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REVIEW

15 Years of the Polish agricultural biogas plants: their history, current status, biogas potential and perspectives

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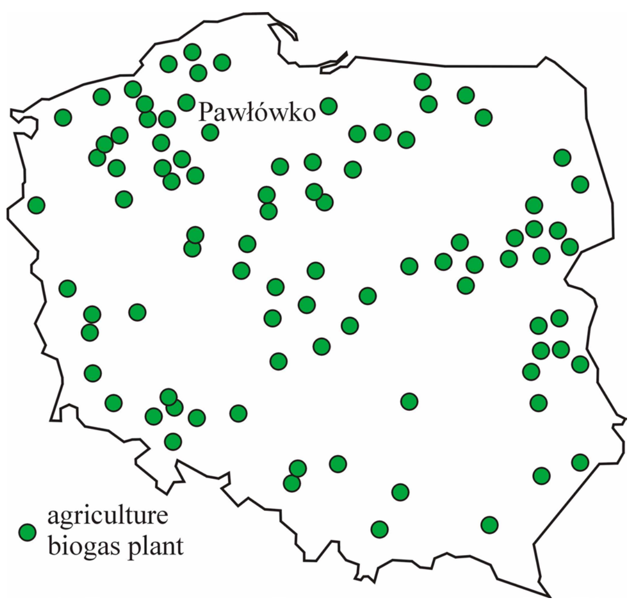
Abstract

15 years have passed since the first agricultural biogas plant in Poland was established. The history of agricultural biogas plants in Poland is presented along with the characteristics of the selected installations. Currently, there are 93 agricultural biogas plants operating in Poland. The formal and legal requirements for the construction of an agricultural biogas plant in Poland are described, and the perspectives of biogas plants development have been presented. The calculated amount of energy that can be obtained from biogas in Poland is 131 PJ/year. Sociometric surveys were conducted among the biogas plant owners. The respondents described the barriers and elements of the investment risk in Poland. A PEST (political, economic, social and technological environment) analysis of agricultural biogas plants in Poland was carried out.

Graphic abstract



Keywords Biogas · Agricultural biogas plant · Renewable energy · Poland · PEST analysis

Introduction

Reduction of the greenhouse gas emissions as well as combating the climate change through the production and use of biofuels is the overarching goal of the sustainable agriculture development programs in Poland, the EU and the

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world (Heesterman 2019). In this context, political support for the development of biogas production technology in agricultural biogas plants (ABPs) appears to be natural because the production of biogas is more beneficial for the environment than its abandoning such plants (Igliński et al. 2011). ABPs not only solve the problem of the methane emissions released from biomass, but also enables the management of all waste biomass (Mukherjee et al. 2020) and its conversion to useful and environmentally friendly energy and agricultural fertilizer (Ribeiro and Rode 2019).

Biogas arises in the process of anaerobic fermentation of organic waste, during which organic substances are broken down by bacteria into simple compounds (Rosas-Mendoza et al. 2018). The gas is a mixture of methane (40–80%), carbon dioxide (30–50%) and other gases in trace amounts resulting from the process of anaerobic biomass decomposition (Weiland 2010). The basic advantage of agricultural biogas is its versatility, in comparison with other renewable energy sources. It can be used for the following purposes:

- To generate electricity and heat,
- After cleaning as fuel for internal combustion engines,
- After cleaning forced into the gas grid (Igliński et al. 2012).

The raw material for ABP can be any kind of organic matter: energy crops, maize and grass silage, expired foods, restaurants and households leftovers, sewage sludge, waste from the agro-food industry and agriculture (liquid manure, manure, sugar beet leaves, etc.) (Markou et al. 2017). Disposing of this waste is both expensive and problematic (Surendra et al. 2014). Using the waste as the raw material for a biogas plant is the cheapest and optimal for the environment method of its disposal (Melikoglu and Menekse 2020). Moreover, the postdigestion fertilizer from ABP is characterized by a high content of mineralized nitrogen, phosphorus and potassium. In addition, in the digestion process, organic components such as the eggs and weed seeds, weeds as well as fecal bacteria, are destroyed (Rosas-Mendoza et al. 2018). In addition, waste heat from biogas combustion is sufficient to run steam explosion technology (Maroušek et al. 2018).

These are not the only advantages of biogas plants but they also provide an additional source of income for farmers, support in the restructuring and modernization of agriculture, create new jobs and increase the incomes of local self-governments. In Poland, they can be developed in every area with high unemployment and low salaries where the number of workplaces does not increase, such as poorer regions, peripheral agricultural communes and underdeveloped economies, as many of these areas have been bypassed by the existing gas pipeline grids (Chodkowska-Miszczuk and Szymańska 2013). The energy obtained from biogas will allow Poland to achieve the target of 15% of energy from renewable sources (Ignarska 2013).

Biogas plants operate all over the world, but the level of technical development varies widely. Millions of technically simple biogas plants made in an economic way have been operating in Asia for decades. In Europe, turnkey, technically advanced biogas plants, works (only in some countries) no longer than 10–15 years. The state of biogas plant development in other parts of the world lies between these two options (Fischer and Krieg 2018).

Global trends in energy development are heading toward technologies that use energy storage and numerous dispersed, mainly renewable energy sources, located as close as possible to end users. For the national economy, investments in this field are an opportunity to build technological advantages, innovate in industry and reduce dependence on imports of energy resources and improve environmental conditions (Igliński et al. 2012).

The aim of the study was to present the history, current status and prospects of the agricultural biogas sector in Poland on the fifteenth anniversary of the commissioning of the first agricultural biogas plant in Pawłówko (2005). We presented how agricultural biogas sector was developed in Poland and in the world. Until now, there have been only a few articles in English describing the agricultural biogas plant sector in Poland. This article is a kind of compendium of knowledge about biogas plants in Poland. In Poland, large, centralized biogas plants are most often developed (similar to Denmark). In recent months, container microbiogas plants (for one farm) have been promoted.

The authors described agricultural biogas plants as early as 2012 (Igliński et al. 2012); however, only 24 were working at the time, and currently 93. Budzianowski (2012) focuses on optimization of the Polish agrobiogas energy system. Chodkowska-Miszczuk and Szymańska (2013) describe the structure of feedstock for agriculture biogas production and the structure of the biogas sector in Poland. Szymańska and Lewandowska (2015) describe the biogas sector in Poland (landfill biogas, agricultural biogas and biogas from sewage treatment plants), with only 42 agricultural biogas plants operating in Poland at the time. We believe that there is a need for a broad description of the biogas sector in Poland to fill this literary gap. The biogas sector has been developing quite rapidly in Poland in recent years, and there is no recent literature in English.

We also calculate agricultural biogas potential in Poland. In addition, a survey was carried out among ABP in Poland, and a PEST analysis was conducted. The PEST analysis tells us whether there are friendly conditions in Poland to invest in ABP. PEST analysis has not been developed and published so far. In our opinion deep analysis of agriculture biogas sector in Poland is important and indicates that further development of this sector is possible in Poland.

Agriculture biogas plants can increase energy security of Poland as well as decrease import of natural gas from Russia. Development of agricultural biogas plants in this country has merits and should be supported financially and organizationally.

Agricultural biogas plants in the Asia

China is one of the earliest countries that has developed and utilized biogas for almost a century. By the end of the nineteenth century, simple biogas digesters had appeared in the coastal areas of Southern China (Gu et al. 2016).

China is the absolute leader in the number of biogas plants—more than 40 million installations, although the vast majority are small, backyard. Chinese leader Xi Jinping announcing in 2016 five priorities for China's development for the coming years, mentioned among them the need to develop biogas plants in order to utilize animal manure and improve the environment (Zhang and Qiu 2018).

In India, the number of biogas plants is estimated at around four million. Biogas plants also operate in many other countries, such as Vietnam, Thailand or others. For the most part, these biogas plants have been made economical and operate on the basis of underground, non-insulated fermentation chambers. These are objects with a very simple structure, but cheap and effective. As a raw material, they use animal manure (Tufaner et al. 2017) and organic debris from the house and process it in batch fermentation mode (Fig. 1). Once a year, they are emptied and the fermented substrate is exported to the fields as a fertilizer. Biogas is harvested and used for cooking and lighting (Biogas in India 2019).

It is estimated in the analysis (Mittal et al. 2019) that the biogas potential will grow from 310 to 655 billion m^3/year in the year 2040 depending upon availability of different resources. The calculated biogas potential in 2040 is around 36% of India's current (2015) total primary energy supply in the high availability scenario.

Fig. 1 Agricultural biogas plant in India (Biogas in India 2019)

The above description does not apply only to two countries: Japan and Korea. Over the last 3 to 4 years in Japan, the biogas market provided by modern agricultural biogas plants has developed. In this context, we use the word 'modern' in the European sense: Many German, Danish and Austrian companies have entered the Japanese market and have sold licenses to several Japanese general contractors (Fischer and Krieg 2018).

More than 70 plants have been built in Russia, more than 30 in Kazakhstan and 1 plant in the Ukraine, where about 3000 biogas plants are planned for biogas production (Comparetti et al. 2013).

The application of biogas technology in Indonesia has been ongoing since the 1980s as a project supported by the Food and Agricultural Organization (FAO) (Khalil et al. 2019). Since then, there have been many projects like this that have been started to explore and utilize the potential application of biogas as an alternative source of renewable energy by the Indonesian government and also in several provinces such as in East Java, Central Java, West Java, South Sumatera and East Nusa Tenggara. The potential amount of biogas in Indonesia that can be generated from animal waste includes manure, rumen content and blood as up to 9597.4 Mm^3/year. In addition, it is also estimated that such a major amount of biogas can potentially be converted to more than 1.7×10^{10} kWh/year of electricity.

Pakistan's livestock accounts to about 159 million animals creating nearly 652 million kg of manure on a daily basis from cattle only, which gives the potential of 16.3 million m^3 of biogas daily over 20 million tons of fertilizer per year (Yasar et al. 2017). In 1959, biogas plant installation at household level was started in Pakistan. Biogas Support Program (BSP) was started by Pakistan government in 2000. Until now, it has completed the target of installing 1200 biogas units, whereas another 10,000 units will produce almost 27% of country's biogas potential in the coming five years.

Agricultural biogas plants in the Australia and New Zealand

There are not many pilot biogas plants in Australia and New Zealand that are used to process animal debris. For some time, biogas plants have been operating at some universities (Fischer and Krieg 2018).

Waste-based production (livestock manure, biosolids, food and water) in Australia has the potential to become a £2.24 billion per year industry. With a livestock population of 29 million cattle, over 2 million pigs, and 101 million poultry in addition to about 24 million people generating biosolids and 290 kg of food waste per year, the potential for biogas is approximately 7.5 million m^3. This can contribute toward achieving renewable energy targets through electricity generation and, if upgraded, can help fuel the 380,000 natural gas vehicles already driving on Australian roads or connect to the 6.5 million homes on the gas distribution network (World Biogas Association 2018).

Agricultural biogas plants in the North America

Recently, the building and operation of agricultural biogas plants has started in Northern America. Nowadays, about 600 plants exist in the USA, of which 100 are in the agricultural sector and 500 at landfills (Comparetti et al. 2013).

