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THE SENSITIVITY OF AGRICULTURAL BIOGAS PLANTS TO CHANGES IN ENERGY PRICES IN POLAND

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ABSTRACT: In Poland, despite ambitious plans from 15 years ago, when it was assumed that by 2020, an agricultural biogas plant would be standard in every commune, the potential of agricultural biogas has not been used due to the lack of stable legal regulations and financing programmes for the construction of the plants. The situation has now changed due to new forms of support systems, which motivated the authors to compare two agricultural biogas plants operating in the certificate system and the support system in the form of feed-in premiums. Moreover, the authors pointed to differences in the number of agricultural biogas plants and their capacity by voivodeship due to changes in legal conditions in force in two periods: from 1 January 2011, to 30 June 2016, and from 1 July 2016, to 19 January 2024. Based on the research methods used – including Earnings Before Interest, Taxes Depreciation and Amortisation, the Internal Rate of Return, risk matrix and data analysis in spatial terms – it was indicated that: 1. agricultural biogas plants are characterised by very high sensitivity related to the probability of risk in the case of investment costs, substrate prices and changes in energy prices; 2. financial support is important at the stage of construction of a biogas plant, which largely makes it possible to shorten the payback period and thus increase the willingness of future investors to invest in biogas plants and 3. in the periods analysed, significant differences were noted in the spatial location of biogas plants due to trends towards lower-power biogas plants, which is probably dictated by the constant and predictable premium system in the new support system.

KEYWORDS: agricultural biogas, energy prices, support system, EBITDA, IRR, risk matrix, Poland

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Introduction

In developed countries, the development of biogas focuses on larger-scale biogas plants operating on agricultural and commercial farms, producing electricity and heat, in contrast to developing countries, where biogas is produced on a home scale to provide fuel for cooking and lighting (Scarlat et al., 2018). In the European Union, most biogas is used as fuel to generate electricity, in power plants producing only electricity or in combined heat and power plants, aiming to maximise the use of heat to increase income and improve the economics of biogas plants. Biogas plants are usually high-efficiency co-generation installations, which means that they produce both electricity and heat in one process. This can be used by a farm, but its surplus can also supply existing local heating networks or be used to heat residential and public buildings, etc., located close to the biogas plant (Bednarek, 2023). According to data from the American Biogas Council (2023), there are over 2,400 biogas production plants in the USA, including 473 anaerobic digesters on farms. By comparison, Germany has almost 10,000 digesters, keeping some communities essentially free of fossil fuels. In Poland, according to the data of the Krajowy Ośrodek Wsparcia Rolnictwa[1] (National Centre for Support of Agriculture) (Krajowy Ośrodek Wsparcia Rolnictwa, 2024), there are 137 entities operating 153 agricultural biogas plants with a total electrical capacity of 155,486 MW and an annual efficiency of agricultural biogas production of PLN 633,580,965,000 m^3 (Teraz Środowisko, 2023)[2]. The use of biogas as an energy source brings various benefits, including reducing costs related to energy purchases and increasing self-sufficiency and energy independence. At the same time, biogas plants are highly sensitive to changes in energy sales prices due to the lack of a guaranteed stable sales price for energy produced from agricultural biogas (Powałka et al., 2013) and changes in the costs of raw materials (Ertop et al., 2023), because these are the ones that mainly influence the economics of the installation. Noteworthy among the environmental benefits are waste management and recycling of organic waste (digestate as fertiliser) (Piwowar, 2020) and a significant reduction in greenhouse-gas emissions (Samson-Bręk et al., 2022; Ertop et al., 2023) thanks to which Poland contributes to meeting the objectives set by the European Union (Parlament Europejski, 2023; Stankiewicz, 2023; Ministry of Climate and Environment, 2021). Moreover, the development of the agricultural biomass market is also expected to benefit in terms of employment opportunities and regional development, especially in rural areas, isolated areas, areas with low population density, and partially deindustrialised areas (Janiszewska & Ossowska, 2023).

In Poland, the potential of agricultural biogas, despite ambitious plans from 15 years ago, where it was assumed that by 2020 an agricultural biogas plant would be the standard in every commune (Magazyn Biomasa, 2023), has not been used due to the lack of stable legal regulations and financing programmes for the construction of the plants (Bednarek et al., 2023). Due to the Act of 13 July 2023 on facilitating the preparation and implementation of investment in the field of agricultural biogas plants, as well as their operation, it is estimated that the new regulations may result in the creation of up to 2,000 agricultural biogas plants in Poland (Gram w zielone, 2023), owing to the potential of rural areas covering almost 93% of Poland's area and concentrating about 30% of all energy consumers (Morawiecki, 2023). As indicated by the Ministry of Agriculture and Rural Development (Morawiecki, 2023), agricultural biogas plants respond to the urgent need to increase the number of stable, weather-independent renewable energy sources in the Polish energy mix. They can produce energy for up to 8,000 hours a year (90% of the time) – unlike other renewable energy installations, whose energy efficiency ranges from 10% to 30%. Agricultural biogas plants created under the new special act are therefore to be local. This type of installation will be able to have a maximum power of 3.5 MW of electricity generated or 10.5 MW of thermal power and an annual agricultural biogas production capacity not exceeding 14 million m^3. As indicated in the justification for the act (Act, 2023), the limits adopted correspond more or less to the average demand for energy or heat in a rural commune (Magazyn Biomasa, 2023).

Each biogas plant production installation may have a different individual design adapted to the technology, including the type of input material. The choice of process and technical equipment for a

[1] According to Act (2015), the authority maintaining the register of agricultural biogas producers is the Director-General of the National Support Centre for Agriculture.

[2] The study does not take into account the number of micro-installations using agricultural biogas that were not entered into the KOWR 42 register, the capacity of which at the end of 2023 was 1,403 MW.

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given installation mainly depends on the substrates available. In Poland, over the last six years, the most frequently used substrate has been distillery stillage, followed by liquid manure and food processing waste (Figure 1). In 2022, almost 5,700,000 tonnes were used to produce agricultural biogas tonnes of raw material, of which the 10 most popular constituted over 90% (Bednarek, 2023).

A still underestimated substrate is digestate from agricultural biogas plants, which, in accordance with the provisions of the Act of 14 December 2012 on waste (Obwieszczenie, 2022), is waste and can be used as agricultural waste for fertiliser purposes following the provisions of the Regulation of the Minister of the Environment of 20 January 2015. Digestate from biogas plants has good fertilising value, similar to natural fertilisers. However, this value may vary depending on the type of substrate used for biomethanation. The composition of the post-fermentation mass is dominated by nitrogen, phosphorus and potassium (Makádi et al., 2012; Rzeźnik et al., 2017; Czekała, 2022); even organic carbon (Pastorelli et al., 2021). It may also contain other elements, such as copper, zinc, iron, manganese, calcium, magnesium or sulphur (e.g. Jadczyszyn & Winiarski, 2017; Rzeźnik et al., 2017). Furthermore, a positive effect of digestate on crops has been proven (Witorożec-Piechnik et al., 2021; Lohosha et al., 2023; Popović et al., 2023). Moreover, locally available post-fermentation mass reduces the cost of mineral fertilisation (Kowalczyk-Juśkoi & Szymańska, 2015). The agricultural use of digestate from biogas plants (resulting from biogas production) as a fertiliser is conditioned by ensuring safety for human health, animals and the environment, mainly the environment of agricultural land and the water environment (Walsh et al., 2012; Łagocka et al., 2016; Mukhtar et al., 2022; Witorożec-Piechnik et al., 2022).

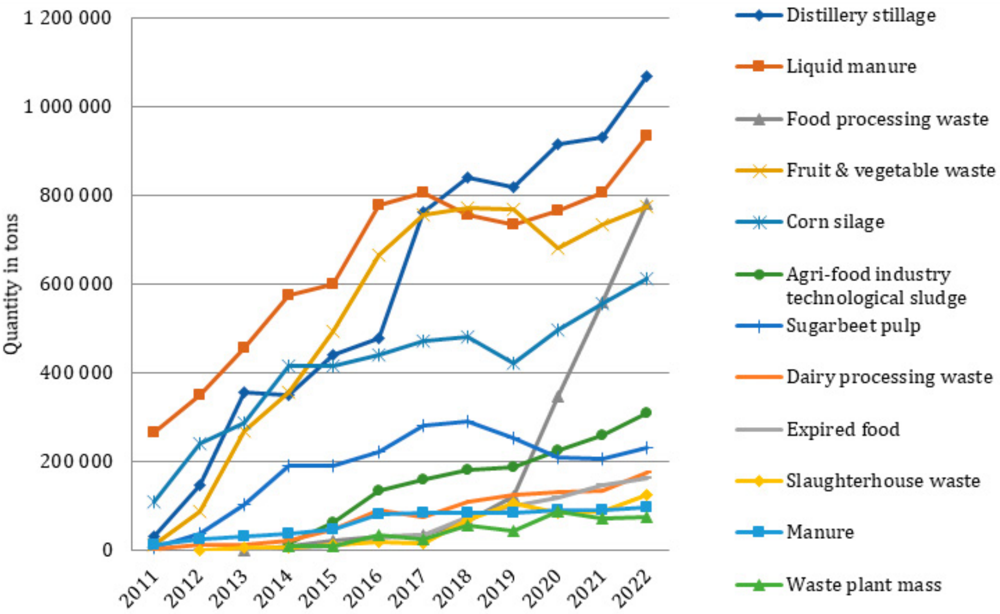

Figure 1. List of selected substrates used to produce agricultural biogas in Poland in 2011-2022
Source: authors' work based on Serwis Rzeczypospolitej Polskiej (2023).

Relating the potential of agricultural biogas production in Poland to the available substrate, it is estimated that it amounts to several billion m^3 per year and is comparable to the potential of Germany, taking into account, for example, the fact that Poland produces approximately 120 million tonnes of manure and slurry annually and at least 8 million tonnes of cereal and rapeseed straw (Bednarek et al., 2023). However, it should be emphasised that the best substrate for a biogas plant is one that is available locally (Koryś et al., 2019; Janiszewska & Ossowska, 2023) and so does not generate additional transport costs (Gadirli et al., 2024; Siudek & Klepacka, 2022). Moreover, reducing the transport distance of raw materials for biogas production also affects the final effect of reducing carbon dioxide emissions (Siudek & Klepacka, 2022).

As part of the state's involvement in the development of agricultural biogas plants, educational activities were undertaken to provide the necessary theoretical and practical knowledge about agricultural biogas plants to potential investors. In 2023, KOWR organised a series of workshops (Kraj-

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owy Ośrodek Wsparcia Rolnictwa, 2023; Wieści Rolnicze, 2023), during which the functioning of agricultural biogas plants was discussed in legal, financial and environmental aspects. The construction of a biogas plant may be co-financed by, among others: the Modernisation Fund, which is a source of funds for the "Energy for Rural" programme lasting from 2022 to 2030. This programme is run by the Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej (National Fund for Environmental Protection and Water Management). Under the programme, whose aim is to use renewable energy sources in rural and rural-urban areas, one can apply for funding for the construction of a biogas plant in the form of a subsidy of up to 65% of eligible costs and/or a loan of up to 100% of eligible costs (Ministerstwo Rolnictwa i Rozwoju Wsi, 2024). The beneficiaries may be: a farmer, i.e. a natural person, a legal person and an organisational unit without personality that runs: a farm or a special department of agricultural production; energy cooperatives and their members and emerging energy cooperatives. Due to the great interest in the programme in 2023, the budget of the first recruitment was extended and increased from PLN 100 million to PLN 1 billion in 2024.

