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Economic Conditions of Using Biodegradable Waste for Biogas Production, Using the Example of Poland and Germany

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Abstract: Biogas production is a process with great potential. It uses the biodegradable raw materials of animal, vegetable and municipal waste. The amount of municipal as well as agricultural waste is increasing every year. This waste is an unmanaged and nuisance waste, and using it in biogas plants reduces the amount of waste. Biogas production is part of the EU's policy to reduce dependence on fossil fuels and use energy from renewable sources (diversification of energy sources). Its importance is certain to increase in the future as energy demand increases. This article deals with the economical use of biodegradable waste for biogas production in Poland and Germany. Both countries have a similar agricultural and municipal waste structure. An agricultural biogas plant is one way of obtaining energy based on renewable energy sources (RES). Energy production from agricultural biogas will allow Poland to meet the 32% obligation imposed by the EU and Germany to continue to be the market leader in biogas plants. The biogas market in Poland is growing, while in Germany, there is a decline in biogas installations. The article indicates what changes need to take place in agriculture and the use of municipal waste in these countries to sustain the development of biogas plants. Both countries should maintain animal husbandry to ensure continuous access to substrate and use waste for production rather than growing maize or other mixtures only for biogas plants. Due to the high price of chemical fertilisers, pulp from biogas plants should be an alternative to chemical fertilisers in both countries, which will contribute to greener crops. The governments of both countries should support such measures.

Keywords: biogas; energy; agricultural biogas plant



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1. Introduction

Limited resources of energy raw materials such as oil [1], coal or natural gas in the situation of increasing energy demands [2] force the societies of many countries to intensively search for and use other energy carriers, such as environmentally friendly renewable energy [3]. The European Union is promoting a Waste-To-Energy (WTE) initiative to minimise waste and greenhouse gas (GHG) emissions and increase renewable energy production [4]. Renewable fuels include organic products [5] whose mass is formed by photosynthesis from water and carbon dioxide absorbed from the atmosphere, and whose combustion does not increase the concentration of CO₂ particles in the atmosphere. The management of animal waste is very important for managing this type of waste and applying sustainable development in agriculture [6]. A characteristic feature of renewable sources is that they are renewable. To ensure energy security and proper use of the earth's resources, it is possible to use biogas plants, which are renewable sources [7]. However, the efficient use of these

plants proves to be a difficult task that requires a comprehensive evaluation [8] of their performance parameters [9]. Biogas enjoys strong support from European Union countries, while the state of technical development of existing biogas plants varies [10]. The highest biogas production is recorded in Germany, Italy and Austria [11].

The aim of this paper is, therefore, to analyse the types of biogas plants and the factors that influence the increase in biogas production from certain types of waste. By analysing the amount of garbage that agriculture has to deal with, the authors undertake an analysis of biogas plants. The key question is, therefore: what actions should be taken in Polish and German agriculture and processing to strengthen the development of the biogas plant sector? The authors try to answer the questions: What measures should be taken to ensure a constant supply of raw materials for biogas production and, as a result, to reduce the amount of waste without subsidising the process?

Agriculture is an important branch of the Polish and German economies, which ensures the countries' food security [5]. At the same time, both countries are exporters of food of animal origin to other countries [11]. Due to the growing demand for meat on the international market, the amount of waste will increase [12]. One of the main problems facing agricultural production is managing the resulting waste from animal and bird farming [13]. This problem is solved by biogas technology [14], which is linked to renewable energy sources [15]. The EU countries, according to the guidelines of the European Commission, aim to minimise [16] the consumption of fossil fuels [17] and replace them with renewable sources [18]. These sources are inexhaustible and offer prospects for development [19].

Germany has been developing RES for a long time. The country is a leader in biogas plants but also ranks first regarding the growth of installed photovoltaic capacity in the EU [20]. According to the Institute of Renewable Energy, at the end of 2021, the installed capacity of photovoltaics in EU countries was 158 GW, representing a growth of 21.4 GW (a market growth rate of more than 15%). Poland was most likely (not all countries confirmed the final and official data) in second place, behind Germany [21].

Structural changes in agriculture are so complex [22] that they have many interrelated external and internal factors of farms [23]. The influence of these factors strongly affects the size of farms [24], the structure of production, the production capacity of farms and ultimately their economic and social situation [25]. Renewable energy policies at the national level in Germany, e.g., feed-in tariffs for biogas production, are also strongly impacting farms and their structure. In Poland, the opportunities to benefit from a subsidy programme for biogas plants are also generating more interest in the topic of biogas plants.

Empirical studies have noted that the higher the biogas production [26] in a region or municipality [27], the higher the increase in the purchase price of agricultural crops [28] and the price or lease of land [29].

However, this does not change the fact that the aforementioned fossil sources are non-renewable resources and their use is becoming more expensive and less energy efficient. An Energy Return On Investment (EROI) barrier is emerging [30]. EROI refers to the ratio between how much energy was involved in the production process and how much energy was received. This is a fairly new concept that is only now gaining importance. The conclusions from its application are quite worrying. Despite the theoretical availability of fossil fuels, taking EROI into account, it may turn out that many of these sources are energetically unviable.

Biogas plants enable the management of waste from livestock and poultry farming, reducing the area for storage of this waste and ensuring environmental safety. The resulting combustible gas can be used for own consumption, reducing the biowaste disposal cost [31].

However, the agri-food industry is a major producer of waste and by-products, both globally and in the primary sector. Material from the food supply chain can be vegetable and fruit waste [32], harvest waste and crop waste of other origin [33].

Primary energy production from biogas in the EU-28 increased only slightly from 2017 to 2021. According to EurObserv'ER, production reached 16.6 Mtoe (million tonnes of oil

equivalent) in 2019, slightly higher than in 2018 but about the same level as in 2017. The introduction of legislation less supportive of the use of food-type energy crops for biogas production has blown apart this overall trend and has been compounded by a reduction in capacity allocated to biogas sales and less attractive payment terms for biogas electricity. It is now less profitable to use food-type crops (wheat, triticale or even maize as grain) for biogas plants because the drought problems Europe has faced in recent years have resulted in shortages in the consumer cereal market and, consequently, some EU Member States have nevertheless seen positive production growth, thanks to their determination both to encourage the injection of biomethane and to recover energy from digestate [34].