The methane potential from landfill material, animal manure, wastewater, and industrial, institutional, and commercial organic waste in the USA is estimated to be about 7.9 million tonnes per year, which is equal to about 420 billion cubic feet or 431 trillion British thermal units (NREL 2019). Table 1 shows estimated methane generation potential for select biogas sources in the USA.

The production of Canadian biogas from all major sources—agricultural organics (excluding energy crops), landfill gas, residential and commercial source-separated organics and municipal wastewater—is equivalent to 3% of Canada's natural gas demand or 2420 million m^3 per year of renewable natural gas. This represents up to 810 MW of electricity and 1.3% of Canada's electricity demand (Canadian Biogas Association 2019).

Agricultural biogas plants in the South America

Ferreira et al. (2018) has reported the potential for biomass in the Brazilian market for the production of biogas and its use for electricity generation. There were 127 biogas plants, in Brazil in 2015 which used agricultural and industry residues, sewage sludge, biowaste and landfill gas, which produced about 1.6 million Nm^3/day (584 billion m^3 biogas/year), representing an electricity generation of 3835 GWh. The installed biogas electricity generation capacity has gone up significantly, reaching 196 MW and 450 MW in 2015 and 2016, respectively (Freitas et al. 2018).

Table 1 Estimated methane generation potential for select biogas sources in the USA (NREL 2019)

Source	Methane potential (Mg/year)
Wastewater	2,339,339
Landfills	2,454,974
Animal manure	1,905,253
Organic waste	1,157,883
Total	7,857,449

In Argentina, the theoretical potential of electricity production from biogas is 38,385 MWh per day (Florencia et al. 2015). The power consumption per capita in Argentina is 3027 kWh per year. So in total, electricity for approximately 4,628,614 inhabitants per day could be generated just only with the biogas produced by animal manure (Florencia et al. 2015).

Agricultural biogas plants in Africa

Biogas technology is still in its infancy in Africa; national biogas programmes have been implemented in Kenya, Uganda, Ethiopia, Tanzania, Rwanda, Cameroon, Burkina Faso and Benin. These countries have benefited significantly from the technology and serve as showpieces for African countries that have the ability to start up similar programmes without outside assistance. Unlike other forms of renewable energy, biogas technology offers numerous advantages, one main advantage being waste management which is a significant problem in Africa (Roopnarain and Adeleke 2017). For example, the potential of energy from biogas in Zambia is 76 PJ per annum (Shane et al. 2015).

Bundhoo and Surrop calculated (Bundhoo and Surrop 2019) that the annual biomethane potential and bioenergy potential from field-based crop residues in Africa are around 31,303 Mm^3 and 1141 PJ, respectively. Combustion of the biomethane in a combined electricity and heat system is thought to generate 109.7 TWh of electricity and 133 TWh of heat annually. 109.7 TWh of electricity potentially supplies 16.3% of Africa's electricity demands. Comparing African countries, Djibouti has the lowest biomethane potential and Egypt has the highest one.

Commercial biogas production potential in South Africa is estimated at approximately 118 million cubic meters, based on estimates of feedstock sources from the wineries industry, pig farms, poultry slaughterhouses, and from agricultural and agro-processing waste, with electricity generation potential of 148 GWh (Kemausuor et al. 2018).

Biogas technology in Kenya has been earmarked as one of the main drivers toward the elimination of energy poverty in majority of rural households and to this end different biogas digester models are actively promoted (Nzila et al. 2012). Consequently, assessing the sustainability of the biogas systems in Kenya is one of the topical issues driving the discussion on biogas development. Hence, developing an assessment technique capable of reliably screening the different alternatives and highlighting the sustainability hot spots is of critical essence in decision making for all biogas stake holders in the country.

Agricultural biogas plants in the EU

In the EU the biogas plants have been built on an industrial scale since the 1980s, but the rapid increase in the number of installations has occurred only in the last dozen of years. This happened as a result of EU countries taking committing to reducing greenhouse gas emissions and promoting renewable energy sources (RES). The use of biogas is widely distributed in Germany, Austria, Denmark and Sweden among others (Torrios 2016). The EU countries have taken measures to promote biogas through the use of effective economic mechanisms to stimulate the development of the sector. Some countries support investments through subsidies in the construction phase of the installation; however, the most popular method of support is guaranteeing fixed electricity purchase prices, the so-called feed in tariff. Such a system is particularly beneficial for small installations, which due to lower profitability and higher general social benefits, receive compensation in the form of support at the stage of operation in the form of subsidies for the production and sale of green electricity (European Biogas Association 2018).

The 2018 report (European Biogas Association 2018) showed that the number of European biogas plants has increased steadily over the past decade, showing that the national biogas markets are well established and strong enough to overcome the political uncertainty which has affected certain countries. By the end of 2017, there were 17,783 biogas plants and 540 biomethane plants in operation in Europe. The total installed electric capacity (IEC) in Europe continued to increase in 2017, growing by 5% to reach a total of 10,532 MW, while the electricity produced from biogas amounted to a total in Europe of 65,179 GWh (European Biogas Association 2018). Europe is the world's leading producer of biomethane for use as a vehicle fuel or for injection into the natural gas grid, with 340 plants feeding into the gas grid with a capacity of 1.5 million m^3 and 459 plants in 2015 producing 1.2 billion m^3. In 2015, 697 biomethane filling stations ensured the use of 160 million m^3 of biomethane as vehicle fuel (Scarlat et al. 2018).

Currently, as in Poland, some countries are switching from a system of certificates and guaranteed prices to an auction system. In France, in the first auction of this type in 2017, which took the form of a guaranteed tariff that was valid for 20 years, 14 out of 41 submitted projects were granted support. The price of the energy provided by the winning projects proposed by investors intending to start biogas or biogas energy production installations was on average 122 EUR/MWh. The French government assumes that the auction will translate into investments worth 170 million EUR, and the installations will produce approximately around 480 MWh of electricity per year (European Biogas Association 2018).

Agricultural biogas plants in Germany

The country with the largest number of ABP in Europe is Germany. Biogas is favored by the German energy policy, which encourages the guaranteed price system for electricity produced by a renewable energy source through low-interest loans (Budzianowski and Chasiak 2011). The minimum price for energy is agreed upon depending on the level of installed capacity, and the price is guaranteed for a period of 20 years. An important factor is also the existence of a well-developed natural gas transmission grid (Biogas market 2018).

There are several hundred companies in Germany involved in the design and construction of biogas plants, delivery of components, technical and laboratory services that employs up to 11,000 people. The agricultural area used for the production of energy crops for biogas production is 450,000 ha. The biogas support system in Germany is complex and is based on a fixed price for the energy produced from biogas and a bonuses system. Support for renewable energy in Germany is regulated by the act on support for RES that was introduced in 2000. It should be emphasized that the system encourages the construction of a biogas plant in the shortest possible time—the sooner it is operational, the higher is the basic guaranteed price (Budzianowski and Chasiak 2011). Basic data on ABP in Germany are presented in Table 2 (Biogas market 2018).

Currently, Germany is working on improving the so-called thermally induced hydrolysis comprising by heating the recycled organic feed to 190 °C under appropriately elevated pressure. The substances with a higher cellulose content, e.g., straw, are subjected to hydrolysis, and other components of the processed raw material are then processed by bacteria into sugars, organic acids and alcohols. With this innovation, the rate of conversion of the raw material into biogas increases from 60 to almost 90%, and in the anaerobic biofermentation, time is reduced by 75% (Biogas market 2018).

Table 2 Agricultural biogas plants in Germany—statistical data for 2018 (Biogas market 2018)

Number of biogas plants	9494
Total power (MW)	4843
Produced energy (TWh)	33.13
CO_2 reduction (mln Mg)	20
Turnover (trillion EUR)	9.3
Employment	47,000

The research results (Lauer et al. 2020) show that adding biogas plants in Germany's future electricity system—compared to their phase-out—requires cost reductions and/or has to be accompanied by further advantages in other sectors and areas to ensure operation economically feasible. Differentiated from a substantial growth, higher net present values were gained in the extension path characterized by a not so high construction rate of new biogas plants.

Agricultural biogas plants in Denmark

Denmark mainly uses waste as the substrates for biogas production (Raven and Gregersen 2007). In large biogas plants, about one thousand tons of postslaughter waste are consumed annually, as well as from the fish, poultry industry and dairies, which allows the production of over 300 million m^3 of biogas per year. The total biogas potential in Denmark is 94 PJ, which would allow 54% of domestic natural gas demand and 64% of transport demand to be met (Curkowski et al. 2009).

One of the interesting solutions in the field of the biogas market support system in Denmark was the Biogas and Green Growth Program, announced for the years 2009–2012, which established the target of processing biogas into 50% of animal waste into biogas (Curkowski et al. 2009).

An additional benefit using agricultural feedstocks in Denmark is the decrease in artificial fertilizer use, with manufactured fertilizer reduced by half approximately compared to levels in 1985 without any nitrogen deficiencies (Curkowski et al. 2009).

On-farm biogas plants in Denmark also accept source-separated organic household wastes, if that is traceable and cleansed from impurities in a pre-processing facility before it enters the digester (Zhu et al. 2019). Majority of the centralized biogas plants which are located in rural areas now codigest manure with food waste and other feedstocks. The inclusion of waste food feedstocks is supported by waste sector policies of high landfill and incineration taxes and also the ban of landfilling of biodegradable municipal waste since 1997. The Danish government has an aim to reuse 50% of household waste by 2022. As the Swedish case, goal has been achieved through constant evolution of legislative drivers and policy supports. What is also clear is that it is not a single sector problem but rather a collaborative engagement between sectors (i.e., waste, energy, agriculture, environment), which delivers multiple benefits not just GHG emissions reduction.

Agricultural biogas plants in Austria

According to the data from the analysis of the daily charge in 55 Austrian biogas plants, the mixtures of 4 or 5 substrates are most frequently applied, of which the energy crops and animal manure (65.5%) are most commonly use. The organic waste is an additional substrate for codigestion (20.0%). In Austria, the Green Electricity Act of 2006–2011 introduced, among other benefits, a price guarantee for 10 years, and over the next 2 years, it is guaranteed that 75% and 50% of this rate will be maintained, respectively. Importantly, in the Austrian system, the price per 1 kWh depends on the size of the biogas plant and ranges from 0.1130 €/kWh for biogas plants with a capacity of more than 1 MWe to 0.1695 €/kWh for plants with a capacity below 100 kWe (Curkowski et al. 2009).

An amendment to the Green Electricity Act in 2009 also introduced an additional system of allowances:

- A raw material allowance—maximum 0.04 €/kWh,
- A technological allowance for gas processing into electricity after being forced into the gas network—0.02 €/kWh,
- An allowance for new CHP installations—0.02 €/kWh (Curkowski et al. 2009).

Agricultural biogas plants in Sweden

The dominant model of biogas utilization in Sweden is a combination of advanced biogas cogeneration installation from municipal waste, sludge from sewage treatment plants and agricultural waste (Lönnqvist et al. 2019). Agricultural substrates, due to the prices similar those to food and feed prices, represent only a limited input, accelerating, strengthening and supplementing for the continuous process of biogas production. A popular application of biogas in Sweden is a fuel for CNG cars (Fig. 2), after its previous refining to biomethane, In this way, about 42% of public transport in Stockholm is supplied with biogas fuel, and other users are also taxis and private cars (Neterowicz et al. 2015).

