzo opłacalnym przedsięwzięciem, bowiem roczny zysk przed opodatkowaniem wahał się w zakresie 1-4 mln zł.
***Słowa kluczowe**: biogaz, substraty, energetyczna i ekonomiczna efektywność*

1. Introduction

After the collapse of the renewable energy sources (RES) market in 2012-2016, the second half of 2016 has brought a diametrical improvement in the sector of agricultural biogas plants. It is closely related to the pressure on the development of this sector, which Polish government put in a new energy policy. Agricultural biogas plants through their stable operation may serve not only as an energy stabilizer of the grid terminal, but also may act as installations for disposal of organic waste [2].

It is worth to be highlighted, that processing of agriculture waste and food-industry waste materials in agricultural biogas plants is one of the best methods of waste management [7].

Under controlled conditions, the waste materials are processed into biogas (which subsequently is used in production of electricity, heat and/or cold), and the second final product is digestate i.e. high quality agricultural fertilizer [7]. Processing of organic waste in biogas plant strongly reduces uncontrolled gaseous emissions to the environment, with special regard of methane (as a main greenhouse gas, just after CO_2) which is produced in large amounts from the waste stored anaerobically.

Moreover, it should be added, that in the national scenario of the development of biogas market, the government supports the divergence from the German script, where more than 9,000 agricultural biogas plants work mainly with maize silage. In this way, the demand for silage in the amount over 60 million Mg per year, caused that even 10% of the German agricultural area is under cultivation of maize intended for biogas plants needs. Consequently, in Germany it creates a very strong social objection and antipathy of the experts from agricultural sector due to the permanent maize monoculture in many regions.

Poland is a country with very high availability of waste biomass and organic waste materials from the agri-food industry [1, 3, 6]. Indicative data related to the mass of the basic substrates that can be used as input for biogas plant:
- animal waste (manure and slurry) - approx. 90 million tons;
- cereals and oilseed rape straw - approx. 8 million tons
- maize straw - approx. 4 million tons
- waste plant biomass, waste from food processing 2-3 million tons.

It should be noted that total straw production in Poland is several times higher than specified in the table above, however large part of straw is used in the production of mushroom ground, as a litter in livestock production or as a substrate in solid biofuels production (pellets, briquettes).

In total, on the basis of the results of laboratory analyses of methane production conducted in the Laboratory of Ecotechnology, at the Institute of Biosystems Engineering, it is possible to evaluate the potential of biogas production in the fermentation process and it amounts to 13.5 billion m^3 of biogas, which contains 7.8 million m^3 of biomethane. It should be highlighted, that this potential is not assessed as a whole. There is a lot of biomass and waste substrates that were not included in the table above, and which are highly suitable for biogas production. The Institute of Biosystems Engineering tested in recent years more than 1100 different kinds of materials, which in major part gave a satisfactory or good result in the biomethane production.

A key factor for the development of biogas market is to ensure the profitability of working biogas plants [4]. Apart from the price obtained for sold electricity, the substrates are the most important factor, particularly the ratio of their acquisition cost to methane efficiency.

Thus, the objective of this paper was to perform energy and economic analysis of the typical biogas plant with a capacity of 1 MWe working in new, favorable market situation (higher prices for blue certificates and in auction system) and using different biomass and waste substrates.

2. Materials and Methods

For analysis purposes, a typical biogas plant with 1 MW electrical capacity has been selected. This type of installation is the most common currently in Poland and installations of such power are more often designed and planned. The cost of installation with 1 MWe capacity made according to Polish technologies is approx. 14 million zł. It was assumed, that the biogas plant would be powered by 4 different kinds of agricultural and waste substrates, such as:
- maize silage (obtained from own farm, price 100 PLN Mg^{-1});
- beet-pulp (from sugar factory, price 40 PLN Mg^{-1});
- re-food (mixture of expired and spoiled food provided by a specialized company with a surcharge for disposal with R3 - fermentation method, price 20 PLN Mg^{-1});
- chicken manure (sourced from farm, price 20 PLN Mg^{-1}).

It should be noted, that aforementioned substrates are usually most often considered in the planned agricultural biogas plants and their use does not result in the loss of the status of agricultural biogas installation.

