

Article

The Efficiency of the Biogas Plant Operation Depending on the Substrate Used

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Abstract: The study aimed to assess the most efficient solution of raw material management in selected biogas plants into the concept of circular economy and evaluate the most efficient solution of raw material management in selected biogas plants due to the quality and quantity of the feed and the final product obtained, which is biogas, as well at the closed circulation (circular economy). The study evaluated two agricultural biogas plants on a real scale and one at the sewage treatment plant (in real scale) in northeastern Poland. A year-long study showed that in technical terms, the best work efficiency is achieved by agricultural biogas plants processing: silage, manure, apple pomace, potato pulp (biogas plant No. 1), followed by biogas plant No. 3 processing chicken manure, decoction, cattle manure, poultry slaughterhouse waste (sewage sludge, flotata, feathers), and finally, the lowest efficiency biogas plant was No. 2, the sewage treatment plant, which stabilized sewage sludge in the methane fermentation process. Moreover, based on the results, it was found that agricultural biogas gives the best efficiency in energy production from 1 ton of feed.

Keywords: biogas plant; substrate; agricultural biogas plants; energy production



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1. Introduction

Energy is the lifeblood of modern civilization. Biogas is a viable source of energy to tackle the problem of this energy crisis in agriculture-based developing countries [1]. The increasing use of biogas, produced from energy crops, is supposed to change agricultural landscapes in Europe [2]. Protecting the environment from these harms and reducing these adverse effects has become the most crucial target of many countries globally [3,4]. The solutions can be found via renewable energy sources by producing “green power”. Currently, the world level of technical development of biogas plants is very diverse. Several million simple installations in Asia are built using economical methods of digging un-insulated fermentation chambers [5]. The study's primary objective in Northern Germany was to quantify the assumed impact of intensive biogas production with the example of an agricultural landscape [2]. It is a cheap, straightforward, and at the same time, very effective way of processing waste [6].

In Europe, the primary biogas producers are Finland [7], Austria, Denmark, and Germany [2,8]. On the old continent, biogas production varies significantly between countries due to the level of development. In 2013–2017, the use of agricultural biogas increased significantly, while biogas from sewage treatment plants, such as landfill biogas in 2015 and 2016, had their best time, which is associated with a slowdown in the development of these installations in favor of agriculture [5,6,8]. The inhibition of these industries is probably caused by the modernization of wastewater treatment and production of less sludge and the growing awareness of residents about sorting and reducing waste production.

As of 31 December 2017, there were 310 biogas plants in Poland, of which 96 were installations producing agricultural biogas and 214 were other biogas plants. In the group of biogas plants, the remaining 50.47% are biogas plants at sewage treatment plants, 47.62% are biogas plants at landfills, and 1.91% are mixed biogas plants [9]. The material used in biogas production from sewage treatment plants is excessive activated sludge precipitated from municipal and industrial sewage. Installations for the production of agricultural biogas use biomass from unique farms growing high-energy plants, by-products of processing, and plant and animal waste. Until 2015, about 1200 farms dealing with cattle breeding, 3000 farms dealing with pig breeding, and 3500 farms dealing with poultry were registered in Poland—a total of 7800 farms with livestock density above 100 LU, where biogas production is possible, technically justified, and economical [10]. It results, among others, from this branch structure in Poland that is characterized by a great degree of fragmentation [11].

The proper management of livestock manure has a much greater potential to reduce methane emissions, especially in cattle manure [4,12–14]. It should be emphasized that manure stored in piles is a source of essential methane emissions, the scale of which may reach tens of thousands of tons per year in Poland [15]. Almost 59% of the world's methane emissions are of anthropogenic origin, of which the largest share (40–53%) is agriculture, especially intensive production [5]. In the EU, the percentage of agriculture in anthropogenic methane emissions is 53%, 26% is methane from waste, and 19% comes from energy production [4,6].