Fig. 2 Biogas car, Linköping, Sweden (photograph B. Igliński)

There are chances on the supply aspect to increase biogas production based on residues and waste, to improve digestate handling, and to expand biomethane distribution infrastructure. However, the sector faces a high risk in biogas investments mainly due to the low predictability of Swedish policy. This, together with the stagnated demand for vehicle gas, is identified as the main obstacles for biogas development. If the intention is to develop the use of biogas in transport policy makers should focus on described barriers (Lönnqvist et al. 2019).

Formal and legal requirements for the construction of the agricultural biogas plant in Poland

Most of the existing installations for the production of agricultural biogas in Poland were implemented based on an investor learning method, and investors gained experience, collected during the implementation of subsequent installations (Curkowski et al. 2011). The first biogas plants that were constructed in Poland by the Poldanor S.A. company were located on large farms, mainly due to the availability of slurry and the possibility of using electricity and heat for the farm owner's own needs. Currently, an increasing number of investors plan to locate installations at the agri-food facilities (fruit and vegetable processing plants, dairies, distilleries) and meat facilities (slaughterhouses, meat processing plants), thus ensuring a greater variety of substrates for fermentation and the additional possibility of annual heat collection from cogeneration (Igliński et al. 2012).

A project starts with the analysis of substrates: their availability, the ability to provide deliveries within a dozen of years and an assessment of biogas productivity. It is advantageous at this stage to sign preliminary agreements or obtain a promise of biomass supplies. When using energy crops, the available acreage and class of land intended for cultivation should be specified. If the substrates are delivered by a means of transportation, the availability of need to expand local roads should be assessed (Igliński et al. 2012).

The availability of electricity, gas and water supply and sewage networks is also very important. In the absence of a water and sewage network, the project should include an investment in its own water intake and its own sewage disposal installation (Igliński et al. 2012).

Obtaining the acceptance of the local community for the construction of an agricultural biogas plant

At the initial stage, it is worth examining whether the local community favors the construction of a biogas plant. Investigating a plant with a power of 1 MWe means the establishment of a large agricultural processing plant, or a biogas plant, in an area where residents are not accustomed to the associated nuisance (e.g., increased vehicular traffic on local roads to transport the supply of substrates). Objections may also be raised to the use of hazardous waste as a source, or the use of fermented biomass, the storage of which is associated with the spread of odors. It is also worth adding that the location of biogas plants in areas under the nature protection (in particular, the Natura 2000 network) complicates the procedures and forces investors to cooperate with environmental organizations (Igliński et al. 2012).

Local community protests can, as early as the development stage, effectively discourage an investor from construction a biogas plant in a given location, even if the initial analysis proves the economic viability of the investment. As a rule, two sides are created: supporters of biogas plants—investors and people interested in environmental protection and renewable energy technologies, on the other hand opponents who are afraid of reduced comfort due to the possibility of the unpleasant odor of digestion gas leakage (Franc-Dąbrowska and Jarka 2014).

Roundtable talks can be an effective means of developing closer relationships with the local community and establishing cooperation with non-governmental organizations. It is desirable to invite people with practical experience who can facilitate a positive result of the meeting (Franc-Dąbrowska and Jarka 2014).

Visiting other biogas plants can give people from the immediate area a better idea of what a biogas plant entails; thus, visiting a plant and learning how it functions may have a great impact on how a plant is perceived. During a visit, people can learn about various aspects of biogas plant operation, economics and production processes. A meeting will also increase the commitment of people employed directly on the site (Franc-Dąbrowska and Jarka 2014).

Area development plan (ADP)

The manner of development and the conditions for building in the area of the biogas plant are determined in the area development plan (Act 2003). In the absence of an ADP, the area development conditions are determined by a decision on land development and development conditions according to art. 4, par. 2 (Act 2003).

Obtaining a decision on environmental conditions

The procedure is based on the provisions of the Act of October 3, 2008, on the provision of information about the environment and its protection and public participation in environmental protection and environmental impact assessments (Act 2008). All actions that may have an impact on the environment were included in the regulation of the Council of Ministers of 9 November 2010 (Regulation 2010). ABPs with an electrical capacity above 0.5 MW are included in projects that could potentially significantly affect the environment—art. 3, par. 1, point 45. This means that an environmental impact assessment report must be prepared and submitted for large biogas plants. The environmental impact assessment report is aimed at demonstrating the absence of a negative impact on the environment and must be carried out in consultation with the local community. The procedure for the preparation of the environmental impact assessment is regulated by the Act of 27 April 2001 Environmental Protection Law (Act 2001).

Preparation of the construction project including the necessary arrangements

An agricultural biogas plant in Poland must obtain a number of permits:

- Water and law permit (Act 2017).

The purpose of this permit is to document the right to manage rainwater and snowmelt in the area of investment, the use of water and sewage disposal.

- Arrangements of the Project Design Coordination Team (PDCT) (Regulation 2001).

These arrangements must be made with the District Council, in PDCT.

- Other arrangements.

During implementation, it is also necessary to carry out the geological surveys and consultations with the Office of Technical Inspection, fire brigade and sanitary inspections.

Connection to the grid and commercial terms for energy

This condition is necessary to connect to the power grid. According to art. 7, par. 8a of the Energy Law of 10.04.1997 (Energy Law 1997), an advance payment of PLN 30 for each kW of connection power is charged for the connection to the grid. The following agreements should be signed:

- Connection agreement,
- Agreement on the energy sales and certificates of origin and
- Agreement on the sale of heat.

Economic activity in the field of agricultural biogas production or electricity generation from agricultural biogas is a regulated activity requiring entry into the register of energy enterprises involved in the production of agricultural biogas. The government official responsible for the register is the president of the Agricultural Market Agency (Register 2018).

Obtaining the construction and use permit

According to the Building Law of 7 July 1994 (Building Law 1994), obtaining a building permit is the last stage of the formal and legal process of investment preparation. Issuing a construction permit is a verification of the correctness of the existing work. Obtaining a legally valid construction permit allows construction of the biogas plant to begin.

In practice, for the construction of biogas plants in Poland, the time needed to prepare the project documentation, obtain decisions and permits and enter into contracts for the implementation phase is approximately 2 years, while the physical implementation of the investment together with the start-up of the biogas plant takes approximately a year (Budzianowski 2012).

The company's responsibilities after commissioning the biogas plant in Poland

Pursuant to art. 9 of the Energy Law (Energy Law 1997), an energy company that performs activities in the field of agricultural biogas production or electricity generation from agricultural biogas is obliged to

- Keeping documentation regarding the following issues:
  - The amount and types of raw materials used to produce agricultural biogas or to generate electricity from agricultural biogas,
  - The amount of agricultural biogas produced, specifying the amount of agricultural biogas introduced into the gas distribution grid,
  - The amount of heat and electricity generated from agricultural biogas in a split or cogeneration system,
- Transferring to the president of the Agricultural Market Agency, within 45 days after the end of each quarter, the quarterly reports containing the information referred to the above, according to the template developed and made available by the Agricultural Market Agency (Energy Law 1997).

Agricultural biogas plants in Poland—history and current state

Initially, ABPs in Poland were constructed by the so-called learning-by-doing method, i.e., learning through action without access to more precise technologies and professional knowledge of biochemical processes. Currently, the number of native and experienced companies in Poland offering "turnkey" construction of a biogas plant is increasing. The location of a biogas plant is dictated primarily by access to appropriate substrates. Initially, ABPs were most often built on large farms, mainly due to the availability of significant amounts of slurry and corn silage (Szymańska and Lewandowska 2015). Currently, there has been a change in investors' preferences, especially in regard to the implementation of larger installations, and biogas plants are now more likely to be located at agrifood processing plants (sugar factories, distilleries, slaughterhouses, meat and fruit and vegetable processing plants and dairies). The reason is the possibility of regularly obtaining cheap waste substrates and a guarantee of the yearly collection of heat from the cogeneration of a given production plant, which is of key importance to the economics of the project (Pilarska and Pilarski 2013).

The current state of development of the ABP market in Poland is largely the result of the current system of operational support for renewable energy sources, i.e., the system of certificates of origin, as well as support for energy production in cogeneration in the form of yellow certificates. In addition, the stimulus of the market in the form of grants and low-interest loans from the EU-2007–2013 financial perspective is the investment support mechanism. The possibility of combining investment support and support for green energy production has created favorable conditions for the planning and construction of biogas plants. The initial effects of this system construction were the dynamic development of the biogas sector and investors' preference for large investments in the 0.5–1.5 MWe range, which account for approximately 55% of projects on the market (Curkowski 2016).

The estimated cost of investment in a biogas plant varies, depending mainly on the scale of the investment. The optimal installations in terms of profitability are those producing power above 1 MW. The average cost of building a 1.1 MW biogas plant is approximately PLN 15 million/1 MW, or approximately PLN 16,500,000. A biogas plant of this size generates demand for approximately 40,000 tons of slurry and 20,000 tons of corn silage as feedstock for the production of gas. The theoretical payback on the investment in this case occurs after approximately 3 years, on average. In the case of a smaller 230 kW biogas plant, the cost per 1 MW of installed electrical power is PLN 21 million, or approximately PLN 4,830,000, and this investment would reach profitability only after 5 years (Curkowski 2016).

The first large ABP in Poland was commissioned in Pawłówko in 2005 (Szymańska and Chodkowska-Miszczuk 2011). Since then, there has been a systematic increase in ABP in Poland—in 2017, there were 93 (Fig. 3) (Register 2018).

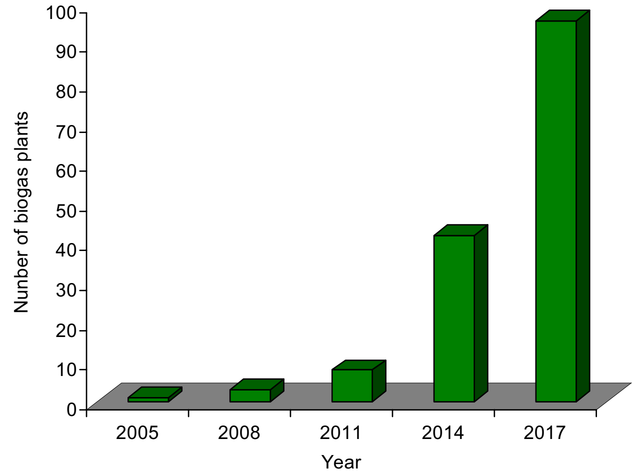

Fig. 3 Number of ABP in Poland in 2005–2017 (Register 2018)

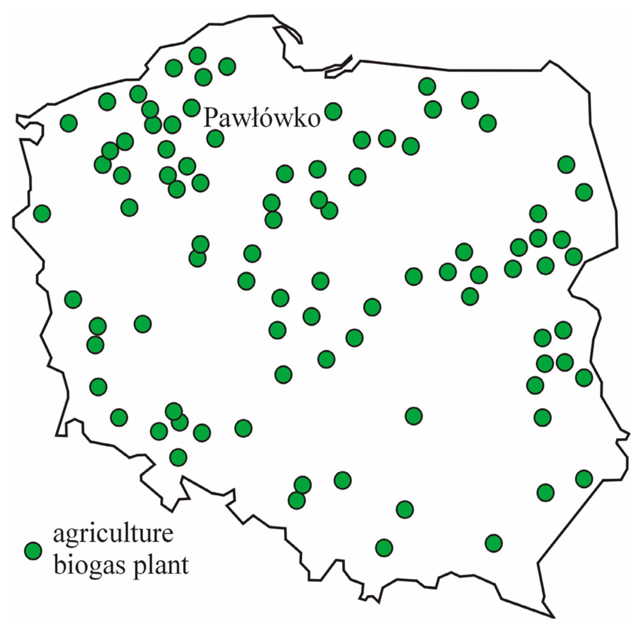

Fig. 4 Location of ABP in Poland (Register 2018)

The first ABP, such as the one in Pawłówko (Fig. 4), was constructed mainly in northwestern Poland. After some time, other biogas plants were developed in other parts of the country (Register 2018).

