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Energy Production from Biodegradable Waste as an Example of the Circular Economy

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Abstract: A growing population, technological progress and economic development result in a constant increase in energy demand. Energy is mostly obtained from fossil energy resources such as coal, natural gas, and crude oil. Burning them leads to air pollution with greenhouse gases (CO_2 , CH_4 , NH_3 and N_2O) and dust ($\text{PM}_{2.5}$ and PM_{10}). They are recognized as the cause of global warming and air pollution. Wind, water, solar and biomass energy are used to eliminate harmful emissions. The latter may come from special plant crops or from biodegradable waste from farming, animal husbandry, the agrifood industry and households. These wastes are transformed into biogas in biogas plants, the basic ingredient of which is methane. Most often, biogas is burned in a cogeneration process, providing electricity and heat. After purification of admixtures, it can be injected into the high-methane gas network or converted into hydrogen in the steam reforming process. In this way, environmentally harmful waste becomes a raw material for energy production, which is an example of a circular economy. The article discusses the functioning of biogas plants in selected EU countries. The current biogas production in Poland was assessed and compared with the production potential of dairy farms. The aim of this article was to show that the production of biogas reduces the emission of greenhouse gases into the atmosphere and the electricity produced from it is not burdened with the cost of purchasing CO_2 emission allowances applicable in the EU.

Keywords: circular economy; waste management; renewable energy sources; biogas plants



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1. Introduction

Energy is required to make the products people need. The growing population, technological progress, and economic development result in a constant increase in energy demand. The energy sector produces almost 90% of CO_2 emissions and 75% of total greenhouse gas (GHG) emissions in developing countries. About half of these emissions arise from the combustion of fossil fuels in power plants and refineries [1]. In developed countries, energy producers and agriculture constitute the main emitters of greenhouse gases, generating 25.9% and 13.5% of annual global emissions respectively [2]. Obtaining energy almost exclusively from fossil energy resources pollutes the atmosphere with greenhouse gases (CO_2 , CH_4 , NH_3 , and N_xO) and dust ($\text{PM}_{2.5}$ and PM_{10}). Greenhouse gases increase the temperature of the atmosphere and oceans. The rapid increase in CO_2 content is causing climate change and sea level rise, which endanger people living in coastal regions and island countries [3–6].

Manufacturing of products and their use as well as meeting human existential needs (food, clothing, heating) generate waste. The increase in the amount of waste and the difficulties connected with its management are becoming a problem that can be effectively solved in accordance with the principles of the circular economy. In this system, waste can become a useful resource [7]. The production of electricity from biodegradable waste is an example of the benefits of the circular economy. Biogas plants are also a part of the concept of sustainable development, bioeconomy, and green economy [8].

Until the industrial revolution, energy was supplied through the muscles of humans and animals, wood, peat, flowing or damming of water, wind, and the Sun. These resources are renewable. The operation of the steam engine, and later the internal combustion engine, is based on the combustion of fossil energy resources: hard coal, lignite, crude oil, and natural gas, which are all non-renewable. Combustion of these raw materials causes the emission of carbon dioxide and sulfur dioxide, nitrogen oxides, and dust into the atmosphere. The emission of these substances increased with the growth of the population and with the related demand for food and industrial products. In the beginning, the increased emissions caused local problems with air cleanliness (smog in industrial cities), which was improved by relocating the industry to developing countries, creating protection zones around industrial plants, building high chimneys for power plants, and establishing combined heat and power plants. These actions temporarily improved the local situation but caused a change in the composition of the atmosphere, resulting in an increase in the content of carbon dioxide in it. This gas is responsible for the increasing temperature of the Earth's surface and adverse weather phenomena. Large CO₂ emissions occur mainly in highly industrialized countries that have not yet undergone the energy revolution. Currently, the main emitter of CO₂ is China, which has declared that by 2030 it will reduce its emissions, per unit of GDP, by 60–65%. In turn, India intends to reduce CO₂ emissions by 30–35% [3–5]. However, carbon dioxide is not the only greenhouse gas whose amount in the atmosphere is impacted by humans. Methane is such a gas as well. Although produced in natural processes, it is more harmful to the environment because it is 25 times as potent as CO₂ [9]. Methane is released from hard coal deposits during the extraction of that resource [10]; it is also produced as a result of anaerobic fermentation of organic matter generated during food production and processing as well as municipal waste management. Its emissions can be reduced by fermenting organic matter in biogas plants [9]. Biogas obtained from them is a mixture of methane (40–80%), carbon dioxide (16–48%), and other gases present in trace amounts. The organic substances (substrates) used for fermentation have an influence on the methane content in biogas. The fat content is of particular importance, as a high fat content allows for the production of biogas with a high methane content.