2.1. Biogas efficiency analysis

The analysis of biogas and biomethane efficiency was made in the Laboratory of Ecotechnologies, placed in the Institute of Biosystems Engineering, at the Poznan University of Life Sciences (PULS). The methodology of biogas production efficiency tests were made in accordance with norms DIN 38 414/S8 and VDI 4630. The physical and chemical analyzes were made according to the Polish standard system: dry matter content within Polish standard norm PN-75C-04616/01 (drying for 24 h in 105°C), organic dry matter within norm PN-Z-15011-3 (combustion of the samples in 525°C for 3 hours) [4].

The reactor system for fermentation tests consisted of 21 biofermentors. Each individual biofermentor (made from glass) had a volume of 2 dm^3. During whole experiments the tests were conducted under anaerobic conditions. The process was carried out under mesophilic conditions at 39°C +/-1°C. The scheme of experimental set-up for biogas fermentation is shown in Figure 1.

Biogas produced from biofermentor chambers has moved via Teflon pipe to the gas reservoirs (inverted cylinder immersed in water) made from plexiglass. Between the water and gas areas, there was a liquid barrier preventing the dissolution of CO_2 in the water. The methodology rules consisted in testing all samples in triplicate.

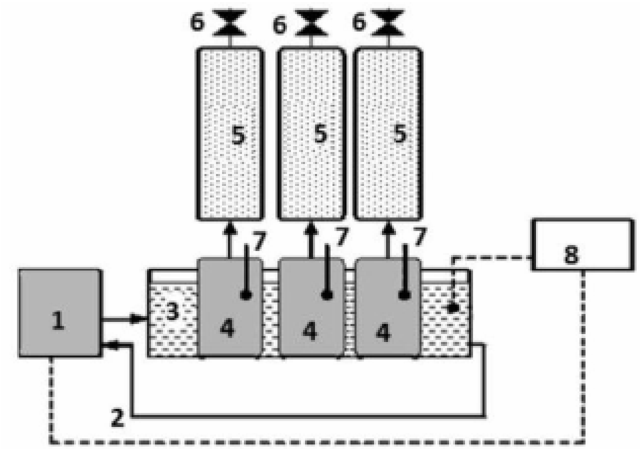


Fig. 1. Schema of biofermentor for biogas production research (3-chamber section): 1: Water heater with temperature regulator, 2: insulated conductors of calefaction liquid, 3: water coat with temperature 39°C, 4: biofermentor with charge capacity of 2 dm^3, 5: biogas reservoir, 6: cutting off valves, 7: sampling tubes, 8: recording central station [5]

Rys. 1. Schemat fermentora do badań produkcji biogazu (sekcja 3-komorowa): 1. ogrzewacz wody z regulatorem temperatury, 2. izolowane przewody cieczy ogrzewającej, 3. płaszcz wodny o temperaturze 39°C, 4. biofermentor o pojemności 2 dm^3, 5. zbiornik na biogaz, 6. zawory odcinające, 7. miejsca poboru próbek, 8. centrala rejestrująca [5]

2.2. Energetic calculation

The calculations of energy efficiency of 1 Mg of the particular substrate and amount of the required weight of a given substrate to power through the whole year the biogas plant with capacity of 1 MW have been conducted according to the methodology developed by Dach and Janczak [8]. Adopted electrical efficiency of cogeneration plant was at the level of 42% and the number of working hours in the year amounted to 8000 h. Two following variants of the energy sale have been adopted in order to create and calculate the incomes system:

- current system of certificates giving the price of 580 PLN /MWh (so called black energy 175 PLN/MWh, blue certificate 280 PLN/MWh and yellow certificate 125 PLN/MWh);
- planned auction system 550 PLN/MWh (minimum starting price, decreased by the price of subsidies - current study includes the biogas plant construction in 80% from the credit, without subsidies).

Economic calculations of the costs, incomes and IRR (Internal Rate of Return) and NPV (Net Present Value) indicators were made using specialized software for economic analysis of biogas investments developed at the Institute of Biosystems Engineering in co-operation with the companies from biogas industry.

3. Results

Basic physical parameters of the tested substrates are shown in Table 1.