As these types of solutions increase, the ratio of greenhouse gas emitted in the atmosphere decreases, which is an exceptionally environmentally friendly approach [3]. Additionally, the production of biogas in agricultural areas may provide additional income from agricultural activities, which can develop the local economy in rural areas and promote circular economy principles in local communities [15–17]. Biogas is considered a renewable energy source [10,18]. Therefore, its production allows the increase of the share of these sources in the national energy mix, which is the EU's goal as set out in the renewable energy directive (RED II) [4,19].

The choice of production technology depends on the type of substrates processed, dry matter content in the fermentation chamber 2–6, number of process stages, and temperature at which the fermentation is carried out.

The paper presents the most efficient composition of a raw materials mixture used in two agricultural biogas plants and one based on sewage sludge. Attention was paid to the possibilities of individual substrates to obtain good quality methane in large quantities. In addition, the environmental aspect of wastewater treatment and agricultural waste disposal has been taken into account. The study aimed to assess the most efficient solution of raw material management in selected biogas plants due to the quality and quantity of feedstock and the final product obtained, which is biogas and the closed circulation (circular economy) [8].

2. Materials and Methods

Three biogas plants in real scale were selected for the research: two agricultural and one based on sewage sludge. A local visit was carried out in each of them, and data related to the type, amount of feed obtained, and technology used were collected. Data collection was carried out throughout 2018 in agricultural biogas plant No. 1, with a capacity of 1 MW. The biogas plant uses technology with the flow of biomass to two digesters with a capacity of 4241 m³ each and the third for storage of digestate with a capacity of 6.433 m³ [8]. In the event of a failure, excess biogas is burned in a flare with a throughput of 600 m³/h. The planned capacity of the biogas plant is 1 MW of electricity generation and 941 kW of thermal energy generation. According to Ahmad et al., the energy is the lifeblood of modern civilization. Biogas is a viable source of energy to tackle the problem of this energy crisis in agriculture-based developing countries [1]. The quantitative composition of administered solid substrates in 2018 divided into months is presented in Table 1.

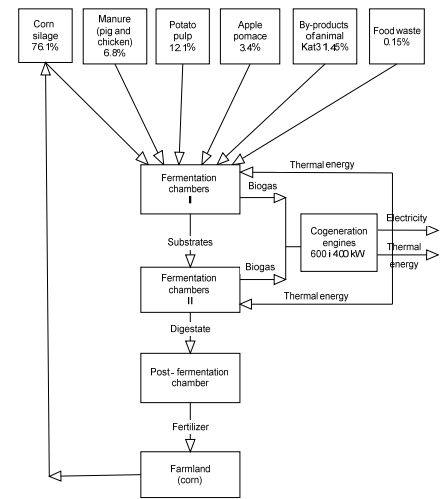
Table 1. Amount of solid substrates fed biogas plant No. 1 in 2018.

Month 2018	Total Silage (t)	Manure (t)	Apple Pomace (t)	Potato Pulp (t)	Others (t)	UPPZ Cat. 2 Stomach Contents (t)	Total Solid Substrates (mln t)	Total Liquid Substrates [t]
I	1135	65.0	0	35	3.50	24.1	1263	1073
II	1067	83.0	0	15	17.6	26.3	1209	864.0
III	944.0	64.0	0	5.0	0	22.2	1035	884.0
IV	725.0	80.0	0	30	0	28.6	863.6	799.0
V	1194	133	0	40	0	26.6	1393	751.0
VI	1274	70.0	0	0	0	30.4	1374	718.0
VII	1240	70.0	0	0	0	20.3	1330	849.0
VIII	996.0	41.0	15.0	0	4.50	23.3	1080	847.0
IX	1018	12.0	170	0	1.00	23.2	1224	788.0
X	820.0	16.0	575	0	0	24.4	1435	945.0
XI	767.0	67.0	626	0	0	29.2	1489	905.0
XII	892.0	64.0	500	51	0	13.0	1520	782.0
Sum	12,072	765	1886	176	27.0	292	15,217	10,204

Biogas plant No. 2 (Figure 1c,d) is built in the sewage treatment plant to stabilize the sewage sludge in the methane fermentation process. Sludge is continuously pumped into the tank to four separate fermentation chambers with a capacity of 7700 m³ each. Biogas is stored in a flexible, low-pressure two-shell gas tank with a capacity of 5000 m³.