The aim of the article is to compare two agricultural biogas plants operating in two renewable energy sources (RES) support systems, i.e. the certificate system and the support system in the form of a guaranteed premium (feed-in premium – FIP). Moreover, differences in the number of agricultural biogas plants and their capacity by voivodeship were indicated in the article due to changes in legal conditions in force in two periods: from 1 January 2011 to 30 June 2016 and from 1 July 2016 to 19 January 2024.

Support system – selected solutions

Since 1 October 2005, PMOZE and PMOZE_A[3] have been in force in Poland, issued by the President of the Energy Regulatory Office. On 28 June 2016 the President of the Republic of Poland signed an amendment to the Act of 22 June 2016 amending the Act on Renewable Energy Sources and certain other acts, which entered into force on 1 July 2016 (Palusiński, 2016). The obligation to present redemption certificates of origin of energy from renewable sources, i.e. green certificates for the entire second half of 2016, has changed from 15% to 14.35%. This meant that the energy seller for the second half of 2016 was obliged to submit a smaller number of green certificates concerning electricity sold to the end user for redemption, which was caused by the introduction of PMOZE-BIO.[4] The separation of blue certificates had positive financial consequences for operating agricultural biogas plants because the prices of green certificates were much lower than the blue ones (Figure 2). A significant decline in the prices of green certificates began in the second half of 2016, and they rebounded again in the second half of 2018. In the case of blue certificates, the highest price (according to the price for a given monthly validity period, i.e. monthly prices for session transactions concluded during the three previous calendar months) was recorded in July 2017, when the price of green certificates reached the lowest level in the entire period analysed.

Since 2010, PMGM, i.e., called yellow certificates, have been issued for gas-fired installations with a capacity below 1 MW, which is concerned with gas co-generation. In the same year (on September 22), the President of the Energy Regulatory Office issued the first certificate of origin of energy from a methane-fired unit – PMMET, the purple certificate (Energy Regulatory Office, 2010). The system of yellow and purple certificates was valid until the end of 2018, with the obligation to settle by 30 June 2019. The price development of PMGM and PMMET in the years they were in force is presented in Figures 3A and 3B.

3 PMOZE and PMOZE_A the yellow certificates, which concerned gas co-generation and were valid from 2010 (TGE, 2024).

4 PMOZE-BIO the blue certificates regarding support for electricity generated from agricultural biogas (TGE, 2024).

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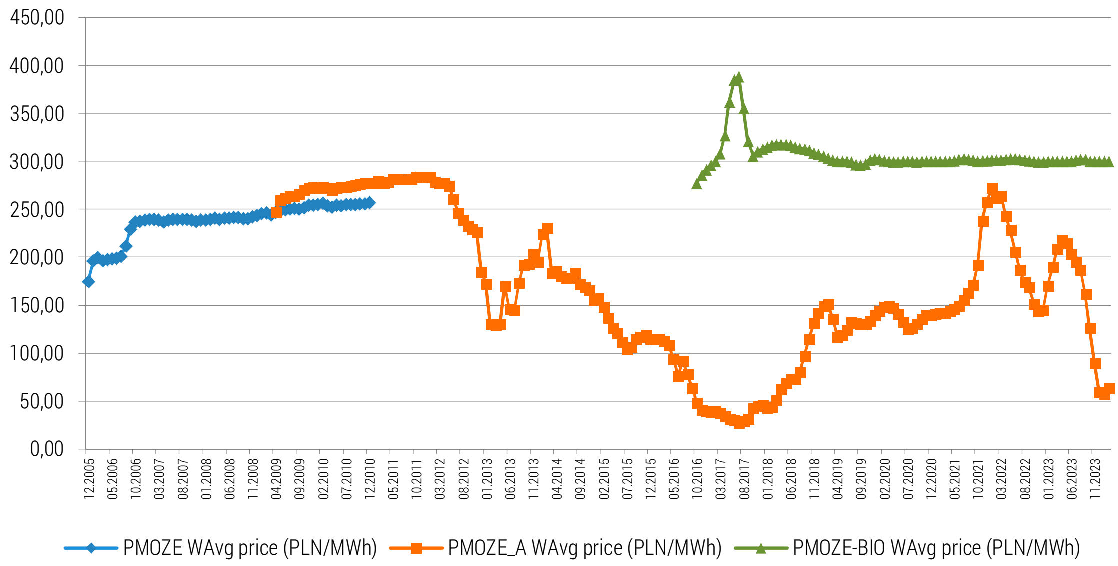

Figure 2. Monthly prices of PMOZE and PMOZE_A and PMOZE-BIO certificates[5] from 2005, July to 2024, February [PLN/MWh]

Source: authors' work based on TGE (2024).

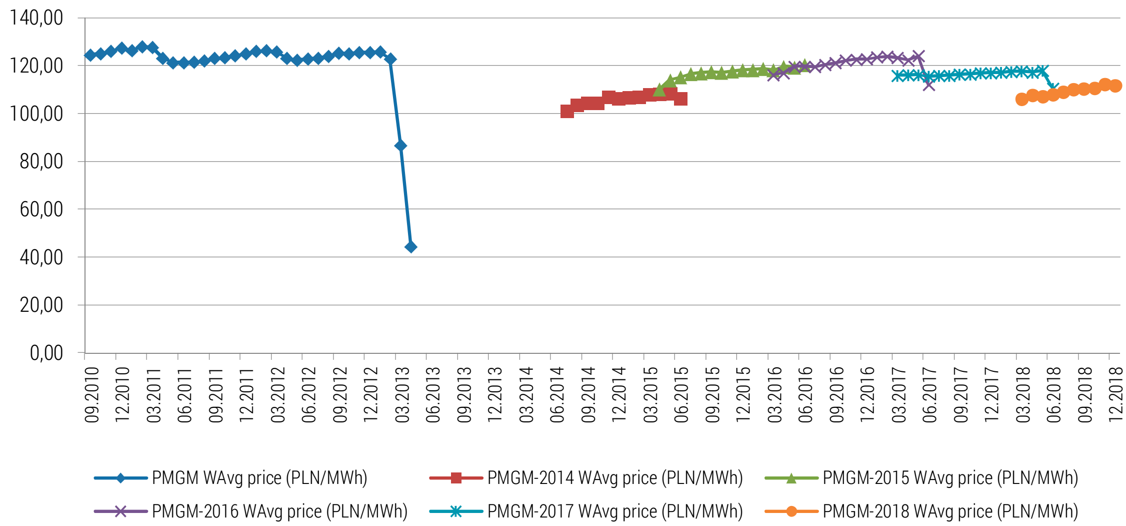

Figure 3A. Monthly prices of PMGM (yellow) certificates in 2010-2018 [PLN/MWh]

Source: authors' work based on TGE (2024).

5 PMOZE and PMOZE_A – price of property rights in accordance with Article 47 section 8 point 2 of the Act on Renewable Energy Sources, indicates the lack of transactions concluded for particular validity period; PMOZE-BIO – price of property rights in accordance with Article 47 section 8 point 1 of the Act on Renewable Energy Sources, indicates the lack of transactions concluded for a particular validity period.

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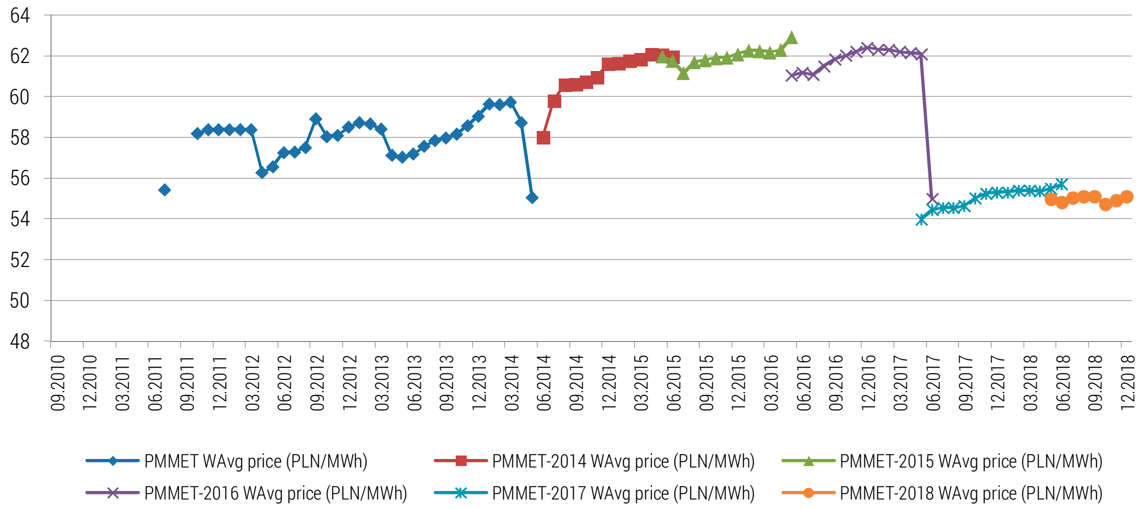

Figure 3B. Monthly prices of PMMET (purple) certificates in 2010-2018 [PLN/MWh]

Source: authors' work based on TGE (2024).

When describing certificates of origin of electricity, it is also necessary to mention the guarantee of origin of the energy. These are used to demonstrate to the end user that a specific part or all of the energy produced was produced from renewable sources. The basic purpose of guarantees of origin is to support producers and demonstrate to the recipient the source of energy they use. The price level of energy guarantees is presented in Figure 4.

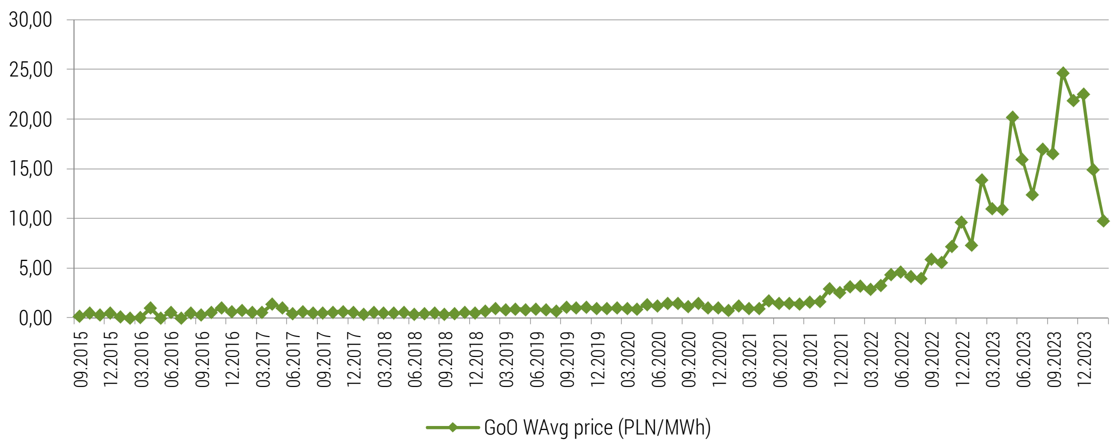

Figure 4. Monthly guarantee prices of origin for renewable electricity (without co-generation) in 2015-2024 [PLN/MWh]

Source: authors' work based on data from the Polish Power Exchange (2024).