The transition to a low-carbon energy system is one of the European Union's main priorities. A precondition for this transition is to increase the share of renewable energy sources in the energy system. The European Union aims to achieve a 32% share of renewable energy by 2030. Achieving the 32% target by 2030 is an EU-wide binding target enshrined in Directive (EU) 2018/2001 (RED II) [35]. This percentage has not been broken down into national binding targets. The European Commission's recommendations for Member States' contributions to the 2030 EU-level renewable energy share target are detailed in a Commission Staff Paper. The Governance Regulation sets out principles for iterative procedures involving Member State governments and the European Commission that are expected to result in a share of renewable energy in gross final energy consumption at the EU level of at least 32% [36]. In addition, RED II includes a sub-target on transport: the Member States must oblige fuel suppliers to supply at least 14% of the energy consumed in road and rail transport by 2030 [37]. The EU Emissions Trading Scheme (ETS), which aims to directly reduce greenhouse gas emissions from installations covered by the directive, also indirectly promotes the use of renewable energy sources, as does the current overall target of reducing greenhouse gas emissions by 2030 compared to 1990 [38].

Due to the war in Ukraine, gas prices on the stock exchange have risen to even more than 100€ per megawatt-hour. In the light of the search for new gas suppliers for European markets, such as Norway, it is worth turning to other resources, namely biogas plants. In Europe and especially in Poland, they are just waiting to be used more, and in Germany they are being used on a large scale [39].

The European Commission in May 2022 presented a new energy plan to eliminate energy imports from Russia within five years, based, among other things, on increasing energy savings, expanding renewable energy sources and diversifying Europe's oil and gas supplies. This provides an ideal opportunity to build biogas plants, especially microplants and other small biogas plants, which are ideal for heat recovery and generate energy to meet farm needs. In Poland, a bill was debated at the end of May, which, among other things, unblocks the development of energy production from biomass. According to it, biogas producers will be allowed to participate in auctions later this year. This will make it possible to start investing in biogas plants more quickly [21].

2. Materials and Methods

The research was conceptual at the outset. The authors searched for answers to the set objectives in the literature.

The literature research was based on industry studies, considering the latest research on the subject. Particular attention in the analysis of global literature was paid to considerations related to the biogas market, taking into account its current development trends. The analysis was critical of current solutions for increasing the efficiency of biogas plants, which strengthen the economic justification for their construction and do not take into account factors such as substrates.

The literature on biogas plants is quite extensive. It presents numerous solutions concerning the technical and economic aspects of biogas plants. The importance of biogas plants for the development of economies and the use of waste has been highlighted. However, there is a lack of relevant studies at the level of individual countries, including

an important topic for the authors, i.e., an assessment of the perspectives of biogas market development in Poland and Germany in the realities of the global energy transition.

Conceptualisation in terms of the objectives set required adherence to the research process and its alignment with interpreting the phenomena analysed and appropriate forecasting. The considerations undertaken in this article are analytical and empirical. The research was based on an analysis of reports and industry studies from the biogas plant market in Poland and Germany, as well as on the results of own research. Methods typical of planning and forecasting were used. Figure 1 shows the research algorithm.

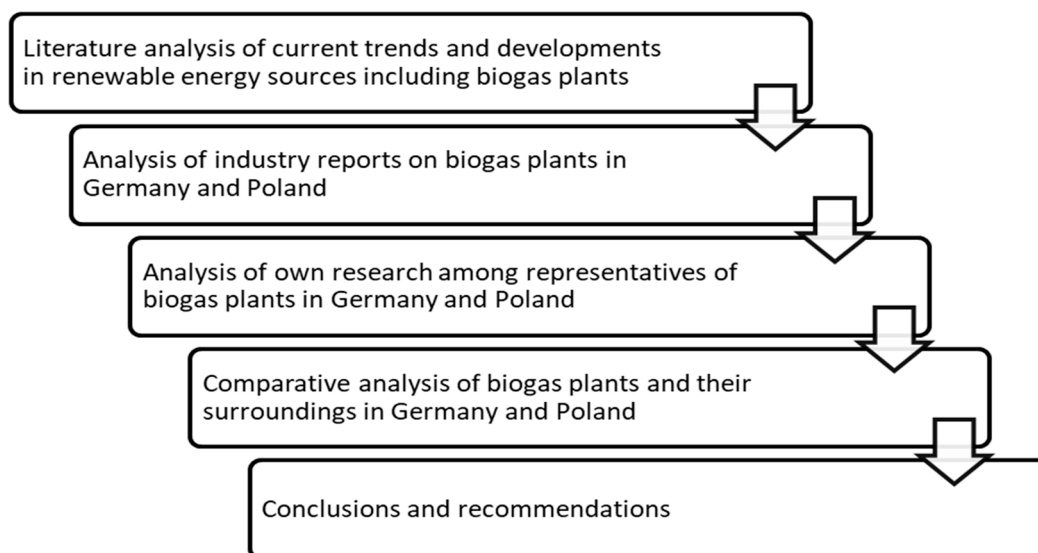


Figure 1. Research algorithm—own study.

The authors used the following methods to achieve the aims and outlines in the introduction:

- Desk research—a literature review was conducted on reports and scientific publications from digital libraries. The desk research results were used to prepare a global overview of the energy situation, particularly the characteristics of biogas plants in Poland and Germany. The desk research results were also used to prepare a CAWI survey to collect information from representatives of biogas plants in Germany and Poland.
- Computer-Assisted Web Interview (CAWI) technique—the authors used this method to collect information from representatives about biogas plants in Poland and Germany, especially their strengths and weaknesses, opportunities and threats. Data were collected in two rounds. The first round of the survey included mainly closed questions. Mainly, a five-point scale was used. In the second round, 10 interviews were conducted with representatives of biogas plants—five from each country. In the interviews, the questions were open-ended.

The questions in the survey concerned:

- Biogas plant development plans or lack thereof;
- Problems faced by biogas plants in the broad area;
- Planned changes in the area of substrates used;
- The extent to which the biogas plant uses liquid manure;
- The area of livestock farmers' problems that affect the restriction of animal husbandry;
- An assessment of the cost-effectiveness of starting up a biogas plant under current economic conditions;
- Evaluation of the technology used in the biogas plant under study;
- Institutional support for biogas plant development;
- Substrate costs.