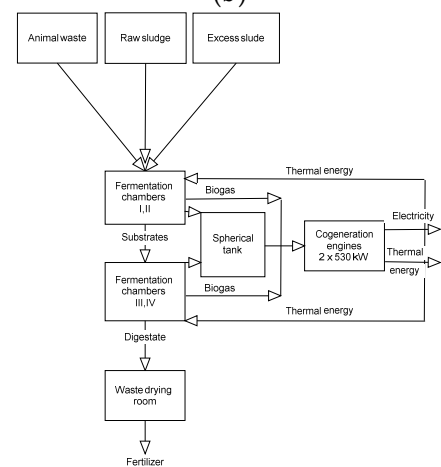
(a)



(b)



(c)



(d)

Figure 1. Biogas plants in Poland: (a) agricultural biogas plant No. 3, (b) scheme agricultural biogas plant No. 3, and (c) biogas plant No. 2 in a sewage treatment plant, (d) scheme biogas plant No. 2 in a sewage treatment plant.

Agricultural biogas plant No. 3 (Figure 1a,b) processes only agricultural production waste, such as chicken manure in the amount of 18,250 t/year, gravel decoction in the amount of 5000 t/year, cattle manure in the amount of 30,000 t/year, and waste from poultry slaughterhouses (sewage sludge, flotation mass, feathers) in the amount of 10,950 t/year. All waste is collected in the 300 m³ primary tank. The purified biogas is directed to a co-generation system, which is known as the combined energy management system, or a combined heat and power system with 1 MW electric and 1.05 MW heat power. In the summer of 2018, the biogas plant took up the most liquid manure, similar amounts of chicken manure and slaughterhouse flotation mass, twice as few flotation mass from dairy and whey from cheese production, and small amounts of plant weight and stomach contents of animals. In the autumn of 2018, chicken manure constituted the most, there was slightly less bovine manure, and flotation mass also played a significant role with whey and dairy flotation mass added to this mix of substrates. The slurry is used to a large extent in winter and spring. Chicken manure is delivered in similar quantities monthly. During the year, agricultural biogas plant No. 3 processed 35,254.97 tons of raw materials. Agricultural biogas plants are becoming attractive in several countries, mainly due to the possibility of obtaining additional incomes by selling energy to the electrical grid [19].

Theoretical Background

The formulas No. 1 and No. 2 were used to calculate the unit biogas production and fermentation efficiency.

Unit biogas production (JPB) is the volume of dry biogas or methane produced per unit time per unit mass of the input substrate. The amount of gas obtained from kg d.m.o. is described by the formula:

$$JPG = G / L_D \quad (1)$$

where JPG —(m³/kg d.m.o.); G —daily biogas production, (m³/d); L_D —daily load, (kg/d).

Fermentation efficiency (degree of conversion) (G_e) is the only indicator that allows comparing the efficiency of different systems, which is defined as the quotient of the daily production of biogas in installations and the daily production of biogas determined under optimal conditions for the same waste (in laboratory conditions at 100% efficiency processing (G_{max})):

$$G_e = G / G_{max} \cdot 100(\%) \quad (2)$$

where G_e —fermentation efficiency, (%); G —daily biogas production in installations, (m³/d); G_{max} —daily biogas production determined under optimal conditions for the same waste (in laboratory conditions with 100% processing efficiency), (m³/d).

3. Results and Discussion

Evaluation of the work of selected biogas plants with the raw materials used.

Three different biogas plants have been assessed. Two of them were agricultural biogas plants and the third was the biogas plant at the sewage treatment plant. All these biogas plants carry out wet fermentation but in different conditions. In biogas plant No. 1, biogas is produced in two main fermentation tanks, and in the third, digestate, additional methane that did not manage to release, is recovered. In biogas plant No. 3, the digestate container is open, and no biogas residues are recovered. In biogas plant No. 2, the digested sludge goes to open averaging and degassing tanks, from where it is fed to compaction and dried to a granular fertilizer. Table 2 presents the most essential components and differences in the construction of a biogas plant. All three biogas plants operate in continuous filling mode.