From 14 July 2018, according to the Act of 7 June 2018, amending the Act on Renewable Energy Sources and certain other acts, provisions came into force (Act, 2018) introducing the feed-in-tariff (FIT) and feed-in-premium (FIP) system (Urząd Regulacji Energetyki, 2018). The first system concerns feed-in tariffs, which involves the generator obtaining the right to conclude an electricity sales contract with the obligated seller at a fixed guaranteed price, which constitutes 95% of the reference price. The second system, the system of subsidies (premiums) for energy prices, consists of covering the negative balance, which is the difference between 90% of the reference price announced for a given installation and the average price on the Polish Power Exchange.

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In the years 2021-2023, following the proposal of the Ministry of Climate and Environment, the applicable reference prices for energy production using only agricultural biogas to generate electricity included six installation-capacity proposals (Urząd Regulacji Energetyki, 2023): 1) with a total installed electrical capacity of less than 500 kW; 2) with a total installed electrical capacity of less than 500 kW, from high-efficiency co-generation; 3) with a total installed electrical power of not less than 500 kW and not more than 1 MW; 4) with a total installed electrical power of not less than 500 kW and not more than 1 MW, from high-efficiency co-generation; 5) with a total installed electrical capacity greater than 1 MW; 6) with a total installed electrical capacity of more than 1 MW, from high-efficiency co-generation. The level of reference prices corresponding to individual installation capacities, taking into account the FIT system (95% of the reference price) and FIP (90% of the reference price), is presented in Table 1. Details regarding the eight forms/instruments of support discussed above are presented in Table 2.

Table 1. Reference price per MWH [PLN] for a range of RES installations/agriculture biogas [kW] in 2021-2023 in auctions and FIT/FIP system

Year	Reference price per MWH [PLN] for range of RES installations/agriculture biogas [kW]									
	< 500 capacity	< 500 capacity FIT*	<500 capacity with high co-generation efficiency	<500 capacity with high co-generation efficiency FIT*	≥ 500 and ≤ 1,000 capacity	≥ 500 and ≤ 1,000 capacity FIP**	≥ 500 and ≤ 1,000 capacity with high co-generation efficiency	≥ 500 and ≤1,000 capacity with high co-generation efficiency FIP**	> 1,000 capacity	> 1, 000 capacity with high co-generation efficiency
2021	650	617.5	760	684	590	531	700	630	570	670
2022	785	706.5	920	828	715	643.5	840	756	700	800
2023	872	784.8	1025	922.5	793	713.7	941	846.9	775	896

Note:
*95% of the relevant reference price – in the case of producers of electricity from renewable energy sources in a renewable energy-source installation with a total installed electrical capacity of less than 500 kW.
**90% of the relevant reference price – in the case of producers of electricity from renewable energy sources in a renewable energy-source installation with a total installed electrical capacity of not less than 500 kW and not more than 1 MW.

Source: authors' work based on Rozporządzenie (2020), Rozporządzenie (2021), Rozporządzenie (2023).

Table 2. General information for selected financing mechanisms for agricultural biogas plants in Poland

Specification	Legal basis	Definition	Validity	General Information
PMOZE, PMOZE_A system, the green certificates	Dyrektywa (2001), Act (1997), Act (2016), Act (2015),	Property rights resulting from certificates of origin of electricity from renewable energy sources, which are an instrument to support electricity from renewable energy sources, which is a separate category of products on the Polish Power Exchange. Companies selling electricity to end users are obliged to purchase them (or they may have to pay a substitute fee in certain circumstances).	From 1 October 2005	For each 1 kWh of renewable energy generated during the supported period, its producer receives one certificate. From 1 July 2016 energy producers in new RES installations cannot apply for the support system based on certificates of origin. From 2020, installations that have completed their 15-year support period are gradually ending their participation in the system. At the end of 2022, there was approximately 7.2 GW of capacity in the green certificate system, while by 2025 approximately 1 GW will have left the system. In the second half of 2016, the obligation to purchase property rights resulting from certificates of origin of electricity from renewable energy sources amounted to 14.35%. The obligation to purchase green certificates from operators of other renewable energy sources for 2017 was 15.4%; for 2018-2019 18.5%, for 2020-2021 19.5%, for 2022 18.5%, and for 2023 12%.

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Specification	Legal basis	Definition	Validity	General Information
PMOZE-BIO system – the blue certificates	Act (2016)	Property rights resulting from certificates of origin of electricity from agricultural biogas separate from the green certificates system.	From 1 July 2016	For each 1 kWh of energy generated from agricultural biogas during the supported period, its producer receives one certificate. In the second half of 2016, the obligation to purchase property rights resulting from certificates of origin of electricity from agricultural biogas was established, which amounted to 0.65%. As part of the regulation of the Minister of Energy of 30 November 2016 it was proposed to define the RES obligation for 2017 by creating a separate obligation to purchase certificates of origin for energy produced in agricultural biogas plants, which amounted to 0.5%.
PMGM and PMMET system, the yellow and purple certificates	Act (2010), Act (1997), Act (2006), Act (2015),	Property rights arising from certificates of origin of electricity produced in high-efficiency co-generation in the sources referred to in Art. 9l section 1 point 1 of the Energy Law (PMGM) or produced in high-efficiency co-generation in the sources referred to in Art. 9l section 1 point 1a of the Energy Law (PMMET), which is an instrument to support electricity generated in high-efficiency co-generation. These constitute a separate product category on the Polish Power Exchange.	From September 22, 2010, to December 31, 2018	According to the amendment to the Energy Law in 2014, the obligation to purchase certificates of origin for energy generated in high-efficiency co-generation was 3.9% and was to gradually increase to 8% in 2018. In the case of purple certificates, the required level is 1.1%. in 2014 and was to increase every year to reach 12.3% in 2018.
Guarantees of energy origin	Act (2014), Act (2015),	Act (2014), Act (2015),	From November 3, 2014	Guarantees of the origin of electricity are not a stock-exchange commodity. They are traded directly in the register of the Polish Power Exchange, which means that companies interested in the contract should contact each other. Guarantees of origin are issued only in electronic form and transferred to the Register of Guarantees of Origin (RGP). They are subject to domestic and European trade. With an offer constructed in this way, it is possible to sell a guarantee regardless of the physical supply of electricity to a given entity. The only thing that matters is the fact of producing and marketing green energy, which fundamentally reduces the demand for energy obtained from fossil fuels.
Feed-in-Tariff (FIT) system	Act (2018)	The FIT system involves the generator obtaining the right to conclude an electricity sales contract with the obligated seller at a fixed price, which constitutes 95% of the reference price. The reference price is determined for a given calendar year by a regulation by the minister responsible for energy, in force on the date of submission of the FIT declaration.	From 14 July 2018	The FIT system can be used by producers of electricity from renewable energy sources in a small installation or micro-installation (for a power not exceeding 500 kW) who sell or will sell unused electricity to the obligated seller. The reference price is published annually by the end of October for the following year and depends on whether the energy is produced in high-efficiency co-generation or not. The fixed purchase price takes into account the public investment aid received and is subject to annual indexation with the average annual price index of total consumer goods and services from the previous calendar year, specified in the announcement of the President of Statistics Poland published in the Official Journal of "Monitor Polski".

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Specification	Legal basis	Definition	Validity	General Information
Feed-in-Premium (FIP) system	Act (2018)	The FIP system is based on a subsidy to the market price (understood as the average price on the Polish Power Exchange on each day of the settlement period). It involves covering the negative balance, which is the difference between 90% of the reference price announced for a given installation and the average price on TGE. The reference price is determined for a given calendar year by a regulation by the minister responsible for energy, in force on the date of submission of the FIP declaration.	From July 14, 2018	The FIP system is intended for electricity producers in renewable energy-source installations with a total installed electrical capacity of no more than 1 MW, who sell or will sell unused electricity to a selected entity other than the obligated seller. The reference price is published annually by the end of October for the following year and depends on whether the energy is produced in high-efficiency co-generation or not.
Auctions	Act (2015), Act (2023), Rozporządzenie (2023)	Support system for producers of renewable electricity in the form of auctions organised by the Energy Regulatory Office.	From December 30, 2016	Auctions are organised at least once a year. The RES auction announcement contains information on the maximum amount and value of electricity from renewable energy sources that may be sold during a given auction. After registering an IPA account, you must submit an appropriate declaration with the necessary information about the RES installation. If all parameters of a given auction are met and a certificate allowing participation in the auction is issued, the auction is won by the participants who offer the lowest prices and whose offers did not exceed the total amount or value of electricity from renewable energy sources included in the auction announcement. The average offer prices during the first auction for existing biogas plants were PLN 503/MWh.

Source: authors' work based on legal basis.

An overview of the literature

An innovative approach in the article is to present the mechanisms of the support system divided into two periods, which correspond to the validity period of certificates of origin from renewable energy sources (certificates) and/or the support system in the form of a guaranteed premium (feed-in premium – FIP). The literature on the subject includes references to guaranteed prices of energy from biogas under feed-in tariffs, which create good conditions for the operation of biogas plants (Kusz et al., 2023; Mamica et al., 2022; Ignaciuki & Sulewski, 2021), or support systems as one of the key factors in the development of agricultural biogas in Poland (e.g. Szyba & Mikulik, 2023; Piwowar, 2020; Igliński et al., 2012); however, the literature on the subject does not present the impact of the support system on price fluctuations in deliberately selected by the authors' periods.

Material and methodology

To conduct a comparative analysis of two agricultural biogas plants, actual financial and accounting data for the years 2010-2022 and estimated data based on historical data for the period from 2023 to 2029 were used. The total analysis period is 20 years. The starting point of the analysis was the amount of electricity generated, i.e. production efficiency, because it determines the amount of energy that can be traded internally or externally and is balanced. Biogas plants are marked in the text as BGR1 and BGR2. BGR1 was launched in June 2010, while BGR2 followed in September 2010. Both biogas plants have the same capacity. However, in the historical period BGR1is characterised by

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higher efficiency, averaging almost 92% in the period from 2011 to 2022. In the period 2011-2022, BGR2 achieved an average efficiency of over 87%. The 5% difference in efficiency was primarily due to technical reasons. The amount of electricity generated in BGR1 and BGR2 in 2010-2022 is presented in the chart Figure 5.