The volume of produced biogas and electricity has also increased systematically (Fig. 5). In 2017, it was nearly 300 million m^3 of biogas and almost 600 GWh of electricity.

Substrates in agricultural biogas in Poland

Currently, biogas plants commonly use a mixture of several substrates, a process called codigestion (Data 2018). The differentiation of substrates enables better process parameters

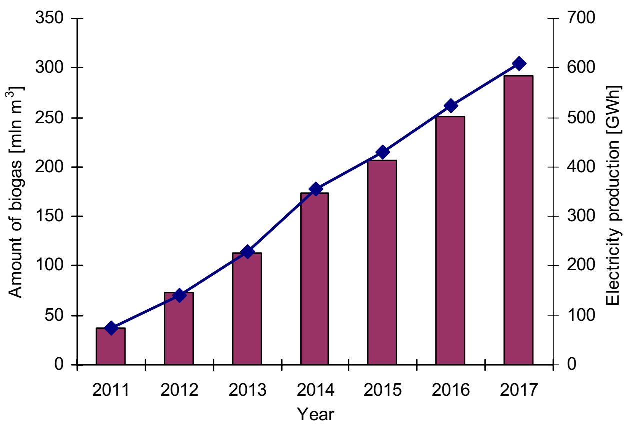

Fig. 5 Amount of biogas (bars) and electricity (line) produced in ABP in Poland in 2011–2017 (Data 2018)

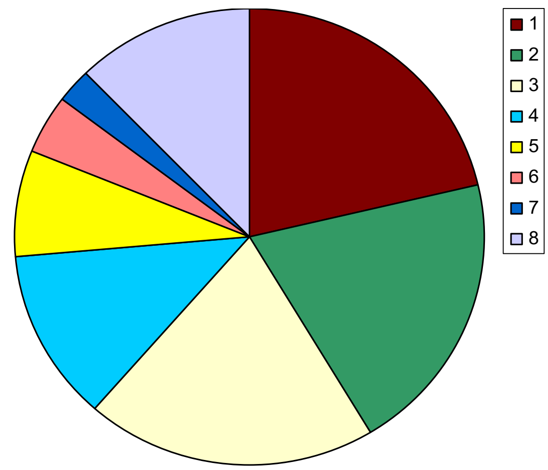

Fig. 6 Raw materials applied in ABP in Poland (%); 1—slurry, 2—distillery waste, 3—fruit and vegetable residues, 4—corn silage, 5—beet pulp, 6—technological waste from the agrifood industry, 7—green waste, 8—other raw materials (Data 2018)

and helps ensure a secure supply of raw material (Filho et al. 2019).

In Poland, in accordance with the generally accepted principle, organic waste is first used, and only then are targeted crops used. The most important substrate for the production of agricultural biogas is liquid slurry (over 21.3%), followed by decoction (20.1%), fruit and vegetable residues (19.9%) and corn silage (12.4%) (Fig. 6). Other substrates include expired foods, slurry, vegetable and fruit residues, waste from the dairy industry, brewery by-products (Olineira et al. 2018) and grains. In total, in 2017, 34 types of substrate were applied in Polish biogas plants. This is a significant increase compared to 2011, when only 15 types of substrate were used. Moreover, in 2011, slurry accounted for more than half of the amount of feed (56.7%), corn silage accounted for 23.2%, and decoction accounted for 6.5% (Data 2018).

Investors in Poland consider waste from meat processing and slaughterhouses to be an important group among the substrates used in biogas plants (Table 3). The attractiveness of obtaining postslaughter waste for biogas production depends primarily on the possibility of obtaining it at no cost from meat and meat processing plants, which are obliged to disposal of such waste. Currently operating meat processing plants in the country, which do not have their own utilization facilities, may be interested in the utilization of waste in biogas installations due to the lower cost of this service compared to that of specialized waste treatment plants (Data 2018).

Technological system of agricultural biogas plants in Poland

ABPs in Poland vary, but common elements can be distinguished, such as the use of raw material reservoirs or a digestion chamber. The general scheme of ABP in Poland is shown in Fig. 7.

Initial and mixing tanks

The preliminary tanks store animal droppings and organic waste, which are fed into the mixing chamber and then into the digestion chamber. In the case of some industrial waste, e.g., postslaughter and pretreatment waste, hygienization/sanitation is required. Some substrates with low hydration, e.g., corn silage, are stored under the shelter and fed into the mixing tank by a belt conveyor. Others with higher hydration, such as glycerin, are stored in silos before being added in appropriate amounts to the mixing chamber. The tanks can be constructed of concrete, reinforced concrete, steel or plastic. The batch material can be prepared once a day and fed into the chamber every 2–3 h (Curkowski et al. 2011).

Digestion chamber

From the mixing tank, the biomass is directed to the fermentation chamber (bioreactor). The fermentation chamber is the basic link of a biogas plant, as the process of the fermentation of organic feedstock and biogas production takes place inside. The bioreactor should meet a number of conditions that guarantee the proper course of the process. Its walls must be tight, and there also must be good thermal insulation, ensuring as little heat loss as possible. The construction of digestion chambers involves steel plates and reinforced concrete. The chambers are usually designed in a cylindrical shape and can be recessed in the ground, freestanding or arranged horizontally on foundations. For an efficient digestion process, the digestion chamber should be equipped with a mixing system. These are usually mechanical stirrers that are placed inside the chamber or hydraulic pumps placed outside or inside the chamber (Curkowski et al. 2011).

Table 3 Characteristics of the selected wastes and plants in terms of methane yield in Polish ABP (Data 2018)

Substrate	Percentage of dry matter in the tone of the substrate (%)	Percentage of organic dry matter in the dry matter content (% dry organic mass)	Production of methane (m^3/tone dry organic mass)
Cow slurry	9.5	77.4	222.5
Pig slurry	6.6	76.1	301
Chicken waste	15.1	75.6	230
Turkey droppings	15.1	72.7	320
Postflotation settlements from slaughterhouses	14.6	90.6	680
Corn silage	32.6	90.8	317.6
Fruit residues and waste	45.0	61.5	400
Vegetable residues and waste	13.6	80.2	370
Molasses	81.7	92.5	301.6
Brewer's brewing	20.5	81.2	545.1
Potato distillery waste	13.6	89.5	387.7
Cheese production waste	79.3	94.0	610.2
Bakery waste	87.7	97.1	403.4

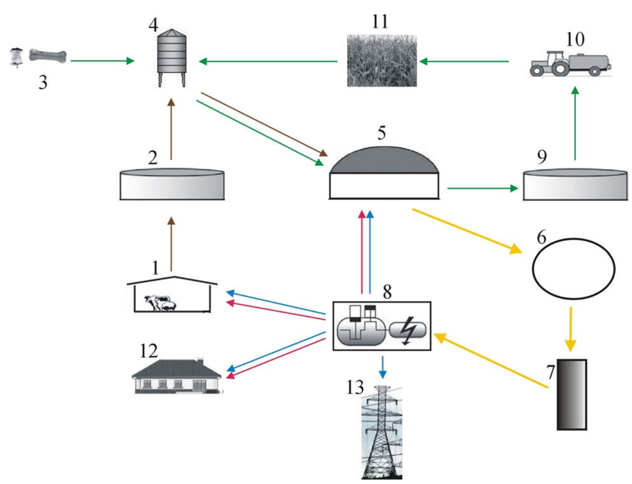

Fig. 7 Diagram of ABP in Poland: 1: cowshed/pig housing/hen housing, 2: prereservoir, 3: agricultural/postslaughter waste, 4: mixing tank, 5: bioreactor, 6: biogas storage tank, 7: biogas cleaning plant, 8: cogeneration unit, 9: postdigestion tank, 10: export of postdigestion fertilizer, 11: corn, 12: offices, 13: energy network

The dynamics of digestion are closely related to the temperature at which the process takes place. The digestion process can take place in the following temperature ranges:

- Psychrophilic 10–25 °C—popular in Asia,
- Mesophilic 32–38 °C—commonly used in Europe,
- Thermophilic 42–55 °C—rarely used.

The heating of the batch material ensures an adequate and stable temperature inside the chamber. The batch material is heated by means of heat exchangers. External and diaphragm exchangers, e.g., spiral exchangers, are used. In addition, the chamber is heated by the heat exchangers built into the walls or the bottom of the chamber (Igliński et al. 2012).

Biogas storage tank

The biogas that is evolved in the digestion chamber is stored in a special tank made of steel or plastic. The wet tank is installed directly above the fermentation chamber, where the biogas from the current production is collected. A wet tank is the cheapest type of biogas tank. The dry tank is a separate structure to which biogas from the digester is transferred and stored until there is a demand for fuel or energy (Curkowski et al. 2011).

Biogas cleaning devices

Previous to the application of biogas for energy purposes, the purification process must be carried out to cleanse biogas of admixtures that could cause damage to the equipment for energy production. The concentration of hydrogen sulfide in biogas can reach 3000 ppm, which may cause corrosion of devices, so the concentration should be reduced to at least 700 ppm. One of the commonly used methods is biological purification, which is carried out by adding air to the raw biogas and passing it through a biological bed. This is the most popular method of removing hydrogen sulfide. Another way to desulfurize biogas is to pass it through a container filled with turf ore. Filter columns with iron compounds, activated carbon and other substances are also applied (Curkowski et al. 2011).

Devices for generating energy

In Poland, biogas is burned to produce electricity and heat in cogeneration. The cogeneration system is composed of two systems: an electric system, which is a gas, and heat engine, for example, a water or steam recovery boiler. Electricity is generated by a generator driven by an internal combustion gas engine or a turbine. The heat is recovered from the cooling heat exchangers, which use a gas–air mixture, lubricating oil, cooling water and exhaust gas. In a modern device, the efficiency of obtaining electricity is 30–40% and that of heat recovery 40–45% (Igliński et al. 2012).

Secondary digestion tank

The digestion process does not end when the processed biomass is pumped out of the digestion chamber. In the storage tanks, this process continues with less efficiency. Up to 20% of the total biogas production can be recovered from the storage tanks provided they are covered with a gas-tight coating and heating is provided from below. For this reason, the biogas-protected tank for fermented organic matter is called the secondary fermentation chamber (the secondary fermentation chamber may also be a lagoon) (Curkowski et al. 2011).