Table 2. Characteristics of selected biogas plants. Source: Own study based on data from biogas plants.

Biogas Plants	Type of Feedstock Used	Amount of Input Material [t/Day]	Fermentation Chamber Volume [m ³]	Volume of Biogas Tanks [m ³]	Biogas Management
1	Corn silage, manure, liquid manure, fruit pomace, mulch, stomach contents, potato pulp	62	2 × 4.241 6.433	Depends on the fermenter filling level	Co-generators: 400 kW, 600 kW
2	Crude sludge, excessive active sludge, co-ferment	47	4 × 7.700	5.000	Co-generation: 2xJENBACHER JMS 312 GS-B/N.L.; 530 kW each; HORUS HE-sec 480/510; 480-B, 480 kW each; Combustion: 2xVITOPLEX 300, 1.400 kW each
3	Liquid manure, chicken manure, slaughterhouse and dairy fleet, poultry feathers, cheese whey, vegetable matter, stomach contents	98	2 × 3.200 770	500	Co-generator: 0.99 MW el

Biogas plants operate using different substrates with higher or lower efficiency (Figure 2). Biogas plant No. 2 processes an average of 47 m³ of sludge per day, which is kept for 40 days. Sixty-two tons of substrates are processed daily at biogas plant No. 1. Biogas plant No. 3 processes around 98 tons of waste per day, which is held for 22 days. The type of raw materials used is not accidental and has an economic basis [7–9].

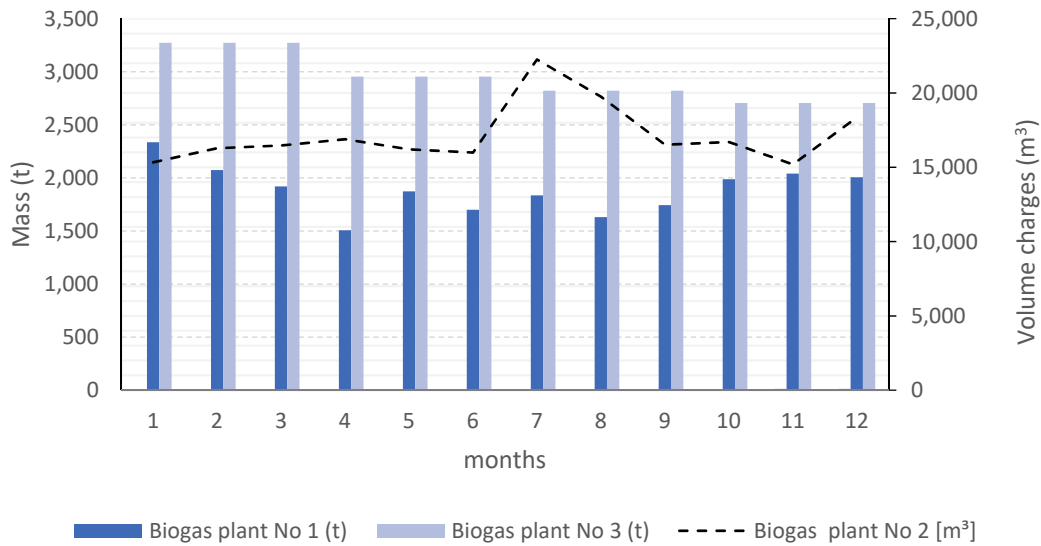


Figure 2. Mass and volume of charges used in biogas plants. Source: own study based on data from biogas plants, t—agricultural biogas plants, m³—biogas plant No. 2.

In the winter months (Figure 2), due to the low air temperature, energy demand did not decrease, and more feedstock was processed in agricultural biogas plants. The opposite (Figure 2) is the situation with biogas plant No. 2, which is mainly used to treat sewage sludge. A sudden increase in the amount of sludge may have resulted from a reduced efficiency of wastewater treatment. The non-concentrated sludge went to digesters with high hydration (>97%), thus inhibiting the amount of biogas produced. For the biogas production from feedstock (Figure 3), the highest amounts are obtained in biogas plant No. 1, which consumes the least raw materials and produces the most biogas [20–22].