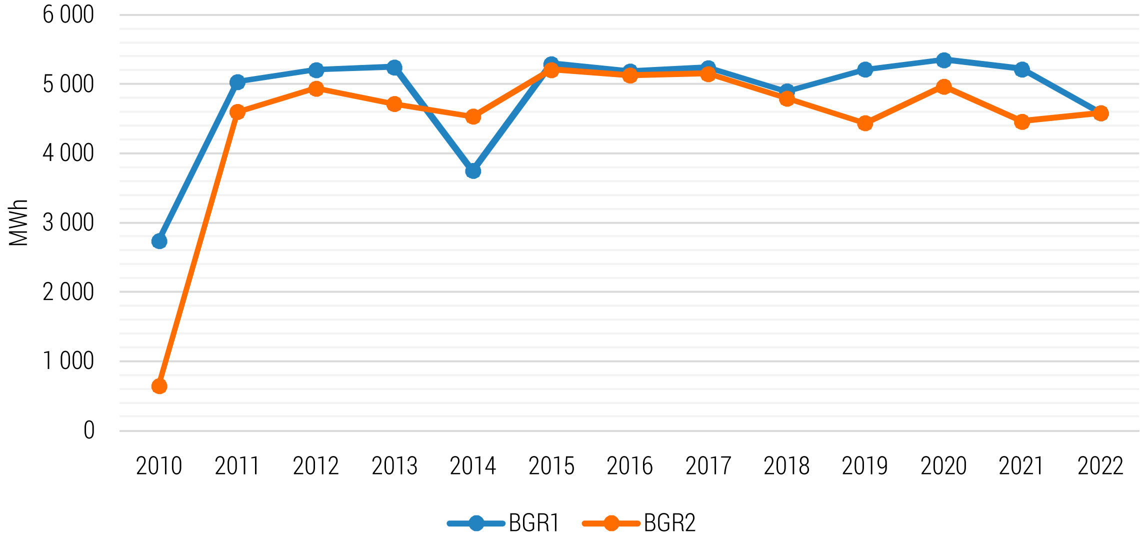

Figure 5. Electricity production in biogas plants analysed in 2010-2022 [MWh]

Source: authors' work based on materials provided by the analyzed biogas plants.

Biogas plants are located near fattening farms, from which slurry comes, which is the basic substrate for the production of agricultural biogas, supplemented with maize silage and other substrates. Other agricultural residues are used from time to time in small quantities (0,5-3% of substrates in BGR1 and 0-0,2% in BGR2). In the case of BGR1, the share of slurry, which is a free substrate from the neighbouring finisher farm, is 70% in the case of BGR2 – 80%. The remaining part is maize silage. The digestate collection from both biogas plants is used as high-quality organic fertiliser on their own fields. This fertiliser is better absorbed by the soil than natural fertiliser in the form of raw slurry. The fieldwork related to fertilisation with organic fertiliser is more labour-intensive than fertilisation with natural fertiliser, but its value compensates for these difficulties. Thanks to this, nitrogen is better used in fertilisation (saving on the purchase of pure nitrogen), and pesticides are reduced because pathogens and weed seeds, as well as various types of bacteria, are destroyed in the fertilisation process. Additionally, replacing artificial and natural fertilisers with the digestate collection reduces greenhouse-gas emissions. In the case analysed, the costs related to fertilisation with the digestate collection, as well as the revenues, are neutral for cash flows because it is its own product and is used on its own. However, there are savings in the purchase of pure nitrogen at the level of approximately PLN 10 per tonne of organic fertiliser (1 tonne of the digestate collection contains approximately 2.5 kg of nitrogen, the price of which is approximately PLN 4/kg).

Both biogas plants benefited from EU funding for the construction of biogas plants. Until November 2020 inclusive, BGR1 and BGR2 used a support system in the form of certificates. Since December 2020, biogas plants have been using two different support systems.

The revenues and costs of the biogas plants analysed were included in the analysis (Table 3). The EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortisation) indicator was used To analyse the operating profit, i.e. the company's profitability indicator, giving a negative value (when the activity is economically unsustainable) and, on the other hand, a positive value (which does not mean that the business is profitable) (Casasso et al., 2021). Moreover, a method was used to assess the economic effectiveness of a tangible investment, i.e. the internal rate of return (IRR) was calculated. A sensitivity analysis was carried out to assess the impact of individual variables on the assessment of investment profitability , including (Earnings Before Interest, Taxes, Depreciation, and Amortisation) EBITA, the Internal Rate of Return (IRR), a net present value (NPV), and return on invested capital (ROIC).

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Table 3. Components of revenues and costs of the biogas plants analysed

Revenues of the biogas plants analysed	Costs of the biogas plants analysed
• Internal sales of energy at the average energy price on the balancing market plus distribution costs and excise tax. This is the equivalent of energy costs if energy were purchased externally, excluding energy-colouring costs and margins. In the case of the biogas plants analysed, there are two types of internal sales: sales via their cable line (no external distribution costs) and sales via the distribution network to facilities without a biogas plant (charged with external distribution costs).	• Raw material costs – mainly the cost of maize silage calculated based on market prices of silage and the costs of waste grain, straw, and raw-material transport
• Sale of surplus energy to the trading company at the average price on the balancing market	• Costs of oil and fuel, including engine oil and grease, as well as diesel fuel
• Internal sale of heat to neighbouring pig farms at a price calculated based on the cost of gas that would have to be purchased to heat the buildings if there were no heat from the biogas plant	• Broadly understood distribution costs relating to energy transmitted to facilities without a biogas plant, included in the internal price of electricity
• Heat sales in the case of BGR1 to external customers	• Maintenance costs
• Sale of property rights resulting from certificates of origin of electricity from renewable energy sources, the green certificates for the period from 2010 to June 2016. The number of certificates of origin corresponds to the amount of electricity generated from renewable energy sources	• Salary costs
• Sale of property rights resulting from certificates of origin of electricity from agricultural biogas, the blue certificates for the period from July 2016 to November 2020 for BGR1 and to date for BGR2	• Taxes and fees, including brokerage commissions for the sale of property rights, excise tax on personal consumption, etc.
• Sale of property rights resulting from certificates of origin of electricity from high-efficiency co-generation, the yellow/purple certificates for the period from 2011 to 2018	• General costs, mainly insurance
• Sale of carbon dioxide emission reductions, the ERU as part of the Joint Implementation project, applicable under the Kyoto Protocol, from 2010 to the end of 2012.	• The inflation level in 2022 was assumed to be 14.40%, and 14.70% in 2023
• Sales of guarantees of origin for energy from renewable energy sources (the number of guarantees of origin corresponds to the amount of energy introduced into the distribution network) from 2016	
• Additional payment for the hidden balance under the FIP support system. This is a support system that is available for the certificate system, which means that in the initial phase, the FIP system is automatically supported under the certificate system. In the case of the BGR1 system, the FIP will be valid from December 2020 until June 2027. In connection with the BGR2 system covering a biogas plant, at the request of the producer, who has spent 15 years since obtaining the first (green) certificate, he finally decided to switch to the FIP system previously, which was induced in BGR1. In the case of the FIP system, the subsidy to the alternative supplement applies only to energy fed into the distribution network	
• Other revenues and settlement during non-returnable subsidies	

Source: authors' work based on materials provided by the analyzed biogas plants.

Time series were used to present archived prices of electricity from agricultural biogas production. Data were obtained from the Polish Power Exchange (TGE) for the period 2005-2016 – prices of green and blue certificates; for the period 2010-2018 – prices of yellow and purple certificates; for the period 2015-2024 – prices of energy guarantees. The remaining data was taken from the TGE website.

To illustrate differences in the number of agricultural biogas plants and their capacity by voivodeship (NUTS 2) in the two periods analysed, combined cartographic methods of presentation were used in the quantitative approach:

- a choropleth map (simple cartogram), which presents the phenomenon under study according to its value within the boundaries of a given territorial unit; in this case, to illustrate RES installations/agriculture biogas by Voivodeship [million m3],
- a diagram map (pie charts cartodiagram), which is used to show the structure of a given phenomenon within a territorial unit; in this case, the number of RES installations/agriculture biogas by power range in Voivodeship [kW].

The maps were produced in MapViewer (version 8.7.752) from Golden Software LLD, which is a thematic mapping and analysis system. The maps used the purposeful sampling method (based on the register of agricultural biogas producers published by KOWR, 19 January 2024) to classify agricultural biogas plants in two periods, i.e. from 1 January 2011 to 30 June 2016 and from 1 July2016 to 19 January 2024 to take into account the legal conditions applicable.

Results of the research

In 2020, a decision was made to transition BGR1 from the certificate system to the FIP system. This was dictated by economic aspects because the reference price for the BGR1 biogas plant for PLN 587/MWh in 2020 and PLN 607/MWh in 2021, taking into account low consumption for one's own needs, was a much more favourable price than the sales price of energy, including the price of blue certificate – PLN 502/MWh (PLN 202/MWh plus PLN 300/MWh). There was no indication that the price of energy would increase dramatically. In addition, the transition to the FIP system was also influenced by the risk of the certificate system expiring at the end of 2021. In 2021, energy prices started to increase. Hence, the revenues in BGR1 and BGR2 are equalised (Figure 5). In the second half of 2021, when prices began to increase dramatically, the FIP system turned out to be much less favourable than the certificate system because the total average annual price of energy and certificates in 2022 amounted to PLN 1,080/MWh compared to PLN 638/MWh in the FIP system. Figure 6 shows the operating profit of both biogas plants analysed, taking into account periods of significant changes in legislation and thus the implementation of new support systems. However, the forecast indicates the potential occurrence of changes, which may contribute to a negative profit for both biogas plants in 2028-2029. The internal rate of return (IRR), on the other hand, indicates the economic efficiency of the BGR1 investment at a much higher level than BGR2 (Figure 7).

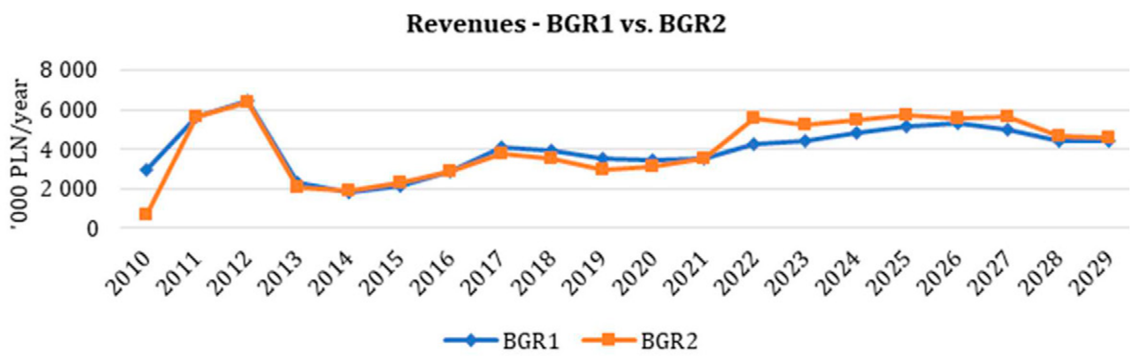

Figure 6. Revenues for BGR1 and BGR2 biogas plants in the years 2010-2029

Source: authors' work based on materials provided by the analyzed biogas plants.