A questionnaire was sent to 495 biogas plants and only 123 responded. Based on these responses, an analysis of the results was prepared.

At the same time, it is necessary to mention methodological limitations resulting from the periods of biogas plants construction in Poland and Germany (older technology in Germany and the newest one in Poland). The study also uses the results of own research concerning the potential development of biogas plants in the Polish and German energy market. Due to the order of evaluation of the problem investigated in the study, the following methods were applied:

- Deductive (fragmentary), growing out of the thesis formula based on synthetic results, allowing the search for causes and effects to identify them in detail;
- Inductive (synthesis), allowing for the exploration of individual threads and their subsequent generalisation in the form of conclusions and evaluations.

The above simple analytical procedural methods were applied to several research dimensions undertaken in this study.

The authors addressed the key trends and issues in the research to answer the questions posed in the study. In this respect, a critical analysis of the current situation was carried out, considering the results of their own research in order to create reliable conclusions.

3. Results

The European Green Deal aims for Europe to become a climate-neutral continent by 2050. Implementation of the objective is required, to a considerable extent, in the energy sector. As we know, the Member States are implementing green solutions at different speeds.

The beginnings of the adventure with biogas plants go back some 20–30 years. Solutions connected with biogas plants are nothing new. The technology was developed on an industrial scale in the 1980s and 1990s and, despite appearances, the scale of development of the industry is exceptionally large. The main players in Europe today are undoubtedly Germany, Italy, the UK and France, which has discovered the potential of biogas over the last decade. Biogas plants are also very strongly used in Scandinavian countries—Sweden and Denmark are leaders in this respect in the European Union [40].

An interesting case of the successful development of the biogas sector is the story of Lithuania, which has become an example in the development of renewable energy for many countries [41]. Between 2000 and 2018, biomass consumption in the heating sector increased from 2 to 70%. Lithuania has set its sights on a large increase in the area of biomass consumption in the heating sector and it is assumed that by 2030 45% of consumed electricity and as much as 90% of heat energy will be produced from renewable energy sources by 2030 [42]. However, many countries have yet to take an interest in biogas solutions [43]. Lithuania's history and its impressive development in the bioenergy sector can inspire other countries to use RES and, thus, raise the bar in setting emission reduction and environmental protection targets [44].

Biogas can qualify as a renewable fuel for electricity generation under state renewable portfolio standards. It also qualifies under the US Renewable Fuel Standard Program as an advanced or cellulosic biofuel and under California's Low Carbon Fuel Standard as a feedstock for low carbon fuels. Nearly all biogas currently consumed in the United States is produced from anaerobic decomposition and used to generate electricity [45].

Some dairy and livestock farms use anaerobic digesters to produce biogas from manure and used bedding material from their barns. Some livestock farmers cover their manure storage areas (also called manure lagoons) to capture the biogas that forms in the lagoons [46]. The methane in the biogas can be burned to heat water and buildings and be used as fuel in diesel generators to generate electricity for the farm. EIA estimates that by 2020. In total, 20 large dairies and livestock farms in the United States produced about 173 million kWh (or 0.17 billion kWh) of electricity from biogas [47].

3.1. Biogas and Its Formation

Biogas plants produce from plant biomass, animal manure, organic waste (e.g., from the food industry), slaughterhouse waste or biological sludge from wastewater [48]. The list of available substrates, apart from target crops, includes waste from food processing (stock, marc, bakery waste, etc.), waste from slaughterhouses, abattoirs, butchers, animal faeces (i.e., manure), slurry, agro by-product biomass (straw, hay, catch crops) or out-of-date food [49].

There are three types of biogas plants, depending on the type of organic matter used:

- Agricultural biogas plant;
- Landfill biogas plant;
- Biogas plant at the sewage treatment plant.

A biogas plant is a complex technological installation in which biotechnology plays a decisive role—it is about ensuring the right conditions for the process of anaerobic digestion. This involves ensuring the right temperature and pH of the hydrated biomass and the mixing of the fermenting biomass. Biogas is produced by processing biomass, which is one of the basic renewable energy sources. Chemically, it consists of methane and carbon dioxide; its composition largely depends on the feedstock derived from it. Biomass as a raw material for biogas production consists of three basic groups of organic compounds: carbohydrates, proteins and fats. In addition to these nutrients, the fermenter also needs soluble forms of potassium, sodium, iron, magnesium and calcium as well as trace elements such as molybdenum, manganese, copper, zinc, cobalt, nickel, selenium and tungsten for the growth of microorganisms. Table 1 shows the characteristics of the fraction and its content in terms of biogas yield.

Table 1. Characteristics of selected plants and selected by-products in terms of biogas yield [50].

Substrate	Dry Matter Content (%)	Organic Dry Matter Content (%)	Biogas Yield (m ³ /t s.m.o.)	Methane Contentch ₄ (%vol.)
cattle slurry	8–11	75–82	200–500	60
pig manure	approx. 7	75–86	300–700	60–70
cattle manure	approx. 25	68–76	210–300	60
pig manure	20–25	75–80	270–450	60
chicken manure	approx. 32	63–80	250–450	60
maize silage	20–35	85–95	450–700	50–55
rye	30–35	92–98	550–680	approx. 55
grass silages	25–50	70–95	550–620	54–55
brewers' pulp	20–25	70–80	580–750	59–60
cereal broth	6–8	83–88	430–700	58–65
potato stock	6–7		400–700	58–65
fruit marc	25–45	85–95	590–660	65–70
shop waste	5–20	80–90	400–600	60–65
gastric contents	12–15	75–86	250–450	60–70
grass cuttings	approx. 12	83–92	550–680	55–65

The substrates most commonly used in biogas plants, such as raw materials and agricultural waste or sewage sludge, contain appropriate amounts of the elements mentioned. When using highly homogeneous substrates with a constant composition, it is necessary to enrich the charge with microelements in a synthetic form or to introduce additives containing elements [50] that are not present in strategic substrates or digestion of different

mixes. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn [51].

Currently, the most commonly used raw materials in agricultural biogas plants are agricultural by-products (slurry, manure, poultry excrement), as well as plants grown for biogas production (corn, rye, triticale, legumes). To ensure the continuity of the biogas production process, these crops are usually preserved and stored as silage. The cost of ready-made silage is approximately EUR 23. Biogas plants also use the waste available in the agricultural environment, among others from plants processing agricultural raw materials, such as distilleries, breweries, cold stores and dairies.