Examples of agricultural biogas plants in Poland

A brief description of selected ABP in Poland is presented below.

Biogas plant in Pawłówko

The first biogas plant in Poland was launched in June 2005 by Poldanor S.A. in Pawłówko (Igliński et al. 2012). The substrate for biogas production is slurry from the farms in Pawłówko and Dobrzyń (approximately 2900 tonnes/year). Additionally, corn silage and waste from nearby meat plants (3500 tons/year) are subjected to hygienization at 70 °C and glycerin application (1000 tons/year). During the year, 3.8 million m^3 of biogas is produced in digestion tanks and it produces 7458 MWh of electricity and 8680 MWh of heat. Some of the electricity obtained from biogas combustion is used to power the biogas plant—for example, stirrers and room lighting. The remaining energy is sent to the power grid. The biogas plant covers the electricity demand of nearly 1800 individual farms. The heat generated in cogeneration is used to heat the farm and office space. The investment expenditure for the first agricultural biogas plant in Poland in Pawłówko amounted to PLN 8 million (Igliński et al. 2012).

Biogas plant in Koczała

The biogas plant in Koczała is one of the largest installations for the production of agricultural biogas in Poland, with a 2.1 MWe and 2.2 MWt cogeneration system (Igliński et al. 2012).

The installation, which is located on a farm with 8000 on-site sows, processes 58 thousand tons of slurry and 32 thousand tons of corn silage annually in the process of cofermentation. Biogas in the amount of 8.7 million m^3 is used in the cogeneration module for generating electricity and heat. The annual production of electricity is 18 GWh, which corresponds to the demand of approximately 3–4 thousand households. The produced electricity is used primarily for the processing purposes of the on-site farm and fodder mixing plant, and the surplus is sold to the grid, whereby green certificates are obtained for all the energy produced. The digested odor-free slurry serves as organic fertilizer on the cultivated fields of Poldanor (Igliński et al. 2012).

The biogas plant was created with an investment of PLN 16.5 million. The investor managed to obtain a subsidy in the form of 15% investment subsidies from the National Fund for Environmental Protection under the program to support high-efficiency cogeneration (Igliński et al. 2012).

Biogas plant in Nacław

The biogas plant in Nacław processes slurry of pigs mixed with corn silage produced especially for the demands of biogas plants. These substrates are processed in the digestion chamber under mesophilic conditions and are then moved into the postdigestion chamber, which ensures the full recovery of biogas (Curkowski et al. 2011).

The heat produced in the cogeneration system (625 kWe/698 kWt) is used in part for heating the farm and office rooms, and nearly half is supplied to homes for local residents and public facilities in the village of Nacław. This has enabled the village to shut down two old boiler rooms for coal and heating oil and ensured a stable heat supply throughout the year for residents. The ecological effect of the biogas plant operation will be the reduction of greenhouse gas emissions—both from the free slurry distribution and from fossil fuels that are currently replaced by biogas as well as the reduction of sulfur dioxide, nitrogen oxides and ashes that is typical of low emissions (Curkowski et al. 2011).

The biogas plant was created with an investment of PLN 9.5 million, of which 40% was covered by the National Fund for Environmental Protection and Water Management from the funds of the Operational Program for Infrastructure and the Environment, Measure 9.1—high-efficiency energy production (Curkowski et al. 2011).

Table 4 Substrates applied in the agricultural biogas plant in Mełno (Buczkowski et al. 2012)

No.	Name of substrate	Total (Gg/year)	Months available	Content of dry mass (d.m.) (%)	Temperature (°C)
1.	Pig slurry	6	January–december	6	ambient
2.	Distillery	41	January–december	10	86 °C
3.	Beet pulp	to 25	January–december	22	ambient
4.	Onion peel	7	September–may	23	ambient
5.	Fruit and vegetable waste	2	July–october	16	ambient

Fig. 8 Cogeneration systems in Mełno (photograph B. Igliński)

Biogas plant in Mełno

In Mełno, biogas is produced in a bioreactor that is powered by waste from nearby food processing plants and liquid manure provided by local farmers (Table 4). The key biomass component, however, is the waste from the hot distillery originating from alcohol production in the plant adjacent to the biogas plant. Thus, the temperature inside the fermentation chambers does not fall below 50 °C (thermophilic fermentation), which significantly accelerates the biogas production process. Most of the energy is used for the needs of the distillery, and the surplus is sold to local recipients (Buczkowski et al. 2012).

Figure 8 shows the cogeneration systems of the biogas plant in Mełno.

The biogas plant is used not only by the distillery and other neighboring plants but also by local farmers. They provide slurry to it, and in return—as a partial settlement—they receive a digestate from this installation (Buczkowski et al. 2012).

Biogas plant in Liszkowo

In the biogas plant in Liszkowo, organic matter that can still be a source of biogas is recycled for reprocessing. This system results in an approximately 95% use of the organic matter in the process. The solution also requires no water uptake after digestion because it is contained in the distillery used as a substrate. Water losses are supplemented by returning water from the clarifier to the technological process (Kocińska 2010).

Fig. 9 Biogas desulfurizer in the biogas plant in Liszkowo (photograph B. Igliński)

In the biogas plant in Liszkowo, a column method called dry or biological desulfurization is applied for biogas desulfurization (Fig. 9) (Aita et al. 2016). The biogas pumped into the lower part of the column moves upwards. Then, it passes through a field of iron oxide granules, the task of which is to stop the precipitating sulfur. As a result of this reaction, water vapor or water is evolved. At the same time as the desulfurization process, the bed is regenerated by adding compressed air. Due to the possible formation of an explosive mixture of biogas and air, the minimum level for the added dose of air is determined. The advantage of the regeneration reaction is that it is an exothermic process. This prevents the condensation of water vapor in the desulfurizer (Kocińska 2010).

Microbiogas plant in Studzionka

The first small-scale biogas plant (microbiogas plant) in Poland, commissioned in November 2009, was established in Studzionka. The biogas plant was constructed economically by individual farmers operating a 40-ha agricultural holding focused on breeding laying hens and pigs. The installation processes approximately 690 tons of chicken waste and 320 tons of pig slurry per year together with additional substrates: corn and grass silage and organic residues of agricultural production from the farm (Curkowski et al. 2011).

The basic unit of the installation is a fermentation chamber—a thermally insulated steel cistern with a diameter of 2.8 m and a length of 10.3 m. The postdigestion pulp is collected in a reinforced round concrete tank recessed approximately 1.5 m in the ground, with a diameter of 10 m and a height of 5 m (Curkowski et al. 2011).

The biogas produced is converted into energy in a cogeneration unit with an electrical power of 30 kWe and a thermal power of 40 MWt. The electricity is currently used for the needs of the on-site biogas plant and farms. The heat is used to heat residential buildings and livestock buildings. The digested slurry is used by the farm owners to fertilize the fields (Curkowski et al. 2011).

The owners spend 1–1.5 h a day on the ongoing service of the biogas plant. The monthly operating costs of the Studzionka biogas plant are currently estimated at approximately PLN 800 (Curkowski et al. 2011).

The total investment expenditure for the construction of the biogas plant amounted to approximately 400,000 PLN. The economic construction of the installation method, the amount of work by the farmers and the support of sponsors allowed significant reductions in the investment expenditures, which, according to the market value of a project of this power, could have reached more than PLN 1 million. The investment did not receive any funding (Curkowski et al. 2011).

In the case of Polish, the development of the biogas sector based on microbiogas plants and small biogas plants could be considered, which help overcome the economic constraints (e.g., raw material procurement, connection at the level of distribution networks, lower installation costs).

Perspectives of agricultural biogas plants in Poland

The development prospects for the biogas market in Poland can be indicated by the 475 projects implemented in 2016, of which 243 were in an advanced state (Table 5) (Gostomczyk 2017).

The Polish model of agricultural biogas plant development is moving in the direction of the Danish pattern. This is evidenced by the steady increase in the number of substrates used and the high share of waste products from farms and agrifood processing plants. The trend of limiting the use of expensive silage from corn and replacing it with fruit and vegetable residues and distillery waste has been steadily growing. Ultimately, ABP will be a permanent and important element of hybrid installations combined in a single related system of agricultural processing, distilleries, organic fertilizer factories, related raw materials and energy in interlocking technological processes (Curkowski et al. 2011).

Microbiogas plants in Poland

The high investment costs of operating microbiogas plants have limited their development on average-size farms. The increased costs can lead to an extended repayment period. This barrier can be reduced by creating energy cooperatives among at least a dozen or so farmers, enabling the construction of one larger biogas plant with lower unit costs for generating 1 kW of power (Table 6). The shareholders jointly provide the raw material feed, mainly from their waste products, and share the profits (Gostomczyk 2017).

Potential of biogas in Poland

The area of Poland is over 31 million ha, and farmland covers approximately 17 million ha, while fallow land and fallow land cover an additional 1 million ha. The annual natural gas consumption in Poland is approximately 14.5 billion m^3. If 1.9 million ha of agricultural land is needed to produce 10 billion m^3 of methane, and over 1 million ha of agricultural land is known to be fallow, then Poland has an area suitable for the development of biogas production—more than 5 billion m^3 of biogas can be obtained (107 PJ of energy) (Pilarska and Pilarski 2013).

Table 5 The number of biogas plant projects according to the Bio Alians database (Gostomczyk 2017)

Projects	Number of projects	Forecast power (MW)	Average power (MW)
Implementation	475	582	1.2
Forecast	154	194	1.3
Advanced	243	295.9	1.2
Abandoned	78	92	1.2

Table 6 Offer prices of Polish biogas plants producers (Gostomczyk 2017)

Power (kW)	Net price (mln PLN)	Price per 1 kW (thousand PLN)	Comments
1000	12.6	12.6	The offer corresponds to current market prices and will not exceed PLN 16 million after VAT. The acceptance of this price may take place after reading the details of the offer, for example, of what materials the installation will be built
500	8.2	16.4	The price offer exceeds the average market prices
350	5.6	16.0	The price per 1 kW for this power size category is acceptable
300	4.8	16.0	The price per 1 kW for this power size category is acceptable
250	4.25	17.0	The price is relatively high but acceptable in conditions of using cheap or free raw materials
150	2.7	18.0	The price is relatively high but acceptable in conditions of using cheap or free raw materials
100	2.1	21.0	Very high price, unprofitable investment
50	1.3	26.0	Very high price, unprofitable investment

The potential of biogas from animal slurry and bird litter

According to data from the Central Statistical Office, the number of cattle, pigs and poultry is 5.9 million, 10.9 million and 169 million, respectively (Central Statistical Office 2017b).