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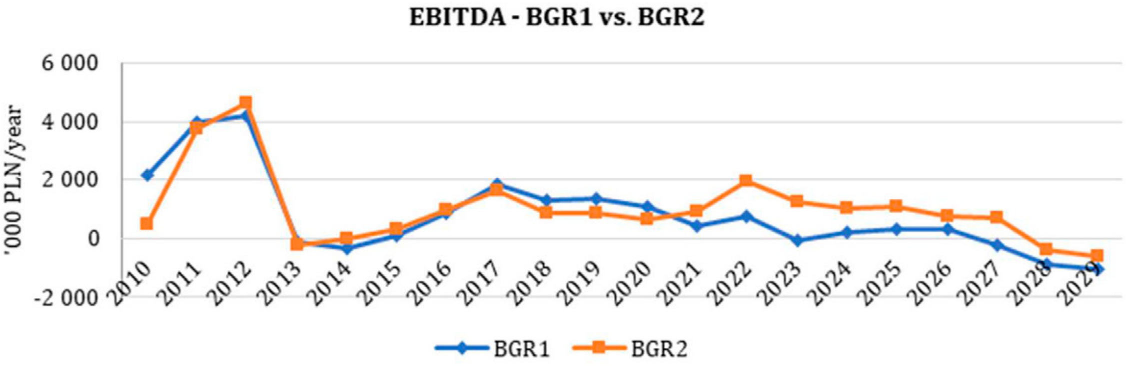

Figure 7. EBITDA for BGR1 and BGR2 biogas plants in 2010-2029

Source: authors' work based on materials provided by the analyzed biogas plants.

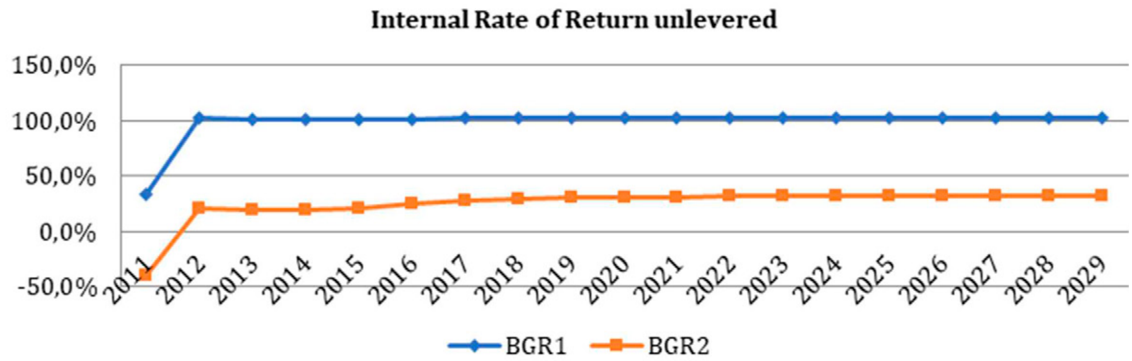

Figure 8. Internal Rate of Return unleveraged for BGR1 and BGR2 biogas plants in 2010-2029

Source: authors' work based on materials provided by the analyzed biogas plants.

Table 4. Sensitive analysis

Sensitive analysis	Electricity price – 10%		Certificate price – 10%		Maize silage price + 10%		Investment cost + 10%	
	BGR1	BGR2	BGR1	BGR2	BGR1	BGR2	BGR1	BGR2
Cumulative EBITDA	-1.91%	-1.59%	-3.34%	-3.23%	-2.38%	-2.39%	0.00%	0.00%
IRR	-5.05%	-1.41%	-9.13%	-2.84%	-5.02%	-2.08%	-31.82%	-10.65%
NPV	-3.52%	-5.44%	-6.16%	-11.01%	-4.33%	-8.12%	-12.79%	-33.25%
ROIC	-1.61%	-0.95%	-2.50%	-2.03%	-2.59%	-1.61%	-10.79%	-8.35%
Cumulative EBITDA (2022)	-3.74%	-3.50%	-5.93%	-12.42%	-9.12%	-8.99%	0.00%	0.00%
IRR in (2022)	-5.46%	-1.68%	-9.63%	-4.18%	-6.38%	-3.27%	-30.19%	-7.30%
NPV in (2022)	-4.37%	-4.63%	-7.05%	-15.45%	-9.90%	-11.11%	-3.53%	-5.06%
Cumulative ROIC in (2022)	-12.81%	-8.75%	-20.29%	-31.03%	-31.21%	-22.46%	-45.29%	-30.43%

Source: authors' work based on materials provided by the analyzed biogas plants.

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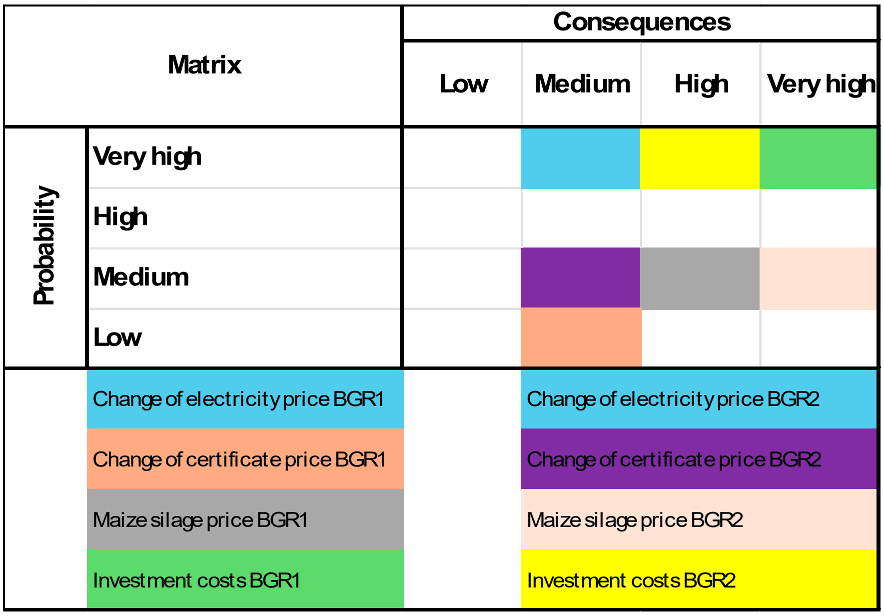

Figure 9. Risk matrix for BGR1 and BGR2 biogas plants

Source: authors' work based on materials provided by the analyzed biogas plants.

Based on the results of the sensitivity analysis presented in Table 3 and the risk matrix (Figure 6), the probability of risk and its consequences is very high in the case of investment costs in BGR1 and medium probability with a very high level of its consequences in the case of corn silage prices in BGR2. A similar situation was observed in the case of investment costs in BGR2 and corn silage prices in BGR1, but with high rather than very high-risk consequences. In the case of changes in energy prices, both in BGR1 and BGR2, the results indicate a very high probability of risk, with an average level of consequences.

Discussion

Agricultural biogas plants are complex installations that consist of many elements, such as buildings: a technical building with a co-generation module and a pump building, tanks for substrates, pre-mixing, mixing, fermentation, post-fermentation, electrical installations and networks with a transformer station, water-supply networks, sanitary and technological networks with a pumping system and component networks, including: with a moving floor, a biogas purification network with a desulphurisation tank, a heating network with boiler room technology, a separator, automation and control, component depots, roads, etc. Such complexity means that investment outlays for this type of project can be much higher than outlays for photovoltaic installations (Klepacka & Pawlik, 2018) or wind turbines.

Analyses carried out in the literature show that (Sulewski et al., 2016), given the assumed level of costs and expenditures, investment in agricultural biogas plants does not ensure a return on the invested funds in most of the cases analysed. According to Klimek et al. (2021), analyses of the profitability of biogas plants showed that without financial support, co-financing at least part of the investment at the construction stage, the investment becomes unprofitable in the assumed period (e.g. 12 years), which may result from a decrease in revenues from energy sales. Financial support is therefore important at the construction stage of a biogas plant, which largely makes it possible to shorten the payback period and thus increase the willingness of future investors to invest in biogas plants (Klimek et al., 2021; Bednarek et al., 2023).

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Table 5. The investment shows the investment outlays for agricultural biogas in three power ranges: < 1000, > 1000, < 2000 and > 2000 kW

Year of construction and installation capacity	Biogas plant with installation capacity (kWel / kWt)		
	2010	2011	2009
	625/690	1 063/ 1 088	2 126/2 206
Investment outlays for construction (PLN)	9 500 000	13 000 000	15 300 000
Total investment outlays (PLN)	10 000 000	15 000 000	21 500 000
Number of animals (JPD) (pigs)	12 300	1 200	9 300
Substrate costs (PLN / year)	1 700 000	2 200 000	6 200 000
Total costs other than the cost of the substrate (PLN / year)	1 400 000	1 700 000	3 000 000
Electricity production (MWh)	5 200	8 500	17 000
Production efficiency (%)	94.98%	91.28%	91.28%
Thermal energy production (GJ)	22 300	38 500	55 000
Heat surplus (to be used) (GJ)	5 800	15 000	16 300
Amount of energy used for energy production (MWh / year)	920	1 640	3 200
Share of electricity from biogas plants in the energy used for energy production (%)	17,69%	19,29%	18,82%
Amount of energy used for energy production (MWh / year)	920	1 640	3 200
Share of electricity from biogas plants in the energy used on the farm (%)	6.92%	8.59%	34.12%
Amount of energy used in other / remote farms (MWh / year)	2 593	6 130	8 000
Share of electricity from biogas plants in the energy used in other / remote farms (%)	11.63%	15.92%	14.55%

Source: authors' work based on Bednarek et al. (2023).

The cost of the substrate is the largest cost factor in agricultural biogas plants, mainly those using maize silage as a substrate, the price of which depends on the market price of maize grain. The value of maize purchased for grain in Poland has increased over six times over the last 12 years (from PLN 650.2 million in 2010 to PLN 4,213.5 million in 2022) (GUS, 2023). The use of silage should therefore be limited to silage made from green maize. Moreover, agricultural biogas plants should mostly use second-generation raw materials, including straw waste (Kowalczyk-Jusko, 2012)[6] or other agricultural by-products that have no other possible use and are cheap or even bring an additional source of income for the biogas plant. Maize silage should only be a supplementary raw material, especially where the biogas plant technology has been adapted to a specific substrate – only then does it make economic sense (Bednarek et al., 2023).