Table 1. The basic parameters of the tested biowaste: dry mass (T.S.), organic dry mass (V.S.) and pH

Tab. 1. Podstawowe parametry fizyczne badanych substratów: sucha masa (T.S.), sucha masa organiczna (V.S.) i pH

Type of biowaste	**T.S. [%]**	**V.S. [% T.S.]**	**pH [-]**
Maize silage	35.1	96.6	3.98
Beet pulp	18.6	93.7	3.45
Refood	15.6	93.7	6.25
Chicken manure	42.1	91.2	5.65

Source: own work / Źródło: opracowanie własne

It has been stated, that two substrates (silage and manure) had higher content of dry matter (over twice higher than beet- pulp and refood). All substrates had high content of organic matter, which was favorable for fermentation process.

The results of fermentation tests of the above mentioned substrates are shown in Table 2.

Table 2. The biogas and biomethane production from fresh mass of analyzed biowaste

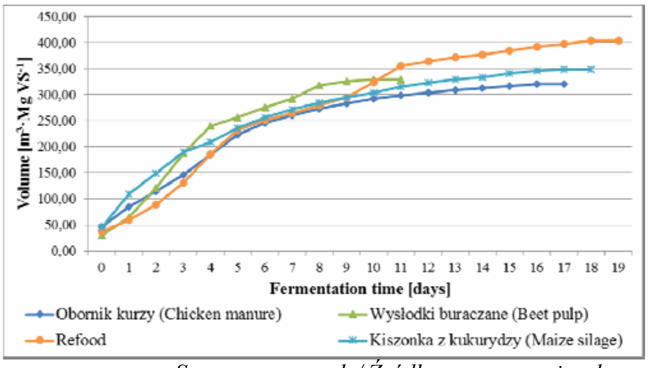
Tab. 2. Produkcja biogazu I biometanu ze świeżej masy analizowanych bioodpadów

Sample	**CH_4 content [%]**	**CH_4 yield [m^3 Mg^{-1}]**	**Biogas yield [m^3 Mg^{-1}]**
Maize silage	54.4	118.4	217.6
Beet pulp	55.9	25.7	46.0
Refood	51.8	58.7	113.4
Chicken manure	58.9	122.7	208.4

Source: own work / Źródło: opracowanie własne

There were significant differences between methane fermentation efficiency of the analyzed substrates. The highest efficiency from one ton of fresh mass of the substrate was in case of chicken manure (122.7 m^3 CH_4), and then for maize silage 118.4 m^3 CH_4. The beet pulp fermented most poorly - only 25.7 m^3 CH_4. These values are extremely important for the operator of biogas plant because the substrates are used in fresh.

However, comparing the methane efficiency of the substrates from 1 Mg of organic dry matter (volatile solids) it should be stated, that differences between the substrates were much smaller (Fig. 2). It was related to the omission of the water content and mineral matter in the tested substrates.



Source: own work / Źródło: opracowanie własne

Figure 2. Cumulative production of methane from 1 Mg of VS of tested materials

Rys. 2. Skumulowana produkcja metanu z 1 Mg suchej masy organicznej analizowanych materiałów

While analyzing the biomethane production it should be noted very short fermentation time, ranging between 11-19 days. It is considerably less than assumed -in case of classic biogas plants i.e. Nawaro - 75 days for substrates in digesters.

3.1. Energy-economic analysis

Obtained results from methane efficiency of the substrates converted into m^3/ton of the substrate, made possible to calculate the essential mass required to supply a year-round operation of biogas plants. The calculated masses of each substrate are shown in Table 3.

Table 3. Amount of substrates needed for biogas plant feeding

Tab. 3. Ilość substratów niezbędnych do zasilenia biogazowni w ciągu roku

Substrates	**Amount [Mg $year^{-1}$]**
Maize silage	18 859
Beet pulp	86 885
Refood	38 040
Chicken manure	18 198

Source: own work / Źródło: opracowanie własne

As it is shown in Table 3, the amount of the substrates necessary to supply the biogas plant with power of 1 MWe ranged from 18 198 Mg in case of chicken manure (and somewhat more for silage maize) up to 89 885 Mg for beet pulp. In practice, these calculations eliminate the beet pulp as the main substrate for agricultural biogas plant, because it would require construction of reservoirs of larger capacity, which could drastically increase the cost of the investment. Due to calculation of the substrates mass and taking into account their unit cost, it was possible to calculate the cost the substrate carried by the biogas plant per year. These data are presented in Table 4.