To estimate the annual biogas energy that could be produced from animal or poultry slurry, the following assumptions have been made:

- The conversion rates of livestock to large conversion units (*LCU*) (500 kg) of livestock are 0.8 for cattle, 0.2 for pigs and 0.004 for poultry (Kutera and Hus 1998),
- The average weight of the animal or poultry produced by a large livestock unit is 44.9 kg/day = 16.4 Mg/year for cattle, 43.5 kg/day = 15.9 Mg/year for pigs and 26.8 kg/day = 9.8 Mg/year for poultry, (Kutera and Hus 1998).
- The yield of biogas is 0.050 m^3/kg = 50 m^3/Mg for cattle slurry, 0.055 m^3/kg = 55 m^3/Mg for swine slurry, and 0.140 m^3/kg = 140 m^3/Mg for poultry slurry (Buczkowski et al. 2012),
- Biogas from animal or poultry slurry contains 60% methane with a calorific value of 35.73 MJ/m^3 (Murandi and Foltynowicz 2014), and
- The technical potential of biogas utilization is 20% of the theoretical potential, and the efficiency of obtaining energy is 80% (Buczkowski et al. 2012).

Formula 1 shows the annual amount of energy that can be obtained from biogas received from animal or bird slurry:

$$E_b = 0.2 \cdot 0.8 \cdot 0.6 \cdot \left(0.8 \cdot N_c \cdot M_c \cdot Y_c + 0.2 \cdot N_p \cdot M_p \cdot Y_p + 0.004 \cdot N_{po} \cdot M_{po} \cdot Y_{po}\right) \cdot C \quad (1)$$

where E_b is the annual energy from biogas obtained from animal or poultry slurry (TJ/year); N_c, N_p, and N_{po} are the number of cattle, pigs and poultry (mln), respectively; M_c, M_p, and M_{pk} are the annual mass of the animal or poultry manure from a large conversion unit of cattle (16.4 Mg/year), pigs (15.9 Mg/year) or poultry (9.8 Mg/year), respectively; Y_c, Y_p, and Y_{po} are the yield of biogas from cattle slurry (50 m^3/Mg), pig slurry (55 m^3/Mg) and bird manure (140 m^3/Mg), respectively; and C is the calorific value of methane (35.73 MJ/m^3).

Figure 10 shows the amount of energy that can be obtained annually from utilizing biogas from animal or poultry slurry in Poland.

The calculated amount of energy that can be obtained annually from utilizing biogas from animal or poultry slurry in Poland is 23.0 PJ/year, with the voivodeships of Wielkopolskie of 5.1 PJ/year, Mazowieckie of 3.7 PJ, Podlaskie of 2.5 PJ/year, Kujawsko-Pomorskie of 2.0 PJ/year and Łódzkie of 1.9 PJ/year, which have the largest livestock farms, having the greatest potential, thus justifying the construction of biogas plants there.

The potential of biogas from biodegradable waste from the agrifood industry

A significant amount of biodegradable waste is generated by the 02 Group, i.e., the agrifood industry (Central Statistical Office 2017b). According to data from the Marshal Offices, the annual weight of such waste in Poland is 4.26 million Mg/year.

To estimate the potential annual biogas energy from biodegradable waste from the agrifood industry, the following assumptions have been made:

- 20% of the biodegradable waste from the agrifood industry will be subjected to methane fermentation (Buczkowski et al. 2012),
- Biogas from biodegradable waste from the agrifood industry is 100 m^3/ton (Buczkowski et al. 2012),

Fig. 10 Energy that can be recovered annually from biogas utilization from animal and poultry slurry in Poland

Fig. 11 Potential energy to be obtained annually from biogas from biodegradable waste from the agrifood industry in Poland

- Biogas from biodegradable waste from the agrifood industry contains 55% methane with a calorific value 35,73 MJ/m^3 (Buczkowski et al. 2012), and
- The efficiency of obtaining energy 80% (Buczkowski et al. 2012).

Formula 2 shows the annual amount of energy that can be obtained from biogas obtained from biodegradable waste from the agrifood industry:

$$E_{ba} = 0.2 \cdot 0.8 \cdot 0.55 \cdot M \cdot Y_{ib} \cdot C \tag{2}$$

where E_{ba} is the annual energy from biogas from biodegradable waste from the agrifood industry (TJ/year), M is the annual mass of the biodegradable waste from the agrifood industry (mln ton/year), Y is the biogas yield from biodegradable waste from the agrifood industry (100 m^3/ton), and C is the calorific value of methane (35.73 MJ/m^3).

Figure 11 shows the amount of energy that can be obtained annually from biogas from biodegradable waste from the agrifood industry in Poland.

The calculated amount of potential energy to be obtained annually from biogas from biodegradable waste from the agrifood industry in Poland is 1300 TJ/year = 1.3 PJ/year, with the Wielkopolskie of 315 TJ and Mazowieckie of 205 TJ, voivodeships, which have the best developed agrifood industry, having the greatest potential.

Auction system in Poland

The auction system in Poland assumes that the support provided for green energy producers is divided into several auction baskets. After the government has announced auctions for the purchase of a certain amount of energy from a given auction basket, the submitted projects will receive support in the form of an energy price offered by the investors at a fixed price during the period set by the Minister of Energy if it is lower than the prices reported by the competition—unless too few projects are submitted for the auction, and the estimated production will not cover the amount of energy that the government desires to purchase in the auction. Price offers that exceed the reference prices in the ministerial regulations will be rejected in advance. The reference prices are according to the Act of June 7, 2018, which amended the act on renewable energy sources and certain other acts (Table 7) (Act 2018).

Currently, there are two support systems for owners of ABP: the green certificate system and the auction system. Most of the producers remain in the green certificates system. The first auction organized on 30 December 2016 met with interest from only 7 of 93 biogas plants operating in Poland. All of the notified biogas plants won auctions, and their capacity in each case was 0.99 MW. A factor that could discourage some biogas plants from switching to the auction system could be the investment support previously received, which would reduce the price obtained under the auction regime. In accordance with the rules of the new support system under the EU regulations, a bid for the sale of energy from an agricultural biogas plant that has received

Table 7 Reference prices for agricultural plants in Poland (Act 2018)

Power of biogas plant (MW)	Price (PLN/MWh)
< 0.5	630
0.5–1.0	570
< 1.0	550

investment support requires that the offered price be reduced by the amount of the investment aid received earlier (Act 2018).

The new auction system, in comparison with the color certificate system, does not seem attractive to the owners of currently operating ABP in terms of income. In the auction listings, the average price per 1 MWh of electricity is PLN 503. A biogas plant with a capacity of 1 MW can generate 8000 MWh of electricity annually, providing an income of PLN 4,024,000 (PLN 503 × 8000 MWh) (Gostomczyk 2017). Biogas plants that remain in the system of color certificates, according to the listings from the beginning of 2017, can receive the following income:

1. From the sale of electricity (so-called black energy)—173 PLN × 8000 MWh = 1,384,000 PLN, (according to the average price per MWh of electricity).
2. From the sale of green certificates—378 PLN × 8000 MWh = 3,024,000 PLN.
3. From the sale of certificates for cogeneration—120 PLN × 8000 MWh = 960,000 PLN (Gostomczyk 2017).

Combined with the sale of energy and color certificates, a biogas plant with a capacity of 1 MW during a given year can receive PLN 5,368,000 of income. Additional income can be obtained from the sale of heat. In 2017, the price of 1 GJ of heat was PLN 36. A 1 MW biogas plant produces 8800 MWh of heat annually (1 MWh = 3.6 GJ). Therefore, the additional income from the sale of heat is PLN 36 × 31,680 GJ = PLN 1,140,480. Other potential sources of income are the fees charged for waste utilization and for the sale of digestate (Gostomczyk 2017).

The risk of being in the system of certificates is their instability, volatility and lack of durability. There is no guarantee that their high prices will persist over a longer period of time.

Future prospects of agricultural biogas plant development in Poland

Green technologies have been receiving much attention globally over the past two decades, driven mainly by ever-increasing demands for more efficient and sustainable uses of resources (Show et al. 2018). Although the process of obtaining biogas has been known for a long time, research on the optimization of this process is still ongoing.

It is worth noting that every year more and more substrates are used for biogas production. For example, Maroušek (Maroušek 2013a) obtained biogas from sunflowers stalks. The presented technology consisting of under hot-water maceration and steam explosion may be considered as a clean and environmentally friendly technology once it does require any additional chemicals and the running energy is utilized solely from the waste heat. Setup of the technology based on the research conducted may achieve up to 99 m^3 methane VS/t.

In the paper (Maroušek et al. 2015), two other methods of waste management of the cellulose casings (anaerobic fermentation and pyrolysis) were biotechnologically analyzed and financially assessed in a commercial scale. The results obtained confirm that regardless of the chemical nature, the surface treatment technology of the casings significantly hampers the biodegradability. This makes the fermentation technologies time-consuming and therefore economically unworkable. Intensive disintegration techniques are therefore necessary. However, the solid residue of the pyrolysis (also called biochar) represents more attractive product.

Waste from public green areas represents large quantities of grassy phytomass. The grass is usually utilized by composting, combustion or anaerobic fermentation. A new method (Maroušek 2013b) of two-fraction anaerobic fermentation of grass waste consisting of a hot maceration, up-flow anaerobic sludge blanket reactor, steam explosion, horizontally stirred batch anaerobic fermentors and a charcoal kiln, all run on waste heat from a cogeneration unit, was investigated on a commercial scale.

Agricultural biogas plants in Poland: surveys

The survey was sent to all ABPs in Poland. Answers were obtained from over 40%. Biogas plants launched after 2010 responded to the survey. Telephone conversations with the operators of several ABP in Poland were also carried out.

The reasons for initializing ABP in Poland were as follows:

- Support for energy production from renewable energy sources,
- Support programs of UE,
- Good perspectives for development of renewable energy production in Poland,
- Increasing economic profitability,
- Methane digestion as way to manage slurry,
- Emergency global trends regarding renewable sources,
- Management of agricultural waste, and
- Energy self-sufficiency.

The investment cost ranged from PLN 8 to 20 million. Biogas plants used several sources of financing. They were as follows:

- Own resources,
- Bank loans and other loans,
- Funds from EU programs,
- Resources of the European Regional Development Fund,
- Cofinancing from the National Fund for Environmental Protection and Water Management,
- Cofinancing from the Regional Fund for Environmental Protection and Water Management,

The most important problems related to the investment stage were as follows:

- High investment costs,
- Resistance by the local community,
- No specialist companies on the market,
- Time-consuming and complicated administrative procedures,
- Legal instability,
- Lack of expert advice,
- Dishonesty of performers, and
- Formal problems with connection to the power grid,

The amount of biogas produced in 2018 ranged from 2 to 9 million m^3.

Of the respondents, 70% are satisfied with the company's turnover, 20% are dissatisfied, and 10% did not answer the question.

Approximately 65% of the respondents answered "yes," 20% answered "no," and 15% said they "exceeded" in response to the question of whether the amount of energy produced is the amount assumed at the investment planning initial stage.

The most serious problems regarding the functioning of the installation are as follows:

- Breakdowns and high repair costs,
- Problems with digestate management,
- High costs of servicing,
- Lack of domestic producers of certain technological devices, and
- Need to adapt to constantly changing legal regulations.

Almost all biogas operators have development plans for their biogas installation:

- Modernizing the plant,
- Construction of an additional transmission grid,
- Construction of a postdigestion tank, and
- Increasing the power of the bioenergy plant.

The following responses were received to the question of how the respondents rate the biogas market in Poland.