Based on the register of agricultural biogas producers, map 1 presents agricultural biogas plants entered in the register in the period from 1 January 2011 to 30 June 2016, and map 2 from 1 July 2016 to 19 January 2024. These periods refer to the functioning of two support systems. The first corresponds to the period of operation of the certificate-of-origin support system, i.e. the certificates. In contrast, the second period corresponds to the support system in the form of feed-in tariffs (FIT)

6 On a national scale, the rate of using hay from meadows and pastures for energy purposes is at the level of 5-10%.

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and guaranteed premiums (FIP). Maps 1 and 2 present power ranges by voivodeship. In the first period 80 biogas plants (over 446 million m^3) operated, while in the second period 73 agricultural biogas plants (over 266 million m^3). In the period until mid-2016, the largest number of agricultural biogas plants operated with a capacity of ≥ 500 kW and ≤ 1000 kW (36 installations) and ≥ 1000kW and < 2000 kW (28 installations) and, respectively, 26 and nine installations in the second period, i.e. from the second half of 2016 to 19 February 2024. In the second period, there were many more, as many as 31, biogas plants with lower power, i.e. in the range of >100 kW and <500 kW. This trend may indicate the possibility of using the new FIT support system (for power not exceeding 500 kW) and FIP (for power not exceeding 1000 kW). Moreover, in the second period, three biogas plants with power < 100 kW were operating. It is possible that the motivator for the creation of biogas plants with the lowest power, i.e. below 500 kW, was the fact that there was no need to carry out an environmental impact assessment, which is associated with additional costs on the investor's side.

The spatial diversity of biogas plant locations also changed significantly in the two periods analysed. In the first period, the largest number of biogas plants operated in the Zachodniopomorskie Viovodeship and Warmińsko-Mazurskie Voivodeship (13 biogas plants respectively), while in the second period, the largest number of biogas plants operated in the Wielkopolskie Voivodeship (18) and Mazowieckie Voivodeship (10). According to the data of Statistics Poland (2023), the highest number of pigs per 100 ha of agricultural land and the share of cereals and potatoes in the total area sown in 2022 was recorded in the Wielkopolskie Voivodeship, while the number of cattle per 100 ha of agricultural land in 2020 was recorded in the following voivodeships: Podlaskie, Wielkopolskie and Mazowieckie. Gadirli et al. (2024) among the voivodeships in Poland with the greatest potential for the production of agricultural biogas from cow manure indicates the following voivodeships: Wielkopolskie, Warmińsko-Mazurskie, Kujawsko-Pomorskie, Mazowieckie and Zachodniopomorskie, while among the voivodeships with the best conditions for the production of agricultural biogas from pig manure indicates the voivodeships of Wielkopolskie, Dolnośląskie and Lubelskie.

Biomass is the only renewable source of raw material that can be processed in many ways: used for energy purposes in thermal processes, i.e. for direct combustion of solid biofuels (e.g. wood, straw), processed into liquid biofuels (e.g. rapeseed oil esters) and used to produce biogas (e.g. agricultural). Increasing consumption, which contributes to the production of increasing amounts of biomass in the form of bio-waste, and regulations on waste management and transformation towards a circular economy will increase the energy use of biomass. It should not be forgotten that it should be done hierarchically, which means that first of all, waste biomass that is not used in other branches of the economy, e.g. biodegradable municipal waste, should be used, then it should be recycled, and if this is impossible then recovery and disposal (Bednarek, 2023; Dyrektywa, 2009).

According to Janiszewska and Ossowska (2023), taking into account individual Polish voivodeships, the technical potential (Pudełko, 2013)[7] of biomass of agricultural origin[8] ranged from 456.67 to 2564.05 ktoe in 2020. The Wielkopolskie Voivodeship (2,564.05 ktoe), the Mazowieckie Voivodeship (2,325.82 ktoe), and the Lubelskie Voivodeship (1,361.58 ktoe) had the greatest potential. Together, these voivodeships accounted for over a third (35.65%) of the total biomass potential of agricultural origin. According to the data, the Wielkopolskie Voivodeship, there for, assumes a privileged place. It is possible that the FIT and FIP system contributed to the dynamic development of biogas to a capacity of ≤ 1000 in the leading voivodeship in Poland in 2016-2024.

[7] The technical potential of straw available for energy purposes is much lower due to the need to use part of the straw in agricultural production.

[8] The largest share in the technical potential of biomass of agricultural origin was straw – 92.4%.

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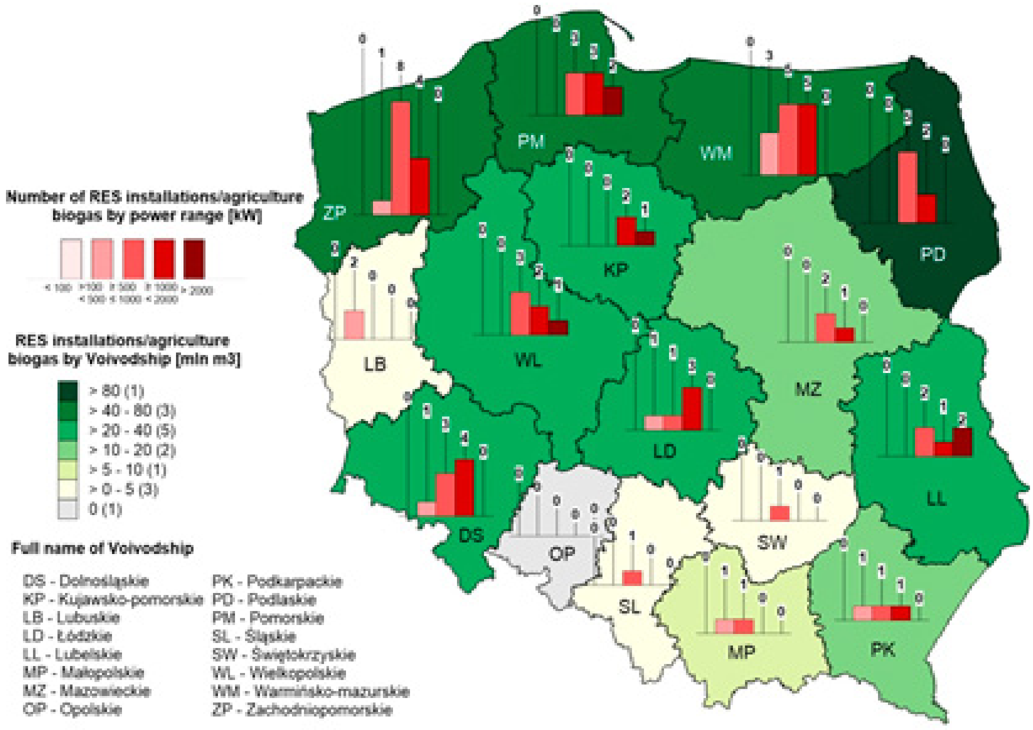

Figure 10. List of agricultural biogas plants by capacity by voivodeship for the period from January 2011 to the end of June 2016

Source: authors' work based on Krajowy Ośrodek Wsparcia Rolnictwa (2024).

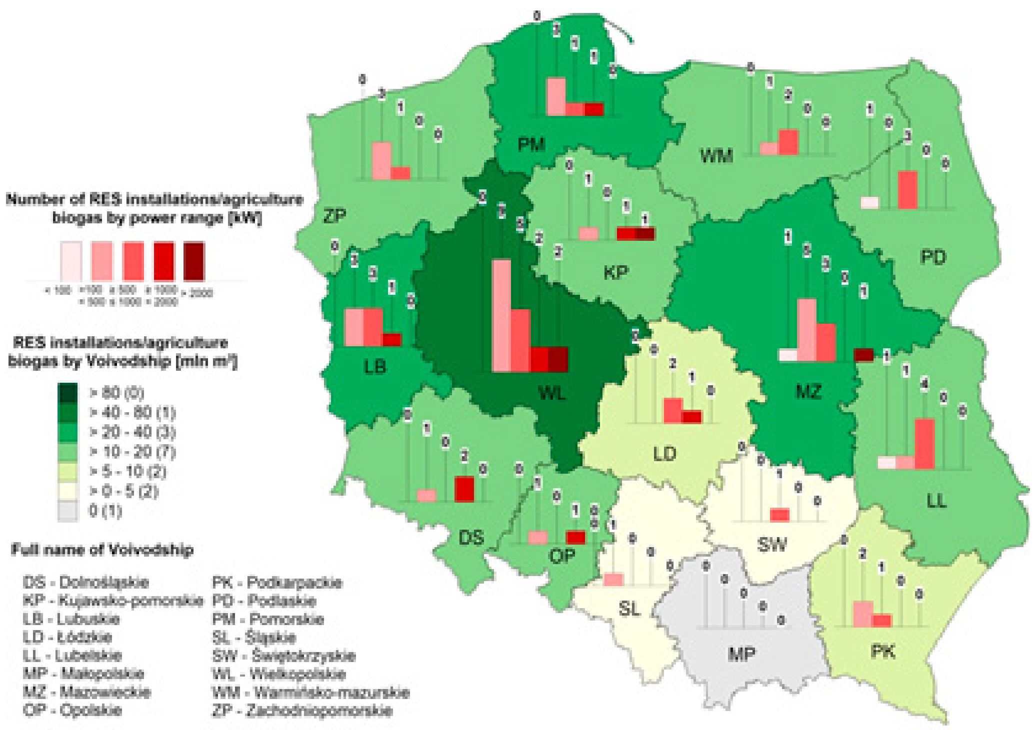

Figure 11. List of agricultural biogas plants by capacity by voivodeship for the period from July 2016 to 19 January 2024

Source: authors' work based on Krajowy Ośrodek Wsparcia Rolnictwa (2024).

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Conclusions

The main conclusion of the analysis is the fact that the operating profit of agricultural biogas plants is determined not only by financial aspects, which are important at the stage of construction of a biogas plant, but primarily by the lack of stable legislation taking into account both support systems agricultural biogas plants, as well as agricultural biogas prices. However, it should be emphasised that the bonus system is permanent and predictable in the new support system. The price guarantee facilitates the formulation of precise financial projects, which results in positive consideration from financial institutions when applying for investment funding. However, it should be emphasised that agricultural biogas plants are characterised by very high sensitivity related to the probability of risk in the case of investment costs, substrate prices and changes in energy prices.

An opportunity for the development of agricultural biogas plants in Poland is the very large substrate raw-material potential for biogas production, originating from both plant and animal production. The differentiation of the power of agricultural biogas installations and the spatial distribution of biogas plants by voivodeships, was confirmed in periods reflecting both periods analysed of the two forms of financing. The results indicated that in the first period, from 2011 to mid-2016, more agricultural biogas plants with a power of ≥ 500kW and ≤ 1000kW were built. In the second period, i.e. from the second half of 2016 to 2024, most agricultural biogas plants had a capacity in the range >100kW and <500kW, which is probably dictated by the constant and predictable premium system in the new support system. Moreover, in the first period, the largest number of biogas plants operated in the Zachodniopomorskie Voivodeship and the Warmińsko-Mazurskie Voivodeship (13 biogas plants, respectively), i.e. places where the first biogas plants in Poland were built based on a substrate derived from pig production. It can therefore be concluded that these biogas plants have, in a sense, become a motivator for biogas plants located in the Wielkopolskie and Mazowieckie Voivodeships (18 and 10 agricultural biogas plants, respectively, in the second period analysed), where there is dairy cattle production. Moreover, in the first period, the largest number of biogas plants operated in the Zachodniopomorskie Voivodeship and the Warmińsko-Mazurskie Voivodeship (13 biogas plants), i.e. places where the first biogas plants in Poland were built based. It can therefore be concluded that these biogas plants have become a motivator for biogas plants located in the Wielkopolskie Voivodeship (18 agricultural biogas plants in the second period analysed), where both pig production and dairy cattle production predominate.