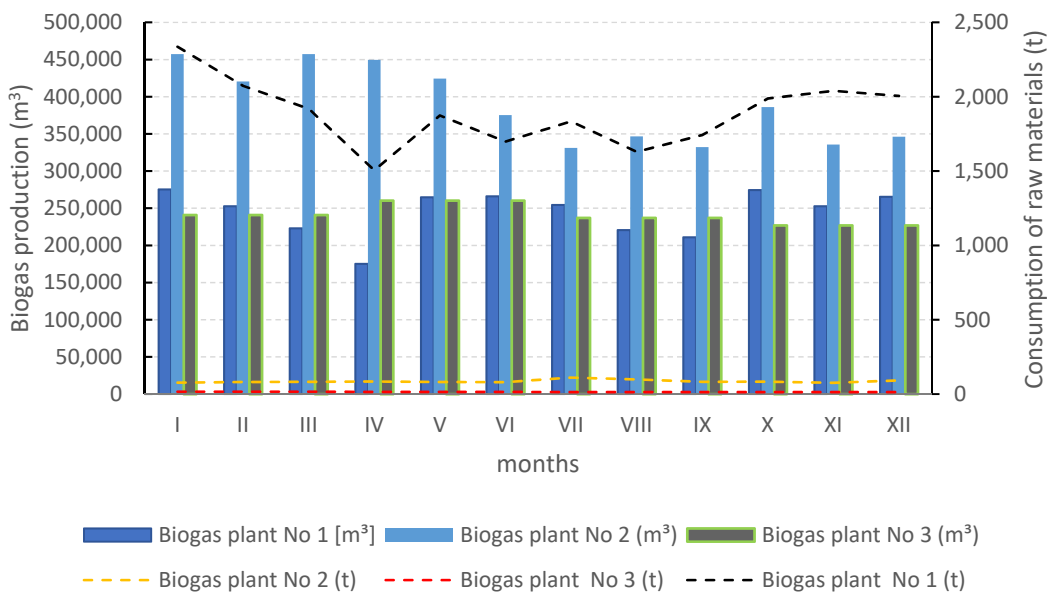


Figure 3. Amount of biogas produced in three biogas plants compared with the amount of substrates used.

In 2018 (Figure 3), biogas plant No. 1 produced on average 117 m^3 of biogas from 1 ton of substrates. The most effective production efficiency in May and June was from 123 to $127 \text{ m}^3/\text{t}$, and it was the lowest in April, September, and November: from 105 to $106 \text{ m}^3/\text{t}$. The only exception was June (127), in which production was recorded for unexplained reasons. This might be due to the supply of large amounts of manure and potato pulp in the previous month, which supplied much biogas only after some retention time. Agricultural biogas plant No. 3 produces slightly less biogas from its substrates. Due to the quarterly data obtained, the monthly amounts presented are averaged. In the third quarter of 2018, the biogas plant monthly produced an average of 85.4 m^3 of biogas from one ton of substrates; in the fourth quarter, this value jumped to $96.2 \text{ m}^3/\text{t}$; in the first quarter of 2019, production was $73.2 \text{ m}^3/\text{t}$, and in the second quarter, it was $76.8 \text{ m}^3/\text{t}$. In Figure 4, winter months were compared with other winter months and summer months with additional summer months. The summary of data from 2019 and later from 2018 illustrates the situation throughout the year.