- Market difficult and unstable,
- Insufficient support from the state,
- The market is still quite small,
- Numerous legal problems, e.g., how to classify a digestate,
- Without legal changes, not very perspective,
- No policy supporting biogas plants, and
- A continuing lack of reliable professionals in the country so that biogas plant operators must learn from their mistakes,

Of the respondents, 52 estimated the biogas resources in Poland as large and 26% as very large.

Nearly one-third of the respondents shared their own comments/experiences. The respondents wrote that they wanted to further improve their installations. Biogas plants should primarily be part of large farms or groups of medium-sized holdings due to the need for a substrates supply as well as digestate management. In Poland, as in other EU countries, a policy should be pursued to support the development of the biogas market.

Several respondents more broadly described the barriers and elements of investment risk in Poland.

Barriers and elements of investment risk in agricultural biogas plants in Poland

The respondents participating in the survey wrote that the development of the biogas sector in Poland is in the initial phase and requires the presence on the market of many specialized companies and the training of relevant specialists. Some of the equipment for the construction of a biogas plant has to be imported from abroad, which may further increase the investment costs. There are still few designers, general contractors, construction companies and technologists specializing in the design, construction and operation of ABP.

An important organizational barrier is also the lack of a national substantive expert background for investors interested in the construction of ABP. A lack of social awareness of the production and use of biogas combined with the lack of an organized system of reliable knowledge transfer result in increased investment risk and cause local communities and officials at various levels to experience unnecessary concern.

The limited availability and capacity of the power grid in rural areas are another barrier of not only a technical but also an organizational and financial nature. Economic efficiency decreases significantly when there is no opportunity to apply heat for local needs. In the case of agricultural households, the high heat demand for heating the digestion chamber coincides with the time (heating period) of the demand for heating livestock barns and farm buildings. The key is to allow heat to be used during the summer, for example, for the drying of cereal grains.

PEST analysis of agricultural biogas plants in Poland

The PEST (political, economic, social and technological) method (analysis) is one of the methods used to examine the environment, in this case the renewable energy sector (Fig. 12) (Gupta 2013). Most often, the environment can be specified as follows:

- Political macroenvironmental factors: among others, political stability, renewable energy policy and legislative framework;
- Economic macroenvironmental factors: among others, the current business environment in Poland and the rest of the world, the job market and interest rates;
- Social macroenvironmental factors: among others, demographics, knowledge of renewable energy sources, human resources structure and availability of workforce; and
- Technological macroenvironmental factors: among others, economic innovation in the renewable energy sector and transfer of techniques and technologies (Koumparoulis 2013).

In the adopted research methodology, it was intended to present investigated factors on a point scale, depending on how much they favor the development of agricultural biogas plants sector. Within the used scale used, the particular points from 1 to 5 are defined as follows:

- 1—a highly unfavorable factor,
- 2—an unfavorable factor,
- 3—a neutral factor,
- 4—a favorable factor, and
- 5—a highly favorable factor.

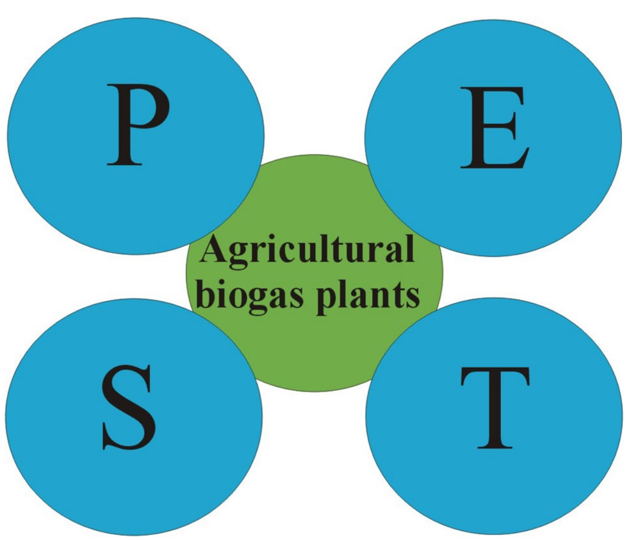

Fig. 12 Macroenvironmental factors for ABP; *P* political, *E* economic, *S* social, *T* technological (PEST analysis)

It was decided to use the formula of the mean value of the selected factors, assuming that the impact on the development of agricultural biogas plants sector as follows:

- Below 2.00 points—a highly unfavorable macroenvironmental factor,
- 2.00–2.99 points—an unfavorable macroenvironmental factor,
- 3.00–3.49—a neutral macroenvironmental factor,
- 3.50–4.49—a favorable macroenvironmental factor,
- 4.50–5.00—a highly favorable macroenvironmental factor (Gupta 2013).

The PEST analysis was conducted using the information provided by the renewable energy producers (surveys), data from the literature, the strategy for the development of renewable energy sources and legal acts and regulations.

Political environment of agricultural biogas plants in Poland

Table 8 presents the political environment of ABP in Poland in the context of its development potential.

The political environment for renewable energy in Poland is generally based on the system and political system. In accordance with the Constitution of the Republic of Poland (Constitution 1997), Poland is a parliamentary republic and implements the principles of national sovereignty, independence and sovereignty, a democratic state of law, civil society, tripartite power, pluralism, the rule of law, a social market economy and inherent human dignity. The stability of the democratic political system, the independence of important state institutions (the central bank, the judiciary) and the relatively friendly administrative approach have a positive impact on the development of the sphere of science and research, including RES.

Public administration is an integral part of the state and is endowed with the privilege of a legislative initiative. Despite many efforts, public administration in Poland does not operate efficiently in Poland and is not conducive to the development of ABP, as investors struggle with bureaucracy in Poland.

The Renewable Energy Act came into force on 1 July 2016 (Act 2015). One of its most important aspects is the

Table 8 The political environment of agricultural biogas in Poland in the context of its development potential

	Factor	Friendliness of ABP
1.	Political system in Poland	4.50
2.	The system of public administration and the efficiency of its functioning	2.50
3.	RES policy at the state level	2.00
4.	Policy on renewable energy at the regional level	3.00
5.	Act on renewable energy sources	4.00
6.	Legal regulations related to using of the environment	4.00
7.	Lobby of conventional energy	1.00
8.	Membership in the European Union	5.00
Total assessment		3.25

definition of a prosumer—the final consumer purchasing electricity on the basis of a comprehensive contract and producing electricity exclusively from renewable energy sources in microinstallations for its own consumption not related to business activity. After 1 July 2016, prosumers could not sell energy to the grid; instead, they must settle accounts with the energy company on the principle of a discount. Additionally, the definition of RES installations was changed, and a new definition of a hybrid renewable energy installation was added. Definitions of energy wood, energy cluster and energy cooperatives were introduced, and the division into technology baskets; the possibility of using locally available resources (primarily biomass); the construction of new, dedicated multifuel combustion plants and test procedures; and the so-called incentive effect for producers of agricultural biogas were also changed (Act 2015).

The introduced auction system is based on the fact that the government orders a certain amount of renewable energy. Producers join the auction, which is won by the one who offers the most favorable conditions. In principle, the auction system will create stable conditions for the development of the RES sector because projects selected in the auction system over 15 years will be provided with stable support.

In Poland, legal regulations related to the use of the environment, including GHG emissions, are regulated by the Environmental Protection Law (Act 2001). The law determines:

- Environmental protection principles,
- Conditions for using the environment,
- The duties of public administration related to environmental protection.

A strong deterrent to the development of ABP in Poland is the conventional energy lobby, mainly the coal lobby. The coal lobby is opposed to new investments in renewable energy, including ABP, in Poland.

The guarantee of institutional "maturity" in Poland is membership in the European Union and other international organizations, such as international tribunals and judicial institutions. Membership in the EU has enabled Poland to make a civilizational leap that has stimulated the development of many economic sectors. The development of the biogas sector in Poland is facilitated by the elimination of borders in political relations resulting from globalization processes, including participation in the European Union. At the time of accession, Poland agreed to take over the EU legal acquis in the fields of science and research. This creates unprecedented possibilities of functioning in the European Research Area in the sphere of science and research in Poland. This allows for the free flow of scientific and research staff, joint projects and the creation of joint research and development centers.

Economic environment of agricultural biogas plants in Poland

Table 9 presents the economic environment of ABP in Poland in the context of its development potential.

Poland is one of the few countries in Europe where economic growth is taking place. Figure 13 shows the dynamics of the volume of output in 2013–2017 (Central Statistical Office 2017a).

The prices of conventional fuels are at a constant, quite low level. The price per ton of coal in Amsterdam-Rotterdam-Antwerp was USD 70.00 (Coal price 2019), the price of crude oil was USD 71.53 per barrel (Crude oil price 2019), and the price of natural gas was USD 2.58 per 1 million btu (Natural gas price 2019).

The important element of the economic macroenvironment of ABP in Poland is the labor market: unemployment rate, structure and employment dynamics, and migration. At the end of the fourth quarter of 2018, the number of vacancies in entities employing at least 1 person was 139.2 thousand. In comparison, at the end of the fourth quarter of 2017,

Table 9 Economic environment of ABP in Poland in the context of its development potential

	Factor	Friendliness of ABP
1.	Socioeconomic development	4.00
2.	The economic situation in the world, world prices of energy and fuels	3.00
3.	Labor market	4.00
4.	The ability to finance biogas investments from investor resources	3.00
5.	Interest rates, availability of credits and loans	4.00
6.	Green certificates, auctions	4.00
7.	Innovation, entrepreneurship and activity	4.00
8.	Globalization—free movement of goods, capital, services	5.00
General assessment		3.88

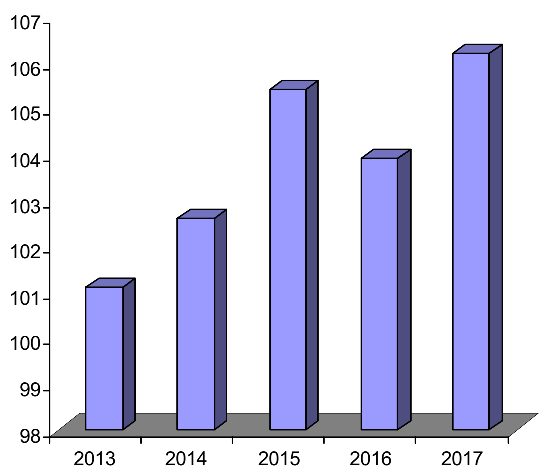

Fig. 13 The dynamics of the volume of global production in Poland in 2013–2017 (Central Statistical Office 2017a)

the number of vacancies was higher by 21.4 thousand, i.e., by 18.1% (Central Statistical Office 2019a). According to the Central Statistical Office (Central Statistical Office 2019b), the unemployment rate in Poland in March 2019 was 5.9%. The unemployment rate is gradually decreasing in Poland.

It is estimated that approximately 35–40 thousand people work in the RES sector in Poland, of whom approximately 600 people work in ABP. Renewable energy is one of the few branches of the Polish economy in which there is an annual increase in employment. According to forecasts, in 2030, at least 70,000 people will be employed in RES in Poland (Buczkowski et al. 2012).

Inflation in Poland has not exceeded unity since 2001. In 2018, inflation was 1.6% (Central Statistical Office 2019c).