The contribution of the authors

Conceptualisation, A.M.K. and A.B.; literature review, A.M.K and A.B.; methodology, A.M.K. and A.B.; formal analysis, A.M.K. and A.B.; writing, A.M.K. and A.B.; conclusions and discussion, A.M.K. and A.B.

The authors have read and agreed to the published version of the manuscript.

References

Act from 10 April 1997. Energy Law. Journal of Laws No. 54, item 348. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19970540348 (in Polish).

Act from 13 July 2023. Act on facilitating the preparation and implementation of investments in agricultural biogas plants. Journal of Laws 2023, item 1597. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20230001597 (in Polish).

Act from 14 March 2014. Act amending the Energy Law and certain other acts. Journal of Laws 2014, item 490. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20140000490 (in Polish).

Act from 17 August 2023. Act amending the Act on renewable energy sources and certain other acts. Journal of Laws 2023, item 1762. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20230001762 (in Polish).

Act from 20 February 2015. Act on renewables energy sources. Journal of Laws 2015, item 478. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20230001436 (in Polish).

Act from 22 June 2016. Act amending the Act on renewable energy sources and certain other acts. Journal of Laws 2016, item 925. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20160000925 (in Polish).

Act from 25 August 2006. Act on biocomponents and liquid biofuels. Journal of Laws No. 169, item 1199. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20061691199 (in Polish).

Act from 7 June 2018. Act amending the Act on Renewable Energy Sources and some other acts. Journal of Laws 2018, item 1276. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20180001276 (in Polish).

Act from 8 January 2010. Act amending the Energy Law and amending certain other acts. Journal of Laws No. 21, item 104. https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20100210104 (in Polish).

American Biogas Council. (2023). *Biogas Market Snapshot.* https://americanbiogascouncil.org/biogas-market-snapshot/

Bednarek, A. (2023). Rolnictwo i tereny wiejskie – jaki potencjał dla polskiej energetyki? Pomorski Thinkletter, 3(14), 102-108. https://www.kongresobywatelski.pl/wp-content/uploads/2023/11/pomorski_thinkletter-3-2023.pdf (in Polish).

Bednarek, A., Klepacka, A., & Siudek, A. (2023). Development barriers of agricultural biogas plants in Poland. Economics and Environment, 84(1), 229-258. https://doi.org/10.34659/eis.2023.84.1.528

Casasso, A., Puleo, M., Panepinto, D., & Zanetti, M. (2021). Economic Viability and Greenhouse Gas (GHG) Budget of the Biomethane Retrofit of Manure-Operated Biogas Plants: A Case Study from Piedmont, Italy. Sustainability, 13(14), 7979. http://dx.doi.org/10.3390/su13147979

Czekała, W. (2022). Digestate as a Source of Nutrients: Nitrogen and Its Fractions. Water, 14(24), 4067. https://doi.org/10.3390/w14244067

Dyrektywa 2001/77/WE Parlamentu Europejskiego i Rady z dnia 27 września 2001 r. w sprawie wspierania produkcji na rynku wewnętrznym energii elektrycznej wytwarzanej ze źródeł odnawialnych, Pub. L. No. 32001L0077, 283 OJ L (2001). https://eur-lex.europa.eu/legal-content/PL/ALL/?uri=CELEX%3A32001L0077 (in Polish).

Dyrektywa 2009/28/WE Parlamentu Europejskiego i Rady z dnia 23 kwietnia 2009 r. w sprawie promowania stosowania energii ze źródeł odnawialnych, Pub. L. No. 32009L0028, 140 OJ L (2009). https://eur-lex.europa.eu/legal-content/PL/ALL/?uri=CELEX%3A32009L0028 (in Polish).

Energy Regulatory Office. (2010). *Pierwszy fioletowy certyfikat wydany.* https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/3714,Pierwszy-fioletowy-certyfikat-wydany.html (in Polish).

Ertop, H., Atilgan, A., Kocięcka, J., Krakowiak-Bal, A., Liberacki, D., Saltuk, B., & Rolbiecki, R. (2023). Calculation of the Potential Biogas and Electricity Values of Animal Wastes: Turkey and Poland Case. Energies, 16(22), 7578. https://doi.org/10.3390/en16227578

Gadirli, G., Pilarska, A. A., Dach, J., Pilarski, K., Kolasa-Więcek, A., & Borowiak, K. (2024). Fundamentals, Operation and Global Prospects for the Development of Biogas Plants – A Review. Energies, 17(3), 568. https://doi.org/10.3390/en17030568

Gramwzielone.pl. (2023). *Ułatwienia w procesie inwestycyjnym w biogazownie coraz bliżej.* https://www.gramwzielone.pl/bioenergia/20151807/ulatwienia-w-procesie-inwestycyjnym-w-biogazownie-coraz-blizej (in Polish).

GUS. (2023). *Statistical Yearbook of Agriculture 2023*. https://stat.gov.pl/en/topics/statistical-yearbooks/statistical-yearbooks/statistical-yearbook-of-agriculture-2023,6,18.html

Igliński, B., Buczkowski, R., Iglińska, A., Cichosz, M., Piechota, G., & Kujawski, W. (2012). Agricultural biogas plants in Poland: Investment process, economical and environmental aspects, biogas potential. Renewable and Sustainable Energy Reviews, 16(7), 74890-4900. http://dx.doi.org/10.1016/j.rser.2012.04.037

Ignaciuk, W., & Sulewski, P. (2021). Uwarunkowania rozwoju sektora biogazu rolniczego w Polsce w kontekście doświadczeń historycznych i wyzwań Europejskiego Zielonego Ładu. Zagadnienia Ekonomiki Rolnej / Problems of Agricultural Economics, 368(3), 55-77. https://doi.org/10.30858/zer/140413

Jadczyszyn, T., & Winairski, W. (2017). Wykorzystanie pofermentu z biogazowni rolniczych do nawożenia. Studia i Raporty IUNG-PIB, 53(7), 105-118. https://doi.org/10.26114/sir.iung.2017.53.08 (in Polish).

Janiszewska, D., & Ossowska, L. (2023). Spatial Differentiation of Agricultural Biomass Potential in Polish Voivodeships. Energies, 16(19), 6828. https://doi.org/10.3390/en16196828

Klepacka, A. M., & Pawlik, K. (2018). Return on investment in PV power plants under changing support regimes (schemes). Problems of Agricultural Economics, 356(3), 168-191. https://doi.org/10.30858/zer/94473

Klimek, K., Kapłan, M., Syrotyuk, S., Bakach, N., Kapustin, N., Konieczny, R., Dobrzyński, J., Borek, K., Anders, D., Dybek, B., Karwacka, A., & Wałowski, G. (2021). Investment Model of Agricultural Biogas Plants for Individual Farms in Poland. Energies, 14(21), 7375. https://doi.org/10.3390/en14217375

Koryś, K. A., Latawiec, A. E., Grotkiewicz, K., & Kuboń, M. (2019). The Review of Biomass Potential for Agricultural Biogas Production in Poland. S*ustainability, 11*(22), 6515. https://doi.org/10.3390/su11226515

Kowalczyk-Jusko, A. (2012). Zasady sporządzania bilansu odnawialnych źródeł energii i oceny zasobów biomasy. In B. Kołodziej & M. Matyka (Eds.), *Odnawialne Źródła Energii. Rolnicze Surowce Energetyczne* (pp. 442). Poznań: PWRiL. (in Polish).

Kowalczyk-Juśko, A., & Szymańska, M. (2015). *Poferment nawozem dla Rolnictwa.* https://ksow.pl/files/Bazy/Biblioteka/files/Poferment_nawozem_dla_rolnictwa_01.pdf (in Polish).

Krajowy Ośrodek Wsparcia Rolnictwa. (2023). *Biogazownie rolnicze: bezpłatne warsztaty*. https://www.gov.pl/web/kowr/biogazownie-rolnicze-bezplatne-warsztaty (in Polish).

Krajowy Ośrodek Wsparcia Rolnictwa. (2024). *Rejestr wytwórców biogazu rolniczego. Stan na dzień: 07.02.2024 r*. https://www.gov.pl/web/kowr/rejestr-wytworcow-biogazu-rolniczego (in Polish).

Kusz, D., Bąk, I., Szczecińska, B., Wicki, L., & Kusz, B. (2023). Determinants of Return-on-Equity (ROE) of Biogas Plants Operating in Poland. Energies, 16(1), 31. https://doi.org/10.3390/en16010031

Łagocka, A., Kamiński, M., Cholewiński, M., & Pospolita, W. (2016). Health and environmental benefits of utilization of post-fermentation pulp from agricultural biogas plants as a natural fertilizer. Kosmos, 65(4), 601-607. https://kosmos.ptpk.org/index.php/Kosmos/article/view/1648 (in Polish).

Lohosha, R., Palamarchuk, V., & Krychkovskyi, V. (2023). Economic efficiency of using digestate from biogas plants in Ukraine when growing agricultural crops as a way of achieving the goals of the European Green Deal. Energy Policy Journal, 26(2), 161-182. https://doi.org/10.33223/epj/163434

Magazyn Biomasa. (2023). *Biogazownia rolnicza w każdej gminie? Specustawa pozwoli uwolnić ten potencjał*. https://magazynbiomasa.pl/biogazownia-rolnicza-w-kazdej-gminie-specustawa-pozwoli-uwolnic-ten-potencjal/ (in Polish).

Makádi, M., Tomócsik, A., & Orosz, V. (2012). Digestate: A New Nutrient Source – Review. In S. Kumar (Ed.), *Biogas* (pp. 295-310). Rijeka: InTech. http://www.intechopen.com/books/biogas/digestate-a-new-nutrient-source-review

Mamica, Ł., Mazur-Bubak, M., & Wróbel-Rotter, R. (2022). Can Biogas Plants Become a Significant Part of the New Polish Energy Deal? Business Opportunities for Poland's Biogas Industry. Sustainability, 14(3), 1614. https://doi.org/10.3390/su14031614

Ministerstwo Rolnictwa i Rozwoju Wsi. (2024). *Program „Energia dla wsi" – wydłużenie terminu naboru i zwiększenie budżetu*. https://www.gov.pl/web/rolnictwo/program-energia-dla-wsi--wydluzenie-terminu-naboru-i-zwiekszenie-budzetu (in Polish).

Ministry of Climate and Environment. (2021). *Polish Energy Policy until 2040.* https://www.gov.pl/web/climate/energy-policy-of-poland-until-2040-epp2040

Morawiecki, M. (2023). *Projekt – Ustawa z dnia o ułatwieniach w przygotowaniu i realizacji inwestycji w zakresie biogazowni rolniczych, a także ich funkcjonowaniu.* https://orka.sejm.gov.pl/Druki9ka.nsf/0/BF8FA2191823ABCAC12589AA00323F40/%24File/3196.pdf (in Polish).