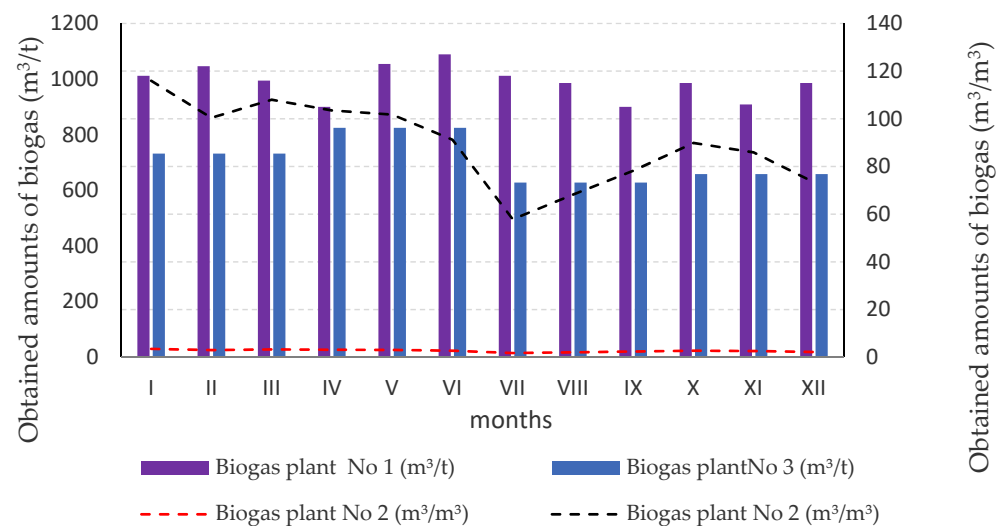


Figure 4. Obtained amounts of biogas per 1 ton or 1 m^3 of substrates, where dashed red line indicates the yield of m^3 biogas from 1 m^3 dry sludge.

In terms of the production of cubic meters of biogas from 1 cubic meter of sludge, the weakest results were obtained in biogas plant No. 2 (Figure 4). Due to high hydration, large volumes of sludge are used for production, and production efficiency is somewhat artificially low. The reactors contain about 3% of dry matter, and in agricultural biogas plants, this amount is much higher. The amount of biogas produced from a cubic meter of sludge from January to June was an average of $27 \text{ m}^3/\text{month}$; in July, a much more considerable amount of sludge was fermented. The rate dropped to $15 \text{ m}^3/\text{month}$; from August to December, the amount of biogas was at a similar level of $20 \text{ m}^3/\text{month}$. Probably, the sludge might not be sufficiently drained, and its volume increased, while production decreased [23–25]. By converting the obtained biogas to the amount of dry mass in the sludge, the situation would become reversed entirely from which it arose. The biogas generated at the sewage treatment plant would be a leader in the production efficiency, with the results from January to June on average $930 \text{ m}^3/\text{m}^3 \text{ DM}/\text{month}$, July $496 \text{ m}^3/\text{m}^3 \text{ DM}/\text{month}$, and from August, $721 \text{ m}^3/\text{m}^3 \text{ DM}/\text{month}$ on average. It should be emphasized that such biogas yield efficiency in agricultural biogas plants cannot be achieved.

Most heat energy (Figure 5) was produced during the heating season (September 1 to May 31 insofar as weather conditions require a continuous supply of heat to heat buildings) [10]. Biogas plant No. 2 (Figure 3) produces more heat than biogas plant No. 1 (agricultural production waste) because of the size of the plant and the technology used. Biogas plant No. 2 at the sewage treatment plant generated the most significant amount of electricity and heat [26]. Biogas plant No. 3 (agricultural production waste, with

technical facilities of 1 MW electric power and 1.05 MW thermal power) comes second in terms of electric energy produced. The biogas plant provides electricity and heat supply to the neighboring plant; therefore, it must work very efficiently throughout the year. The least produced biogas was shown by plant No. 1, which did not produce 100% of its power all year round because of its generator failures. This biogas plant consumes a small amount of available energy for its needs; hence, it can afford small decreases in energy produced [27–30]. In Turkey, there are detailed systems in an industrial biogas plant; thus, as an alternative method to the classical energy productions, the concept that energy can be consumed where it is produced has been successfully applied today to minimize the increase energy costs and use more efficient and clean energy [3].