Detailed information on the chemical composition of biogas obtained from various substrates is presented in Table 1. Biogas obtained from household waste may also contain trace amounts of aromatic, halogenated, and organofluorine compounds [11]. Sulfur dioxide and water vapor must be removed before the combustion of biogas in cogeneration units, as these cause corrosion of their components.

Table 1. Chemical composition of biogas obtained from various substrates.

Components	Unit	Household Waste	Sludge from Sewage Treatment Plants	Agricultural Waste	Wastes from the Agri-Food Industry
CH ₄	[%] by vol.	50–60	60–75	60–75	68
CO ₂		34–38	19–33	19–33	26
N ₂		0–5	0–1	0–1	-
O ₂		0–1	<0.5	<0.5	-
H ₂ O		6	6	6	6
H ₂ S	mg/m ³	100–900	1000–4000	3000–10,000	100
NH ₃		-	-	50–100	400

Source: Own study based on [11].

The biogas yield and its composition are also influenced by the fermentation temperature, retention time, decomposition technology, and raw material pretreatment [12,13]. In order to counteract the further increase of greenhouse gases in the Earth's atmosphere, intensive development of technologies enabling the use of renewable energy sources (RES) has started. In recent years, the greatest progress was made in the production of electricity

from wind and the sun. However, due to the variability of weather conditions, energy systems cannot rely solely on these sources. It is, therefore, necessary to build energy storages and increase the possibilities of the production of electricity from biogas [14]. Biogas plants, unlike other RES, are multi-energy systems as these provide biomethane that can be used to generate energy in various processes. Currently, it is most often burned in cogeneration units producing electricity and heat. After cleaning, it can be injected into natural gas networks or, in a compressed form, used as fuel in cars with CNG installations [6,12,13,15–17]. After steam reforming, it can become a source of biohydrogen used as fuel in fuel cells. Due to the development of renewable energy sources (including biogas plants), electricity can be generated close to end users. This, combined with the possibility of storing energy, reduces the losses associated with its transmission, diversifies energy sources, and reduces dependence on fossil energy resources [12]. Japan can serve as an example of this approach. A self-sufficient energy farm project was created there, in which electricity and heat will be produced, as well as fuel that will fully meet the farm's own needs [18].

Many developing countries comprise predominantly municipal landfills where unsorted waste is collected. A large part of that waste is biodegradable. Such a method of collection is very burdensome due to the limited availability of land, limited resource management, and the need to reduce greenhouse gas emissions to the atmosphere. Alternative methods of processing biodegradable municipal waste can be applied, such as [19,20]:

- anaerobic storage,
- semi-aerobic storage,
- landfill gas capture,
- composting,
- pre-composting before landfilling,
- biogas production.

Composting and pre-composting produce compost and liquid fertilizer used in agriculture. Electricity is generated during landfill biogas capture and biogas production in biogas plants and then sold to a power grid [19,21,22].

A study by the World Bank showed that about 50% of the organic waste produced could be used for biogas production. Based on the level of income of the population, it is estimated that in 2025 half of household waste will contain 50% of biodegradable waste [23].

Biogas plants are the best way to manage organic waste generated in the agri-food and municipal sectors because these reduce the amount of greenhouse gases emitted into the atmosphere by burning fossil fuels. Therefore, they are a part of the circular economy. This concept organizes agricultural production according to the following principle: resources-agricultural products-renewable energy sources, focusing on recycling and re-use of waste and by-products instead of traditional and extensive production. Circular agriculture requires the implementation of several changes, namely the reduction of the resource and energy consumption, maximization of their use in production and consumption systems, and the reduction of waste and pollutant emissions. Integrated production systems are created, such as: “grain production-pig breeding-fish breeding”, “cattle breeding-biogas plant-vegetable growing”, or “pig breeding-biogas plant-fish farming” [24–27].