Mukhtar, S., Yasar, A., Mahfooz, Y., Rasheed, R., Tabinda, A. B., Ashraf, M. A., Nauman, M., & Malik, A. (2022). Value addition and risk assessment of dairy digestate as biofertilizer on crop yield and soil fertility. Arabian Journal of Geosciences, 15, 245. https://doi.org/10.1007/s12517-021-09354-8

Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 3 marca 2022 r. w sprawie ogłoszenia jednolitego tekstu ustawy o odpadach. (Dz. U. z 2022 r., poz. 699). https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20220000699/T/D20220699L.pdf (in Polish).

Palusiński, B. (2016). *Nowelizacja ustawy o odnawialnych źródłach energii – konsekwencje dla odbiorców końcowych.* https://www.eecc.eu/blog/2016/06/30/nowelizacja-ustawy-o-odnawialnych-zrodlach-energii-konsekwencje-dla-odbiorcow-koncowych (in Polish).

Parlament Europejski. (2023). *Noty tematyczne o Unii Europejskiej. Walka ze zmiana klimatu.* https://www.europarl.europa.eu/factsheets/pl/sheet/72/walka-ze-zmiana-klimatu (in Polish).

Pastorelli, R., Valboa, G., Lagomarsino, A., Fabiani, A., Simoncini, S., Zaghi, M., & Vignozzi, N. (2021). Recycling Biogas Digestate from Energy Crops: Effects on Soil Properties and Crop Productivity. Applied Sciences, 11(2), 750. https://doi.org/10.3390/app11020750

Piwowar, A. (2020). Agricultural Biogas – An Important Element in the Circular and Low-Carbon Development in Poland. Energies, 13(7), 1733. https://doi.org/10.3390/en13071733

Popović, V. M., Ikanović, J., Ristić, V., Gantner, V., Kolarić, L., Rajić, Z., Bojović, R., & Petković, Z. (2023). Influence of digestate on the productivity of oats in different environmental conditions. *Proceedings of the 6 International Conference Village and Agriculture*, Bijeljina, 118-133. https://fiver.ifvcns.rs/handle/123456789/4039

Powałka, M., Klepacka, A. M., Skudlarski, J., & Golisz, E. (2013). Aktualny stan sektora biogazu rolniczego w Polsce na tle krajów Unii Europejskiej. Zeszyty Naukowe SGGW w Warszawie – Problemy Rolnictwa Światowego, 13(3), 203-212. https://doi.org/10.22630/PRS.2013.13.3.51 (in Polish).

Pudełko, R. (2013). *Ocena Potencjałów Biomasy Ubocznej i Odpadowej w UE – 27 i Szwajcarii oraz ich Regionalizacja.* Puławy: IUNG. https://iung.pl/images/pdf/habilitacje/Pudelko-hab.pdf (in Polish).

Rozporządzenie Ministra Klimatu i Środowiska z dnia 16 kwietnia 2021 r. w sprawie ceny referencyjnej energii elektrycznej z odnawialnych źródeł energii w 2021 r. oraz okresów obowiązujących wytwórców, którzy wygrali aukcje w 2021 r. (Dz. U. z 2021 r., poz. 722). https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20210000722 (in Polish).

Rozporządzenie Ministra Klimatu i Środowiska z dnia 8 listopada 2023 r. w sprawie ceny referencyjnej energii elektrycznej z odnawialnych źródeł energii, okresów obowiązujących wytwórców, którzy wygrali aukcje, oraz referencyjnych wolumenów sprzedaży energii elektrycznej. (Dz. U. z 2023 r., poz. 2440). https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20230002440 (in Polish).

Rozporządzenie Ministra Klimatu z dnia 24 kwietnia 2020 r. w sprawie ceny referencyjnej energii elektrycznej z odnawialnych źródeł energii w 2020 r. oraz okresów obowiązujących wytwórców, którzy wygrali aukcje w 2020 r. (Dz. U. z 2020 r., poz. 798). https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000798 (in Polish).

Rzeźnik, W., Bartkowiak, A., Jadczyszyn, T., Mac, J., Matros, B., Matyka, M., Mielcarek, P., Stekla, J., Talarczyk, W., Zbytek, Z., & Witorożec, A. (2017). *Różne aspekty wykorzystania biomasy pofermentacyjnej.* Falenty: Instytut Technologiczno-Przyrodniczy. (in Polish).

Samson-Bręk, I., Owczuk, M., Matuszewska, A., & Biernat, K. (2022). Environmental Assessment of the Life Cycle of Electricity Generation from Biogas in Polish Conditions. Energies, 15(15), 5601. https://doi.org/10.3390/en15155601

Scarlat, N., Dallemand, J.-F., & Fahl, F. (2018). Biogas: Developments and perspectives in Europe. Renewable Energy, 129, 457-472. https://doi.org/10.1016/j.renene.2018.03.006

Serwis Rzeczpospolitej Polskiej. (2023). *Dane dotyczące działalności wytwórców biogazu rolniczego.* https://www.gov.pl/web/kowr/dane-dotyczace-dzialalnosci-wytworcow-biogazu-rolniczego (in Polish).

Siudek, A., & Klepacka, A. M. (2022). The Logistics Aspect in Research on the Reduction of Carbon Dioxide Emissions from Agricultural Biogas. Sustainability, 14(16), 10124. https://doi.org/10.3390/su141610124

Stankiewicz, P. (2023). Pięć sił zielonej transformacji. Jak Europejski Zielony Ład i dekarbonizacja oddziałują na polską gospodarkę. Studia BAS, 2(74), 109-126. http://cejsh.icm.edu.pl/cejsh/element/bwmeta1.element.ojs-doi-10_31268_StudiaBAS_2023_14 (in Polish).

Sulewski, P., Majewski, E., Wąs, A., Szymańska, M., Malak-Rawlikowska, A., Fraj, A., Trząski, A., Wiszniewski, A., & Amrozy, M. (2016). Uwarunkowanie ekonomiczno – prawne i opłacalność inwestycji w biogazownie rolnicze w Polsce. Zagadnienia Ekonomiki Rolnej, 346(1), 119-143. https://doi.org/10.30858/zer/83043

Szyba, M., & Mikulik, J. (2023). Analysis of Feasibility of Producing and Using Biogas in Large Cities, Based on the Example of Krakow and Its Surrounding Municipalities. Energies, 16(22), 7588. https://doi.org/10.3390/en16227588

Teraz Środowisko. (2023). *Biogaz w Polsce 2023. Nowe otwarcie*. https://www.teraz-srodowisko.pl/publikacje/biogaz-w-polsce-2023/teraz-srodowisko-publikacja-biogaz-w-polsce-2023.pdf (in Polish).

TGE. (2024). *Dane statystyczne*. https://tge.pl/dane-statystyczne (in Polish).

Urząd Regulacji Energetyki. (2016). *Gwarancja pochodzenia – dokument pochodzenia energii elektrycznej z odnawialnych źródeł energii*. https://www.ure.gov.pl/pl/oze/gwarancje-pochodzenia/6816,Gwarancja-pochodzenia-dokument-pochodzenia-energii-elektrycznej-z-odnawialnych-z.html (in Polish).

Urząd Regulacji Energetyki. (2018). *Aktualizacja Informacji Prezesa URE nr 60/2018 oraz dokumentów dla sytemu FIT/FIP.* https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/7771,Aktualizacja-Informacji-Prezesa-URE-nr-602018-oraz-dokumentow-dla-sytemu-FITFIP.html (in Polish).

Urząd Regulacji Energetyki. (2023). *Dziś wchodzi w życie rozporządzenie określające poziom cen referencyjnych dla tegorocznych aukcji OZE.* https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/11449,Dzis-wchodzi-w-zycie-rozporzadzenie-okreslajace-poziom-cen-referencyjnych-dla-te.html (in Polish).

Walsh, J. J., Jones, D. L., Edwards-Jones, G., & Williams Prysor, A. (2012). Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. Journal of Plant Nutrition and Soil Science, 175(6), 840-845. https://doi.org/10.1002/jpln.201200214

Wieści Rolnicze. (2023). *KOWR wspiera rozwój OZE na terenach wiejskich.* https://wiescirolnicze.pl/kowr-wspiera-rozwoj-oze-na-terenach-wiejskich (in Polish).

Witorożec-Piechnik, A., Matyka, M., Wolszczak, P., & Oleszek, M. (2021). Yield an selected physiological parameters of maize, sorghum, and triticale depending on fertilization system. BioResources, 16(4), 7870-7883. http://dx.doi.org/10.15376/biores.16.4.7870-7883

Witorożec-Piechnik, A., Matyka, M., Woźniak, M., & Oleszek, M. (2022). The effect of fertilization with the digestate on the quality and chemical composition of selected plants intended for biogas production. Polish Journal of Agronomy, 48, 28-36. https://doi.org/10.26114/pja.iung.478.2022.48

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WRAŻLIWOŚĆ BIOGAZOWNI ROLNICZYCH NA ZMIANY CEN ENERGII W POLSCE

STRESZCZENIE: W Polsce potencjał biogazu rolniczego pomimo ambitnych planów sprzed 15 lat, gdzie zakładano, że do 2020 roku standardem będzie biogazownia rolnicza w każdej gminie, nie został wykorzystany ze względu na brak stabilnych regulacji prawnych oraz programów finansowania budowy biogazowni rolniczych. Sytuacja obecnie uległa zmianie ze względu na nowe formy systemów wsparcia, co zmotywowało autorów do porównania dwóch biogazowni rolniczych funkcjonujących w systemie certyfikatów oraz w systemie wsparcia w postaci feed-in premium (FIP). Ponadto, autorzy wskazali na różnice w liczbie biogazowi rolniczych i ich mocy według województw w związku ze zmianą uwarunkowań prawnych, obowiązujących w dwóch okresach: od 1 stycznia 2011 roku do 30 czerwca 2016 roku i od 1 lipca 2016 roku do 19 stycznia 2024 roku. Na podstawie zastosowanych metod badawczych, m.in. Earnings Before Interest, Taxes Depreciation and Amortisation (EBITDA); Internal Rate of Return (IRR); risk matrix; oraz analiza danych w ujęciu przestrzennym wskazano iż: 1. Biogazownie rolnicze charakteryzują się bardzo wysoką wrażliwością związaną z prawdopodobieństwem wystąpieniem ryzyka w przypadku kosztów inwestycyjnych, cen substratów oraz zmiany cen energii.; 2. Wsparcie finansowe jest istotne na etapie budowy biogazowi, które w dużej mierze pozwala skrócić okres zwrotu i tym samym zwiększyć skłonność przyszłych inwestorów do inwestowania w biogazownie; 3. W analizowanych okresach odnotowano istotne różnice w rozmieszczeniu przestrzennym biogazowni ze względu na tendencje w kierunku biogazowni o mniejszej mocy, co prawdopodobnie jest podyktowane stałym i przewidywalnym systemem premii w nowym systemie wsparcia.

SŁOWA KLUCZOWE: biogaz rolniczy, ceny energii, system wsparcia, EBITDA, IRR, macierz ryzyka, Polska

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