The choice of substrates depends on the location of the biogas production unit, the availability of organic waste, and to a large extent on the prices of these raw materials. Available raw materials have a significant influence on the efficiency and composition of the produced biogas [52]. The amount of biogas produced, its composition, calorific value and pollution [52], as well as the quality of the digestate depend on the process conditions [53].

The methane fermentation process depends on many factors which can be divided into physical, chemical and biological. The most important factors affecting the process are the type of biomass, the dry matter content, the volatile organic matter load, the homogenisation method and the temperature [54]. In a proper process, the pH level, the alkalinity of volatile organic acids, the content of trace elements and the content of toxic compounds must be taken into account [55].

The average daily production of slurry per LU is 55 dcm^3 . In the case of cattle, 182 days that the animals are housed $\times 55 \text{ dcm}^3/\text{day}$ equals approximately $10 \text{ m}^3/\text{DJP}$ of slurry. If the animals are housed year-round, their annual slurry production is $20 \text{ m}^3/\text{DJP}$. Slurry comes from non-cage housing and is a mixture of fermented animal faeces and urine, containing significant amounts of nitrogen, phosphorus and potassium. Slurry, on the other hand, is produced under shallow litter farming conditions.

According to many scientists [56] and practitioners [14], the technical design of a biogas plant should consider the availability of raw materials in a given area [17]. From the amount of slurry required, the amount of silage needed is determined. Whole-crop maize silage with a dry matter content of 28–35% is particularly suitable. The average daily slurry production per livestock unit is 55 dm^3 . In the case of cattle, 182 days that the animals are housed $\times 55 \text{ dm}^3/\text{day}$ equates to approximately $10 \text{ m}^3/\text{DJP}$ of slurry. If the animals are housed year-round in livestock buildings, their annual production of slurry is $20 \text{ m}^3/\text{DJP}$. An essential element is the dry matter content of the storage mixture (charge) in the digester. The dry matter content of 11–15% is assumed, resulting from the possibility of its pneumatic transport and the possibility of mixing. The dry matter content of slurry and silage is variable. Therefore, the quantitative share of each substrate in the mixture changes. Assuming a dry matter content of 7% in slurry and 30% in silage, 6 tonnes of maize silage with a dry matter content of 30% should be added to achieve a dry matter content of the desired level 22 m^3 slurry. The mixture will have a dry matter content of 11.9% ($22 \times 0.07 = 1.54$; $6 \times 0.30 = 1.8$; $1.54 + 1.8 = 3.34$; $28 = 11.9\%$) [57].

A farm with 410 livestock units (pigs) produces 8200 m^3 slurry with 7% dry matter annually. For 8200 m^3 of slurry, 2236 t of maize silage with 30% dry matter must be available. This yields 11.9% dry matter in the total mixture. To obtain the required amount of silage, considering harvesting and ensiling losses of 12%, 2504 t of green fodder must be produced. With a yield of 45 t/ha, 56 ha of land must be devoted to growing maize for biogas. A biogas plant is a major logistical and raw material challenge [58].

When cultivating plants for biogas production, the same rules apply for food, fodder or agri-food processing. The basic criterion for the selection plants for biogas production is the dry matter yield per unit area, the content of easily fermentable components and the ease of storage after harvesting the fresh mass.

The dry matter yield (dt/ha), after accounting for harvest losses and preservation by ensiling, which needs to be achieved for biogas production to be viable, should be:

- 80–165—maize with 32% dry matter;

- 85–115—whole cereal plants harvested at the stage of milk maturity of the grain;
- 60–100—field grown grasses, clover with grasses;
- 40–90—lichen from grassland;
- 50–85—cereal grains [58].

Maize silage is one of the most popular feedstocks in agricultural biogas plants.

Although it is no longer the main substrate for most new installations based on production or livestock waste, the vast majority of biogas plants still use silage to stabilise the fermentation process and to facilitate the disposal of slurry or sewage sludge.

The choice of the amount and type of substrate used is key to the efficiency of the plant. When selecting substrate mixtures, it is important to maintain the correct ratios, e.g., of carbon to nitrogen. With the necessary knowledge in this area, we can select the optimum substrate and technological parameters for the individual investor.

Awareness of these conditions is extremely important at the stage of technology selection, but also during operation of the installation. Therefore, Uniserv offers technological care over the operation of biogas plants. It is worth taking this opportunity to dispel an unfair myth. It is not true that a biogas plant is a source of unpleasant odours. On the contrary, a biogas plant does not emit odours if properly designed and operated. The reaction product of the biogas plant is biogas and digestate, which is a good quality organic fertiliser. The digestate is virtually odourless. It is worth mentioning that the so-called post-ferment, i.e., fermented substrates, constitute an excellent natural fertiliser. Post-fermentation pulp is a rich source of nutrients for soils and plants, and a good alternative to the use of artificial fertilisers or liquid manure.

Biogas is an energy-rich gas produced by biomass's anaerobic decomposition or thermochemical conversion. Biogas consists mainly of methane (CH₄), the same compound in natural gas, and carbon dioxide (CO₂). The methane content of raw (untreated) biogas can vary from 40–60%, with CO₂ making up most of the remainder, along with lesser amounts of water vapour and other gases. Biogas can be burned directly as a fuel or processed to remove CO₂ and other gases for use, similar to natural gas [59]. Purified biogas can be called renewable natural gas or biomethane [60].

Anaerobic biomass decomposition occurs when anaerobic bacteria—bacteria that live without free oxygen—eat and decompose or digest biomass and produce biogas. Anaerobic bacteria occur naturally in soils, in bodies of water such as swamps and lakes and in the digestive tracts of humans and animals. Biogas is formed and can be collected from municipal solid waste landfills and animal manure ponds. Biogas can also be produced under controlled conditions in special tanks called anaerobic digesters. The material remaining after anaerobic digestion is called the digestate, which is rich in nutrients and can be used as fertiliser.

3.2. Biogasification in Poland

The market for biogas plants in Poland is developing very slowly due to the lack of stimulation from the state. Energy from biogas may account for as much as 18% of current electricity in the country.

In Poland, most biogas plants are enterprises with an installed electrical capacity of more than 1 MWe.