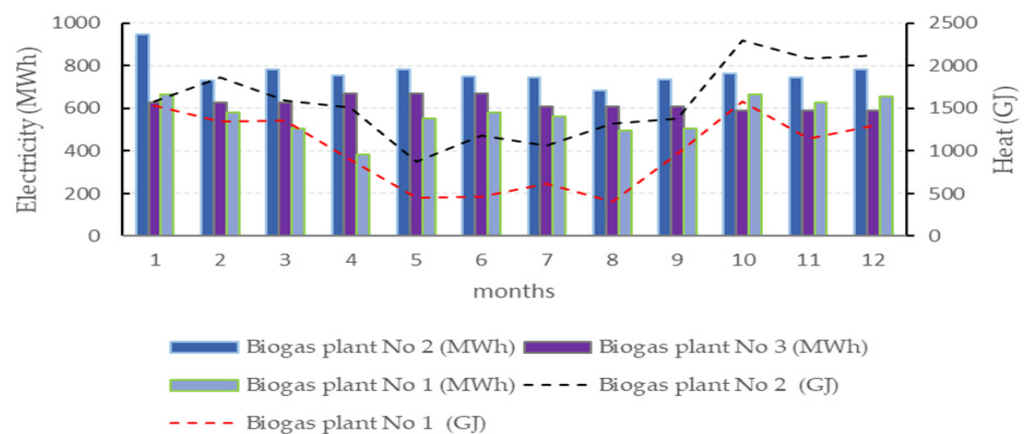


Figure 5. Volume of electricity and heat production in biogas plants No. 1, No. 2, and No. 3 in 2018.

It was found (Figure 6) that for the production of 1MW of energy, the most feedstock was used in biogas plant No. 2, an average of 22.56 m³ of sludge; to improve biogas yield from one m³, it would be necessary to reduce the sludge hydration. Given that biogas produced at the sewage treatment plant is during sludge disposal, there is no reason to increase the sludge thickening before fermentation and increase production efficiency [23,24]. As an excellent alternative choice, biogas production by evaluating organic wastes in an industrial biogas plant, methane gas is produced and converted into heat and electricity energy in co-generation systems [3]. Biogas plant No. 3 needs an average of 4.7 tons of charge to produce 1 MW of power, while biogas plant No. 1 needs only 3.37 tons. Considering the amount of feedstock to produce 1 MW of energy in a biogas plants, the input used has more methane and is more caloric than the input used in biogas plant No. 3. The efficiency and reliability of the devices used significantly impact the final effect of obtaining the biogas for production. The higher the reliability, the higher the efficiency [31–35].

When comparing agricultural biogas plants and sewage treatment plants, the purpose of their operation should be kept in mind [36,37]. The best feedstock working in an agricultural biogas plant will not meet the expected goal in a biogas plant and vice versa. First of all, agricultural biogas produced from corn silage, manure, slurry, fruit pomace, mulch, stomach contents, and potato pulp give the best energy production efficiency from 1 ton. If you want to create profitable production, you must produce most of the annual demand for substrates yourself or import them at very bargain prices. The size of a biogas plant has a considerable impact on production. It can be seen in the example of biogas plant No. 3, which has the minor biogas facility producing an average amount of biogas, consuming a moderate amount of substrates, and having an average efficiency of biogas production compared to other biogas plants. Still, it processes vast amounts of waste (35 255 t/year) at the expense of a short holding time of substrates. It is possible to increase biogas production from the feedstock, which is liquid manure, chicken manure, slaughterhouse, and dairy flotation mass, poultry feathers, cheese whey, plant mass, and

stomach contents [26,38,39]. An additional sealed digestate tank should be built to recover biogas and modify batch hold time.