Table 4. Mass and costs of substrates needed for biogas plant feeding
Tab. 4. Masa i koszty substratów niezbędnych do zasilenia biogazowni

Sample	**Substrate mass for biogas plant**	**Unit cost of substrate**	**Total substrate cost**
	Mg*year^{-1}	PLN*Mg^{-1}	PLN*year^{-1}
Maize silage	18 859	100	1 885 900
Beet pulp	86 885	40	3 475 400
Refood	38 040	-20	- 760 800
Chicken manure	18 198	20	363 960

Source: own work / Źródło: opracowanie własne

For a complete economic analysis, in order to calculate IIR and NPV indicators, costs of the substrates have been compared with the price of the installation (14 million PLN), amortization costs (1 035 256 PLN per year) and fixed costs (credit, interest, employment, technical service and technological support, accounting service, insurance). As a result, NPV and IRR indicators have been calculated for option no. 1 (certificates system - Table 5) and for option no. 2 (auction system - Table 6).

Table 5. Economic parameters of biogas plant working in certificates system
Tab. 5. Parametry ekonomiczne biogazowni pracującej w systemie certyfikatów

Substrate	NPV [PLN]	IRR [%]	Average profit before tax [PLN/year]
Maize silage	3 424 579	25	1 393 849
Beet pulp	- 4 213 181	-4	- 132 360
Refood	16 759 202	62	4 058 430
Chicken manure	11 038 051	47	2 915 206

Source: own work / Źródło: opracowanie własne

Table 6. Economic parameters of biogas plant working in auction system
Tab. 6. Parametry ekonomiczne biogazowni pracującej w systemie aukcyjnym

Substrate	**NPV [PLN]**	**IRR [%]**	**Average profit before tax [PLN/year]**
Maize silage	2 133 445	21	1 135 849
Beet pulp	- 5 504 316	-13	- 390 360
Refood	15 468 067	59	3 800 430
Chicken manure	9 746 917	44	2 657 206

Source: own work / Źródło: opracowanie własne

The economic analysis of the biogas plant profitability shows that in 2 cases (refood and chicken manure) the profit from installation exploitation can be very promising (respectively 4.1 and 2.9 M PLN). Maize silage used as a substrate shows positive economic balance but 2-3 times lower comparing with previous substrates. In contrary – beet pulp is discouraged to use as main substrate because this scenario has negative economic balance.

The results presented in Table 6 indicate that, as in case of certificates system – in the auction system operation of a biogas plant with use of waste materials (refood, as well as chicken manure) is the most profitable. Use of the beet-pulp, due to the high price in comparison to the low efficiency of biomethane should be limited. Extremely high rate of the return of investment in a biogas plant working on refood should be noted, because 59% NPV makes that installation brings profits considerably higher than vast majority of the shares, all available debentures (interest-usually a few percent or even below 0 %) or bank deposits.

Moreover, It should be also noted that the analysis does not include the potential that can be rational use of heat, pulp fermentation (valuable fertilizer) and CO_2 from combusted biogas (eg. in greenhouses or cold rooms).

4. Conclusions

1. The substrates (especially their biogas efficiency from 1 ton of fresh mass and price) are one of the most important parameters determining the profitability of biogas plant.
2. From the analyzed substrates - the most energy effective was the chicken manure, just after maize silage. However chicken manure is 5 times cheaper.
3. Refood is the most profitable substrate for biogas plant working in both variants (certificates and auctions), and slightly less favorable - chicken manure. It is related to the best price - methane efficiency ratio, since the adoption of refood for biogas plants receives payment in the amount of 20 PLN per ton.
4. In vast majority of analyzed substrates, investment in agricultural biogas plant is now becoming a very profitable venture, because annual profit before tax fluctuated in the range of 1-4 million PLN.

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This paper was created within realization of the project „High-efficient proecological technology of biogas production based on chicken manure", contract number POIR.01.01.01-00-0548/15-00.