The biogas and biomethane market in Poland is in a special position. After years of looking with envy at thousands of installations in other countries, favourable conditions for the operation of these very useful installations, not only for the agricultural and food industry, are finally being created in this country [59].

The potential of Polish biogas, estimated at several billion cubic metres a year, is comparable to that of its western neighbours. Poland produces about 120 million tonnes of manure and slurry annually and at least 8 million tonnes of cereal and rape straw [60]. The following plants are recommended for the production of green fodder that can be used in biogas plants in Polish conditions: maize, pure sowing cereals, cereal mixtures, cereal–legume mixtures, sunflower, grasses of all kinds, lucerne, clover, mixtures of lucerne

or clover with grasses, sugar beet leaves and others that may be applicable [61]. Greens can be tipped from municipal lawns, golf courses, stadiums and airports. Biowaste that is collected from residents could be a popular source of organic matter. However, not all fractions would be suitable for biogas plants [62].

These conditions favour the establishment of biogas plants and, in addition, currently, some of the available substrates present a significant problem for farmers. Farmers diversify their crops to utilise manure and slurry. A biogas plant represents a major logistical and raw material challenge. The design of each biogas plant is individual and depends on the composition of the input material. Similarly, the technological equipment for the plant depends primarily on the available substrates. The amount of substrate determines the size of all aggregates and the volume of the tanks. The quality of the substrates (dry matter content, origin structure, etc.) determines the layout of the process technology. Biogas projects are generally smaller in scale compared to other renewable energy investments and, therefore, are less profitable [63].

The number of agricultural biogas plants in Poland is overgrowing despite many barriers (over 300 biogas plants are in the construction phase). The main barrier are formal and legal problems during investment preparation and the lack of an act on renewable energy sources [59]. There is widespread ignorance on the part of public administration bodies, as these are new investments that are little known. High investment outlays and a high degree of complexity make such projects difficult to build and operate. This is particularly important in the case of small investments, as unit costs increase dramatically, and such undertakings need to be more strongly supported, which is proposed in the draft Law on Renewable Energy Sources [63]. The lack of qualified design and construction staff makes implementing such investments exceedingly difficult. Difficulties in connecting installations to the grid are partly due to resistance from the professional energy sector and partly to the poor state of the energy infrastructure. In addition, there is often resistance from the local community, which most often results from a lack of awareness. Many farmers construct small installations despite the lack of proven models. Designs for small biogas plants are being developed, sometimes modularly, so that they can be expanded as needs and generation factors change [64].

Innovative projects are emerging where electricity and heat are generated from biogas. Farmers are using the Rural Development Programme to help them build biogas plants on their farms, giving them many benefits. One of the most important factors is independence from energy supply, particularly in peripheral areas, where very large voltage drops and complete blackouts often occur. Farmers can sell surplus energy to the grid and, thus, generate additional income for the farm [65]. A biogas plant in such an area stabilises the electricity grid in rural areas. The operation of a biogas plant generates new jobs, which is important in rural areas (in Germany, more than 100,000 new jobs have been created in biogas plants). By-products from agriculture and the agri-food industry can be used in biogas plants, which is important for environmental protection as the disposal of these products generates high costs. The zero balance of carbon dioxide emissions from energy production (not counting transport issues) and the reduction of greenhouse gases, mainly methane, is also important for the environment [48].

There are currently around 10,000 agricultural biogas plants in Germany, whereas in Poland, there are currently over a hundred. It is estimated that several or a dozen thousand installations could be successfully operating in Poland.

3.3. Biogasification in Germany

Germany is Europe's largest biogas market, both in terms of the number of generation units and the amount of fuel produced. In Germany, this raw material accounts for 14% of electricity generation from renewable sources. The facilities for the production and use of this fuel are spread relatively evenly across all the federal states of Germany, although the greatest concentration is in northern Germany [12].

The dynamic development of the sector is mainly due to well-tailored legislation introducing favourable support systems—this refers to the so-called EEG (Erneuerbare-Energien-Gesetz) law, which came into force in 2000, introducing, among others, feed-in tariffs. Since 2017, the solutions offered by this document have also included longer funding prospects for existing units (until 2030), a support package for developing biogas-based energy and provisions to make existing regulations more flexible. As a result, 9527 biogas plants were operating in Germany in 2019 [13].

Within the EU, Germany has developed biogas plants the most. There are currently more than four thousand biogas plants in operation in Germany and this number is growing. German agricultural biogas plants use crops specifically cultivated for biogas, slurry and by-products from processing plants for food. Taking the total amount of substrates converted to biogas as 100%, 45% are plant energy feedstocks, 24% slurry and 15% plant waste products. The remaining raw materials are used as supplementary additives.

In Germany, taking the number of biogas plants as 100%, the percentage of biogas plants using individual energy sources are shown below:

- 97%—whole-crop maize silage;
- 50%—cereal grains, mainly wheat and triticale;
- 49%—whole-crop silage;
- 35%—grass silage;
- 8%—green fodder from grass;
- 3%—maize grain;
- 1%—other raw materials, i.e., sunflower silage, beet, hay, straw, distillery stock, potatoes [13].

In Germany, 93% of agricultural biogas plants use slurry mixed with silage and other raw materials. Cattle slurry is used in around 75% of biogas plants, while pig slurry is used in only 39%. Only those plants are used which produce a lot of biomasses from April to the end of October [12]. The following crops are recommended for green fodder production under German conditions: maize, pure sowing cereals, cereal mixtures, cereal/legume mixtures, sunflower, Jerusalem artichoke, grasses, lucerne, clover, lucerne or clover/grass mixtures, sugar beet leaves and others. Green fodder from city lawns, recreational areas, golf courses, stadiums and airports is valuable for biogas plants. A popular source of organic matter is water lily and algae [66].

Until the second decade of the 21st century, biogas plants were seen as electricity generators. This was particularly evident around 20 years ago in the German market, where biogas plants were geared almost exclusively towards electricity generation. Therefore, plants in the range of around 1 MW were built as so-called optimum plants. Biogas plants were intended to generate electricity for the farms where they were placed. This concept was supposed to make these farms self-sufficient. Initially, farm waste was placed in the biogas plants to produce electricity. With time, a shortage of waste occurred, since the cattle population decreased, and so did the amount of manure and other waste used to produce gas. Therefore, German farmers were forced to process silage, mostly from maize, into biogas plants. It is worth noting that in Germany, as much as 10% of the agricultural potential is used for special maize varieties bred specifically for biogas plants. One could say that the whole idea has been somewhat perverted, because something that was supposed to be used to process mainly waste is being fed into special agricultural production—as much as 10% of the area is being used for biogas plants that produce electricity [67].