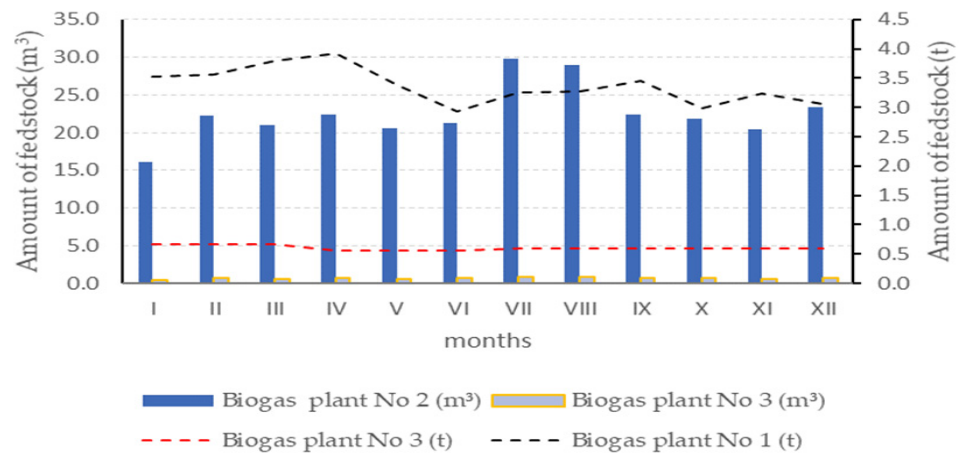


Figure 6. Amount of feedstock used to generate 1 MW of energy.

Biogas plant No. 1 is characterized by the highest efficiency coefficient of biogas production, with the lowest biogas production and consumption of substrates. Low demand for products also translates into lower maintenance costs, i.e., higher earnings. This biogas plant fits best with its technology and the substrates used for biogas production in terms of price and output. In addition to financial aspects, it is necessary to pay tangible ecological and legal benefits for building the biogas plants [14,15,17]. Due to this, it cares for the environment without using non-renewable natural resources and eliminating the effects of global warming [10].

Biogas plant No. 2 at the sewage treatment plant has a different purpose than a typical agricultural biogas plant. Biogas can be used to produce and reduce the operating costs of the treatment plant. Substrates for biogas production are waste from other processes at the treatment plant. No costs are incurred, which translates into potential profit. The biogas produced is valuable waste from sludge disposal and is of outstanding quality. Since substrates are obtained for free while protecting flora and fauna against harmful effects of wastewater, biogas plants at sewage treatment plants are the best solution for biogas production [40]. Biogas production in wastewater treatment plants (WWIPs) plays a decisive role in reducing CO₂ emissions and energy needs in the context of the water–energy nexus [41–45].

In technical terms, the best work efficiency is achieved by biogas plant No. 1, followed by biogas plant No. 3, and finally biogas plant No. 2. Given that biogas installations are designed to do more than just economic profit, namely environmental protection, and natural resources, biogas plants at sewage treatment plants are the unquestioned leader in this respect. They produce suitable quality biogas during waste disposal, which is perfectly suited to turning it into energy reused [46–50]. As Kowalczyk-Juśko et al. showed for the biogas production in Poland, there is a lot of interest in constructing installations of various scales [51].

4. Conclusions

Considering that the input used is one of the most critical factors determining the amount and energy value of biogas, there is still no information on the efficiency of energy production from agricultural waste and sewage sludge, especially when designing biogas plants. Comparing the production efficiency of various methods of obtaining energy from biogas enables the detection of factors that make the processes carried out more efficiently. When preparing models of financial and economic analysis of projects for the construction of agricultural biogas plants, both those that are smaller (up to 0.5 MW) and more prominent, researchers should pay attention to the “energy quality” of the substrates,

whose chemical energy in the fermentation process in the final stage is used to power the co-generation system into the environment. It means that the values of the dry matter content of the substrates and the dry organic matter content of the dry matter can significantly influence the efficiency already in the early planning of a biogas plant project. Therefore, it is vital at the initial stage of the project to perform a substrate efficiency test, and on this basis, specific technological solutions of a biogas plant should be adopted, which is necessary for the performance of an energy balance allowing, as a result, estimation of the amount of produced electricity and heat. The data presented in the article show that the tested biogas plants did not analyze the energy content of the raw material but focused on the ease of obtaining the raw material, which in turn translated into benefits in the form of reducing greenhouse gas emissions to the environment and improving energy security. Moreover, the analyzed agricultural biogas plants will stimulate the development of local entrepreneurship and activate the countryside economically by creating new jobs. The use of the produced biogas leads to a reduction in purchased energy consumption and waste disposal in a biogas plant based on a sewage sludge treatment system at a sewage treatment plant.

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