At the beginning of March 2019, interest rates in Poland were lowered, and they are currently recorded as low. The reference rate is 1.50%, the Lombard rate is 2.50%, the deposit rate is 0.50%, and the bill of exchange rediscount rate is 1.75% (National Bank of Poland 2019).

Investors in the biogas sector in Poland may apply for cofinancing/loans from both European Union and national funds. For example, for projects related to the production of thermal energy, the National Fund for Environmental Protection and Water Management (NFEPWM 2019) has allocated PLN 200 million. This is the fifth recruitment financed by the Cohesion Fund. Interested entrepreneurs will be able to submit applications for financing from March 30 to May 28, 2019. The maximum share of cofinancing in eligible expenditures at the project level, not more than 85%, is determined in accordance with the state aid rules. The total value of support from public funds (from all sources) for one entrepreneur per project cannot exceed EUR 15 million.

Polish investors, despite the extensive bureaucracy, show a high level of entrepreneurship and activity in building RES installations. They frequently include their own ideas that improve existing technology. An increasing number of investors are developing 2 or more types of RES, e.g., biogas plants and photovoltaic panels.

The opening of borders after Poland's accession to the EU allowed the free movement of goods, technologies and services. The latest technological developments of the EU are increasingly being implemented in Poland.

Social environment of agricultural biogas plants in Poland

Table 10 presents the ABP social environment in Poland in the context of development potential.

In December 2018, the Polish population amounted to 38,412, live births amounted to 8.4/1000, and the natural increase was negative and amounted to −2.4% (Central Statistical Office 2019d). Polish society is aging, and the number of children is decreasing. Therefore, among other programs, the 500+ program was developed to provide monthly support for the second and subsequent child in Poland (500+ Programme 2019).

Table 10 The social environment of ABP in Poland in the context of development potential

	Factor	Friendliness of ABP
1.	Demographic situation	3.00
2.	Education level	3.50
3.	Knowledge about biogas technology	3.50
4.	Social acceptance of ABP	3.00
5.	Social acceptance of the construction of a low-emission economy	3.00
6.	Structure of human resources and the availability of human resources	3.00
7.	Impact of ABP on the labor market	4.50
8.	Membership in the European Union	5.00
General assessment		3.56

In 2018, 22.2% of women and 22.7% of men in Poland had received a primary education, 44.3% of women and 47.9% of men had received a secondary education, and 33.4% of women and 29.5% of men had received a higher education (Central Statistical Office 2018).

For the Polish people, almost unlimited access to the Internet, promotion of RES (seminars, conferences, demonstrations) and travel abroad means that their knowledge and support of renewable energy (and ABP) is gradually increasing.

Polish society generally accepts the construction of a low-emission economy, although people fear that it will significantly increase the costs of energy and consumer goods.

In recent years, over 40 universities have expanded their offer by introducing RES-related studies. This is both for the engineers (technologists and designers) responsible for the technical side of the project and specialists in the field of economic and legal sciences who will deal with issues related to investment planning and analysis of profitability. Currently, in Poland, there are a number of opportunities related to gaining knowledge in the field of renewable energy.

As before, the dynamically growing renewable energy market needs employees, most often in rural areas with high unemployment. The development of ABP can reduce unemployment in rural areas of northeastern Poland. This type of power plant can be installed close to rural communities, which significantly reduces transmission costs and the associated energy losses. In addition, a bioelectric plant may constitute an element that stabilizes the energy system for a rural community based on the distributed energy facilities.

Moreover, EU membership ensures the free flow of new technologies and hence new jobs in the RES sector. In the case of ABP, new places are created in rural areas in Poland and thus in areas with the highest unemployment. The supply of waste materials for biogas plants also improves the material situation of local farmers.

Technological environment of agricultural biogas plants in Poland

Table 11 shows the technological environment for the agricultural biogas plant in Poland in the context of development potential.

The RES sector is one of the fastest-growing branches of the economy in Poland and in the world. Extensive research in scientific centers results in an increase in the efficiency of obtaining energy from renewable sources as well as a drop in the prices of RES installations. The development of RES is an impulse for further research in and development of new technologies, including biogas technology. It is expected that along with the development and increase in production of biogas plants, the investment costs will be reduced, which is currently an important barrier to the implementation and development of such facilities. For example, methane for powering car engines usually comes from natural gas, but it can also be obtained from biogas. Biomethane, purified and refined biogas (CBG—compressed biogas) obtained

Table 11 Technological environment of ABP in Poland in the context of development potential

	Factor	Friendliness of ABS
1.	Innovation of the economy and the biogas sector	3.00
2.	Degree of energy infrastructure consumption	4.00
3.	Condition of the power grid in Poland	2.00
4.	Connection with the power grid in Poland	2.50
5.	Domestic producers of biogas installations	3.00
6.	Ability of science-economy cooperation	2.00
7.	Efficiency of obtaining energy from biogas	4.50
8.	Transfer of technicians and technology (EU membership)	5.00
General assessment		3.25

as a result of the treatment and subsequent compression to 20–25 MPa, corresponds to the quality and chemical composition of natural gas (CNG).

Polish power units are outdated, and many are 30–40 years old. Their poor technical condition means that exclusions are expected in the near future. It is worth turning obsolete coal blocks into renewable energy installations, including biogas installations.

The electric power transmission grid is poorly developed, especially in northern Poland. It should be emphasized that the northern part of Poland has excellent conditions for the development of ABP—energy would be sent to the recipient almost without transmission losses.

The development of biogas technology is also an opportunity for industry in northern Poland. All devices for biogas plants should be produced locally by Polish manufacturers. This would imply further development of the region as well as further new jobs. Polish devices could be successfully sold almost anywhere in Europe. The demand for these devices is great, as virtually all countries are developing biogas technology.

There is still little cooperation between science and industry in Poland. This also applies to biogas technology. The relationship between science and business is an important problem in both disciplines and is strategic in terms of the economy. Companies do not create a new reality; they do not perceive innovation as a factor that stimulates development. However, scientific institutions do not communicate with companies and do not share innovations. In the development of ABP in Poland, it is necessary to support science in the implementation of research and development programs, including the improvement of technological processes.

The efficiency of RES installations is equal to or sometimes greater than that of conventional energy installations. ABPs, cogenerating electricity and heat, achieve an efficiency of up to 85%. It is worth noting that the efficiency of Polish coal-fired power plants is approximately 36%.

Opportunities for the development of RES potential lie in membership in the European Union (cooperation and transfer of knowledge within the European Research Area), development of the information society and development of information and telecommunications technologies.

Discussion

The political environment of biogas technology in Poland can be defined as neutral (3.25 points). The stable political system (4.50 points) and EU membership (5.00 points) represent opportunities for the development of ABP in Poland. The greatest threat is the strong conventional energy lobby (1.00 points) as well as the unfriendly energy policy (2.00 points).

The economic environment (3.88 points) should be considered friendly for the development of ABP. An opportunity for development is globalization (5.00 points). The opening of borders allows the free flow of information, including biogas technologies. The greatest threat is the uncertain worldwide economic situation (3.00 points) as well as the low ability to finance biogas investments from an investor's own resources (3.00 points).

The social environment can be considered quite friendly to biogas technology (3.56 points). The greatest advantage is membership in the EU (5.00 points) as well as the positive impact of biogas plants on the labor market (4.50 points). The threat is the poor demographic situation (3.00 points), low social acceptance of biogas technology (3.00 points) as well as a low-emission economy (3.00 points) and low availability of qualified employees (3.00 points).

The technological environment can be considered neutral (3.25 points). The transfer of techniques and technologies (5.00 points) provides an opportunity owing to membership in the EU. Another advantage of biogas technology is the high efficiency of obtaining energy (4.50 points)—in cogeneration, up to 85%. The greatest threat is the poor condition of the power grid in Poland (2.00 points) and thus the problem with connecting further ABP to the grid. Poor cooperation between industry and science is still a threat (2.00 points).

Conclusions

Agricultural biogas sector in Poland is still in the early growth stage. In the article, formal and law requirements were presented which should be met during investment. Using technologies in Poland that were described, surveys and PEST analysis were conducted. The following conclusions can be seen from the conducted research:

1. In Poland, due to the binding legal regulations, the construction of biogas installations is complicated and time-consuming, and connection to the power grid involves financial and time expenditure. To start the construction of an installation, it is necessary not only to obtain permits but also to be accepted by the local community, which is often unaware of the positive aspects of biogas plant operation in terms of production and use.
2. In Poland, there are a number of problems resulting from the legal, technological, organizational and economic barriers encountered by investors in the construction of ABP. The legal barriers arise primarily from unfavorable legislation that determines the legal and administrative procedures related to the implementation of technologies and locations of installations using RES. The second factor is the difficulty in enforcing the obligation to pur-

chase energy from renewable sources and the lack of a guaranteed stable price for the sale of energy produced from ABP or the possibility of trading in emissions. The problem also includes the high costs of investment preparation and investment outlays on biogas technologies (4–5 million EUR/1 MW), which to a great extent inhibit the development of this branch of renewable energy.

3. An opportunity for further development of ABP in Poland is their great potential. The potential energy from biogas from agricultural land is 107 PJ, the potential energy from animal and poultry slurry is 23 PJ, and the potential energy from biogas from biodegradable waste from the agrifood industry is 1.3 PJ. Poland may, thanks to biogas plants, reduce gas imports from Russia and increase its self-sufficiency in terms of energy.
4. In Poland, the production of biogas also allows for a significant reduction of odor emissions, which are released in large quantities during the natural decomposition of animal slurry that is distributed in fields. The emissions are caused by the release of hydrogen sulfide and other gases that cause an unpleasant odor. Because of their high corrosivity, these gases are removed from biogas, usually through biological desulfurization, before being burned in a cogeneration unit.
5. The construction of ABP brings benefits nationwide in terms of saving fossil fuel resources, meeting international obligations and improving the energy security of the country. The production of electricity and heat using biogas reduces the demand for energy from the combustion of fossil fuels, which adversely affects the natural environment.
6. The political environment of biogas technology in Poland can be defined as neutral (3.25 points). The economic environment (3.88 points) should be considered friendly for the development of ABP. The social environment can be considered quite friendly to biogas technology (3.56 points). The technological environment can be considered neutral (3.25 points). The PEST analysis shows that there are fairly good conditions in Poland to invest in agricultural biogas plants.
7. Process of gradual transformation from the market based on coal to the one using ecological technologies, low-emission, fulfilling social needs, giving diversification of energy sources, energy security-not only in local scale but also in regional scale and even long-term perspective. These transformations can already be seen in Poland. If these criteria are met, the sustainable development of energy could be implemented in Poland.

The development of agriculture biogas plants in Poland is fully justified and should be supported in financial and organization way. Taking new law about RES from 20 February 2015 into consideration, possibility of producing electrical and heat energy by prosuments should be positively evaluated. Prosuments can deliver the energy surplus to energy grid. In this way, central energy grid (through small energy production units) should lead to full energy security in regions and is also used in RES energy potential in Poland.

The development of biogas technologies as well as other RES technologies will allow a gradual departure from fossil fuels in Poland and in the world (Khoie et al. 2019). Importantly, energy from biogas plants is obtained in a stable manner, so together with hydroenergy, biomass energy will be the foundation of Poland's future energy mix.

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