The situation of biogas plants in Germany is not clear. Due to problems with maize silage in German agriculture, the development of biogas in Germany is changing, and in 2020 alone, there were 100 fewer biogas plants in Germany. Instead of building more biogas plants to contribute to the success of the German Energiewende, the number of biogas plants is falling, despite political and financial support. On the other hand, the capacity of the new plants is increasing, so that the total capacity produced by German biogas plants is growing. The problem lies mainly in market developments, which greatly benefit large biogas investors. Large companies pull raw material from the market, and smaller biogas

plants can, therefore, have problems with the raw material. Small biogas plants are much less efficient and are owned by individual farmers. The recent drought that has affected Europe has exacerbated the situation for smaller biogas plants. The reduced quantity and deterioration of the raw material from which farmers produce maize silage has significantly impacted decisions to close the most unprofitable biogas plants. Dairy farmers and feedlots were eager to build biogas plants until a few years ago because it was the ideal opportunity for them to use the waste and earn extra money. During the 2010–2015 boom, as many as 2300 biogas plants were built in Germany. On average, new biogas plants have a capacity of 693 kW, whereas those built before had only half that [66].

The total capacity generated in German biogas plants has already reached 6.2 GW, which corresponds to about 3% of German electricity production and about 5% of electricity supply from renewable sources. The German government continues to set its sights on expanding biogas plants in Germany so that capacity levels reach 8.4 GW by 2030.

The decisive change from the farmers' perspective was the phasing out of the previous fixed remuneration, which initially amounted to EUR 0.24 per kWh, and the switch to the auction system, which brings the farmer an average of EUR 0.14 per kWh. Such a significant drop has made energy production simply unprofitable for some farmers.

After last year's significant decrease in the number of small biogas plants with a capacity of up to 150 kW, German legislators have decided to continue to support these installations for another 10 years. The 700 biogas plants in question use an average of 70% pig and cattle slurry to produce biogas. This decision has stabilised small installations, which the legislator does not want to eliminate from the system. Small biogas plants can, therefore, still count on guaranteed support, but at the same time, they are obliged to sell part of their electricity on the free market. In this way, biogas plant owners are supposed to operate according to the rules of the free energy market in relatively safe circumstances. Biogas plants that are no longer subject to support for renewable energy sources (EEG programme) have to seek their fortune on the free market and sell the energy they produce at market prices. This is now a positive aspect, as electricity prices are very high. At the same time, operating on the free market and bearing the risk of such sharp fluctuations in electricity prices as in recent years is a major challenge for many agricultural enterprises. In addition, the German state's support and the regulations created in this regard encourage investment in biogas plants [67].

The market for biogas production has become highly professionalised in Germany in recent years. Instead of a supplementary income, electricity has for many companies become a central part of their business. These companies often find themselves much more comfortable in the complex administrative maze that ordinary farmers complain about. The professionalisation of biogas plants can be evidenced, for example, by investments in the size and efficiency of production. In the last two years, the average output of biogas plants in Germany has increased from 672 to 749 kW or by 11%.

In Germany, large biogas plants are now being built and, as they become more efficient than smaller competitors, they will begin to displace them. It will not be worthwhile for farmers to maintain small biogas plants just for their own needs. As mentioned above, if there is a possibility to make extra money and reduce the waste generated on the farm, then this is desirable. If the farm has to buy substrates or the production of substrates becomes less and less profitable, the latter of which will happen because of high fertiliser prices. The owners of smaller biogas plants will start to liquidate them.

4. Discussion

The best substrate for a biogas plant is available locally on the farm and does not incur additional transport costs. The most cost-effective solution is biogas production without contamination from the non-woody parts of energy crops. The most commonly used substrates for biogas production in Polish biogas plants are post-harvest waste, maize silage or waste from the fruit and vegetable industry. For the stability of the technological process, it is better if the feedstock is a mixture of several substrates, including liquid

manure. In Polish biogas plants, cattle slurry and by-products of the dairy industry are most commonly used. German biogas plants use liquid manure (usually cattle or pig slurry) mixed with silage and other raw materials. Slurry is 10 times worse in terms of yield than maize silage and 3 times worse than manure. If a biogas plant were to run on slurry alone, much larger tanks would have to be built.

Due to the decreasing number of livestock in 2021, Poland is 6.37 million heads of cattle and 11.04 million heads in Germany [68], there is a threat that biogas plants will be deprived of manure [60]. In June 2021, the cattle population in Poland amounted to 6400.9 thousand, which was 57.2 thousand (by 0.9%) more than the year before and 122.0 thousand (1.9%) more than the herd size in December 2020 (Figure 2). A similar decline in the herd applies to German farmers; they kept 262.2 thousand cattle less (2.3%), which meant a decrease to 11.04 million (Figure 3).

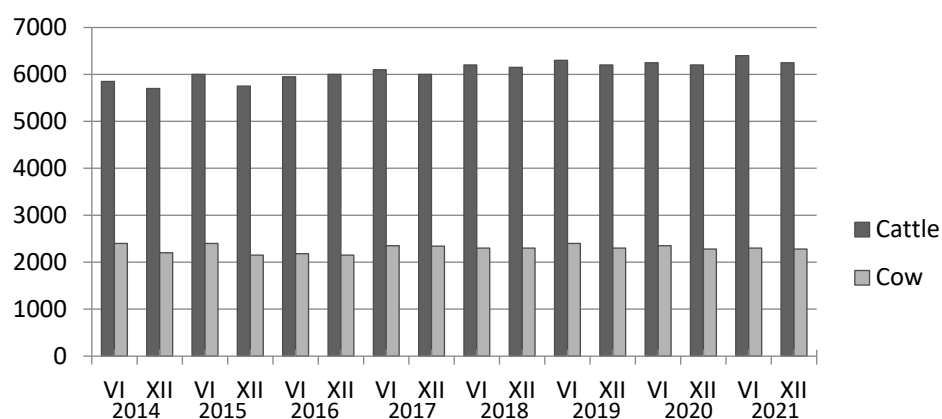


Figure 2. Cattle population (in thousands) including cows 2014–2021 in Poland [69].

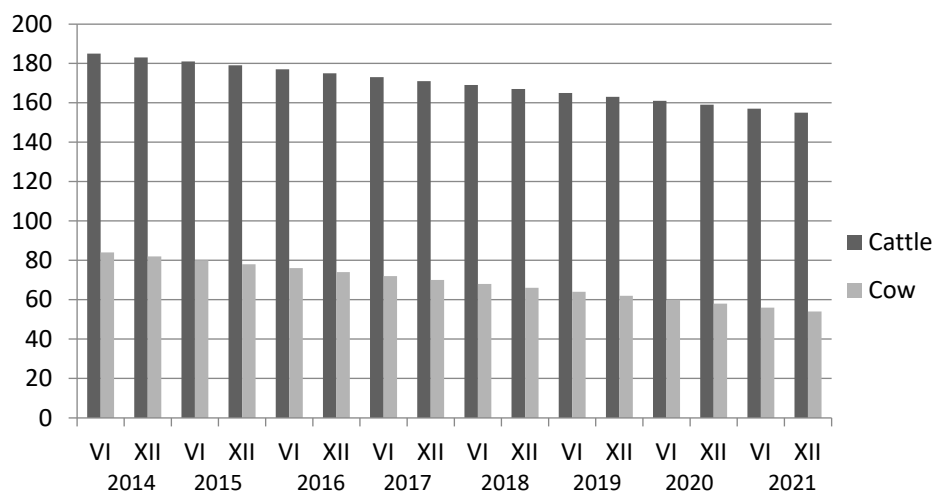


Figure 3. Cattle population (in thousands) including cows 2014–2021 in Germany [70].

A similar situation applies to pig farming. The pig population in December 2021 in Poland amounted to 10,242.4 thousand [31], and in Germany at the same time, about 23.8 million pigs were kept [70]. The number of pig farms was 18,800 as of 3 November 2021, a decrease of 7.8% or just under 1600 farms from November 2020. As of November 2019, the number was still 21,200 farms, a decrease of 11.1% or 2400 farms in the last two years [34]. At the beginning of December 2021, the pig population amounted to 10,242.4 thousand and was 1485.0 thousand fewer (12.7%) than that recorded in the corresponding period of 2020, and compared to the pig herd size in June 2021, 1190.2 thousand fewer, i.e., 7.2% [69].

The average cattle manure production per year is about 15 m³ [71] and the average pig manure production per year is 2.64 m³. Analysing these data on liquid manure and

the cattle and pig populations, if the decline in livestock farming continues, there may be a shortage of the raw material, i.e., liquid manure, in 5–6 years.

Among the voivodships in Poland, the greatest potential for agricultural biogas production from cow manure is found in the following voivodships: Wielkopolskie, Warmińsko Mazurskie, Kujawsko-Pomorskie, Mazowieckie and Zachodniopomorskie. The following provinces have the best conditions for producing agricultural biogas from pig manure: the Wielkopolskie, Dolnośląskie and Lubelskie provinces, and from chicken manure: the Mazowieckie, Wielkopolskie and Łódzkie provinces. Thus, it can be seen that in this statistic, the most privileged place is occupied by the Wielkopolskie Voivodship, and in this voivodship, the dynamic development of biogas plants in Poland can be seen.

Polish agriculture, therefore, has great potential for biogas production. However, it remains largely untapped, although this appears to be a temporary situation. In fact, it is estimated that by 2030, all of the real economic potential concerning maize silage and nearly 60% of that coming from wet organic waste can be utilised.

The increase in the price of artificial fertilisers (Figure 4) due to the turbulence surrounding the supply of natural gas [72], which is one of the main components, means that the cultivation of maize for silage for biogas plants is not profitable, as one tonne of silage on the market (currently EUR 35–60) is beginning to equal the fee that farms receive for the kW produced. Therefore, farms will look for other solutions or will close their biogas plants. Biodegradable waste, which could be collected from the public and sent to the biogas plant, could be a solution. However, there are still the costs of transporting and collecting the material, which is significant in the case of dispersed housing.

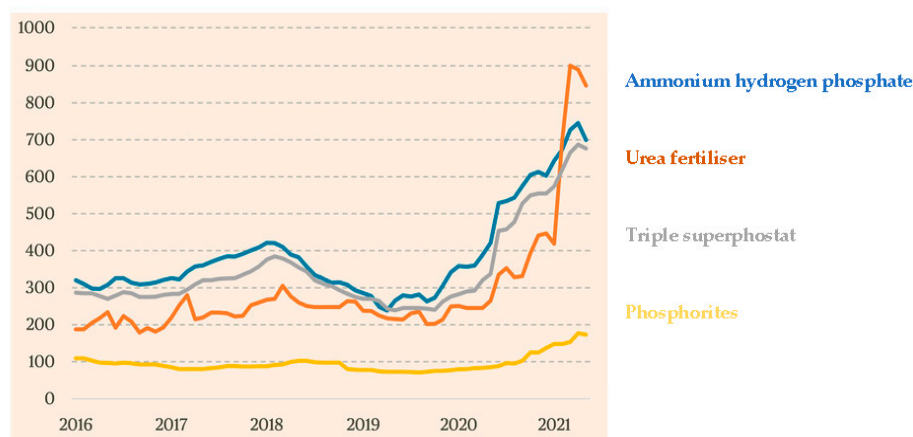


Figure 4. Fertiliser prices on world markets in dollars per tonne [72].

One of the solutions to the problems of managing the biodegradable waste fraction is to put it into biogas plants. Considering the complicated, unclear legal requirements, too low limits for accepting this fraction to particular installations or the lack of a guaranteed market for the produced compost, such solutions can help biogas plants solve the problem with substrates. The problem is the lack of a strategy for managing this type of waste by municipalities and the cumbersome certification mechanism for products made from its processing.

The potential for development of biogas plants in Poland and Germany is a good direction for biogas projects. In Poland, most land is farmland, as in Germany. This potential should absolutely be exploited. It is an important direction for waste reduction and reducing the need for individual consumers to purchase electricity or gas.

When analysing the results of their own research, biogas plant users in Poland and Germany indicated that they look closely at substrate availability and price when analysing the current situation. In Poland, users are mostly reluctant to change substrates, while in Germany, the situation is the opposite: most are considering changing substrates in the

future (Figure 5). German users pointed out the difficulties in sourcing slurry in the future and the high costs of cultivation.

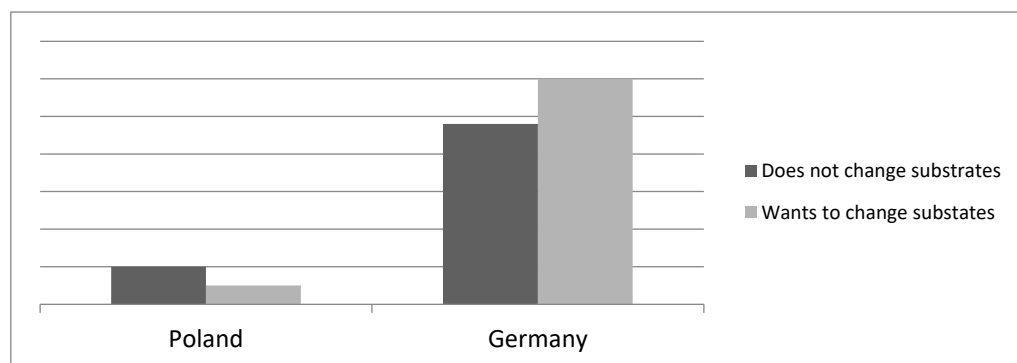


Figure 5. Willingness of biogas plant users to change substrates based on own research.

The appropriateness of the development of biogas plants is confirmed by the results of the referred studies, which show that:

- (a) 82% of biogas plant managers are interested in expanding their plants;
- (b) 62% of respondents indicate current and future problems with substrate acquisition;
- (c) 47% of respondents do not plan to change substrates, while 26% want to make changes in this area and look for new development directions;
- (d) 96% use liquid manure and want to follow this path;
- (e) 46% of the producers who use liquid manure observe a significant decrease in the number of cattle and pigs in their area, which may be a threat to the further operation of their biogas plant;
- (f) 87% of those surveyed in Poland and 48% of those surveyed in Germany consider the process of setting up a biogas plant to be costly and without a quick return on investment;
- (g) 45% of those surveyed in Germany consider the technology they are using to be outdated and do not intend to modernise it for the time being;
- (h) 88% of respondents indicate that state aid and support could facilitate the development of biogas plants and their modernisation;
- (i) 86% of respondents indicate that changes in substrate acquisition are necessary due to the increasing costs of obtaining substrate from maize or other crops, which are grown only for use in biogas plants.

The presented research results indicate a significant potential for developing biogas plants in Poland and Germany. In this regard, it seems necessary to take action in order to:

- (a) Work on the most effective use of existing biogas plants, so that they do not lack raw material and at the same time the substrates used in biogas plants solve the waste problems of particular communes or areas;
- (b) Solutions should be sought so that individual biogas plants deal with waste that is located in the immediate vicinity of the biogas plant so as to reduce the cost of transporting the raw material;
- (c) Cooperation of companies that produce waste with large companies that own biogas plants so that their investments are correlated with the plans of companies that have waste, because only then can changes in the substrate acquisition process be responded to;
- (d) Promotion of knowledge about biogas plants among cattle, pig and poultry farmers to encourage investment in biogas plants.

Interest in biogas plants will grow due to a growing market for biodegradable waste. The development of biogas plants can contribute to the expected improvement in waste management and ultimately impact the climate, in connection with the ambitious global

objective of climate neutrality [72]. The implementation of large-scale green solutions, such as biogas plants, is an excellent step towards strengthening environmental performance and lending credibility to long-term environmental goals.

5. Conclusions

The agricultural biogas plants that have been built in western Europe, particularly in Germany, for more than 20 years were designed for substrates derived from target crops, mainly maize. Nowadays, trends are different—the price is high for technologies that allow gas production mainly from agri-food industry waste. To sum up: our new plants will be more modern and better able to meet the environmental policy objectives of the European Union.

It is worth noting that at the end of 2020, the average carbon footprint of 1 kWh of electricity in Poland was 770 g. The same value for, e.g., Germany is about 450 g/kWh, while it is 250 g/kWh for Lithuania and less than 50 g/kWh for Sweden.

Biogas plants will significantly help agri-food entrepreneurs to sell their products through the possibility of carbon footprint labelling. We already see expectations from large retail chains for producers on carbon footprint labelling.

The production of green energy from biogas and the utilisation of waste from agricultural production will also contribute to avoiding or reducing possible future greenhouse gas emission charges for farmers. This is a not insignificant factor, as CO₂ emission allowance prices are now close to 60 EUR/t.

Agricultural biogas plants stimulate local economic development, enhance the economic activation of their area and create favourable conditions for local entrepreneurship. The construction of such facilities contributes to the creation of new jobs, thereby ensuring an increase in regional revenues. In addition, it enhances regional development, improves the surrounding infrastructure and leads to a change in the structure of local business through the introduction of a new business profile. From the point of view of the socio-economic impact assessment, however, the creation of new jobs seems to be the most important.

Biogas plants have advantages for the country's electricity system. They are dispersed sources, allowing transmission losses in the electricity grid to be reduced. They are stable sources of renewable energy, unlike wind farms and photovoltaics, which are characterised by their dependence on temporary weather conditions and require back-up sources. Biogas plants have energy storage potential. They can store biogas when they have a suitable reservoir. They can also provide a focal point around which a local energy centre will form.

Biogas production can be based on biomass of various origins, especially environmentally troublesome by-products and waste requiring appropriate storage and disposal conditions. The management of such substances is troublesome due to the increasing volumes of waste and the costs of storage and disposal, which is further exacerbated by specific disposal legislation. Appropriate management makes it possible to protect the environment and produce clean energy at the same time. The creation of new biogas plants allows markets to be created for the agricultural products that are substrates for them.

As a by-product of the processes taking place in an agricultural biogas plant, a fermented mixture of the input material used is produced, which is very suitable for soil fertilisation and compost production. As a result of the technological processes taking place in an agricultural biogas plant, pathogenic organisms are destroyed.

In order for biogas plants to operate efficiently and be a solution to the numerous energy and waste disposal problems, they must be fed with substrates that solve local waste problems.

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