In a biogas plant, the fermentation process utilizes waste generated during agricultural production, including plant cultivation, horticulture, and livestock breeding. All these release large amounts of GHG into the atmosphere. On livestock farms, due to the regulations on nitrates, slurry is stored through the winter. Only in spring is it used as a fertilizer on arable fields [2]. Livestock farms generate large amounts of waste in the form of animal manure, which is a source of greenhouse gas emissions [28]. Traditionally, manure is used directly for natural fertilization. Chicken manure can serve as an example, as it is spread as fertilizer on farmland or grassland directly, without additional preparatory steps. The disadvantage of such use of chicken manure is the emission of NH_3 and N_2O to the atmosphere. An alternative is to use it as a substrate in a biogas plant. During methane

fermentation, manure is converted into biogas and into a by-product of the process, i.e., digestate. Research by Meyer et al. proved that converting manure into biogas is associated with reduced greenhouse gas emissions reaching the atmosphere [29]. Kreidenweis et al., also proved that greenhouse gas emissions are reduced when broiler manure is used to produce biogas. Methane emissions are lower because the manure is neither stored in the air nor composted, resulting in higher emissions than is the case with the storage of untreated chicken manure [6]. This method of producing renewable energy from biogas is promoted in European countries such as Germany, Switzerland, and Austria [2].

Biogas can also be produced from organic waste from grocery stores: from fruits, vegetables, flowers, dairy products, meat waste, and confectionery. Kitchen waste and other municipal biodegradable waste can be used to produce biogas as well. Research has shown that they can be used to obtain biogas containing from 44.3% to 75.4% methane. The temperature that should be taken into account when fermenting food waste is also an important factor in the process [23].

The aim of this article is to demonstrate that the production of biogas from biodegradable waste and the reduction of the emission of greenhouse gases into the atmosphere allow us to reduce the costs of electricity generation which stem from the system of purchasing CO₂ emission allowances in force in the EU. This goal will be achieved through the analysis of the operation of biogas plants in the EU countries based on literature. Based on data from the Central Statistics Office and Energy Regulatory Office, the current biogas production in Poland was described. For dairy farms, an attempt was made to estimate the potential of biogas production. A possible reduction from the lack of burdening it with the costs of purchasing CO₂ emission allowances.

2. Emission Allowances Prices in the EU and Their Impact on the Price of Electricity

The total amount of greenhouse gases that can be emitted by industry, power plants, and other fixed installations covered by the EU Emissions Trading Scheme (EU ETS) is limited by the cap on emission allowances. Each allowance gives its holder the right to emit [30]:

- one ton of carbon dioxide (CO₂), the main greenhouse gas; or
- the equivalent amount of two more powerful greenhouse gases: nitrous oxide (NO₂) and perfluorocarbon (PFC).

Each year, the allowance ceilings for fixed installations are reduced. In 2013, the ceiling was 2,084,301,856 tons of CO₂. In the third phase of the EU ETS (2013–2020), its level was reduced each year through the application of a linear reduction factor of 1.74% of the average total number of allowances issued annually in 2008–2012. This resulted in a reduction of 38,264,246 tons of allowances per year, i.e., the number of allowances that can be used in fixed installations was 21% lower than it was in 2005. To achieve the target of reducing emissions in the European Union by 40% by 2030 compared to the year 1990, from 2021, the level of allowances is reduced by 2.2% each year. This will reduce emissions from fixed installations by approximately 32% by 2030 as compared to 2005 levels. By 2050, emissions should be reduced by around 90% from 2005 levels [31]. Auctioning is the primary allocation method under the EU Emissions Trading System (EU ETS). Companies wishing to use solid fuels have to buy an increasing percentage of emission allowances at auctions. In the opinion of the European Commission, this is the clearest method of allocating emission allowances, as it follows the “polluter pays” principle. Pursuant to Art. 10 of the Emissions Trading Scheme Directive, in 2021–2030, 90% of emission allowances for auctioning will be allocated to the EU Member States based on their verified emissions and 10% of allowances will go to poorer EU countries to foster economic growth and cohesion [31].

Figure 1 shows the price of CO₂ emission allowances, which stood at EUR 25.31 on 1 January 2020 and at EUR 82.76 on 12 December 2021, i.e., it increased by 227.98%. During this period, the price of allowances for Polish companies increased from 107.77 zł to 381.78 zł (an increase of 254.25%). One of the largest investment banks, Goldman Sachs,

predicts that carbon prices will grow by around 7% annually in the coming years. More pessimistic scenarios assume that prices could rise to EUR 100.

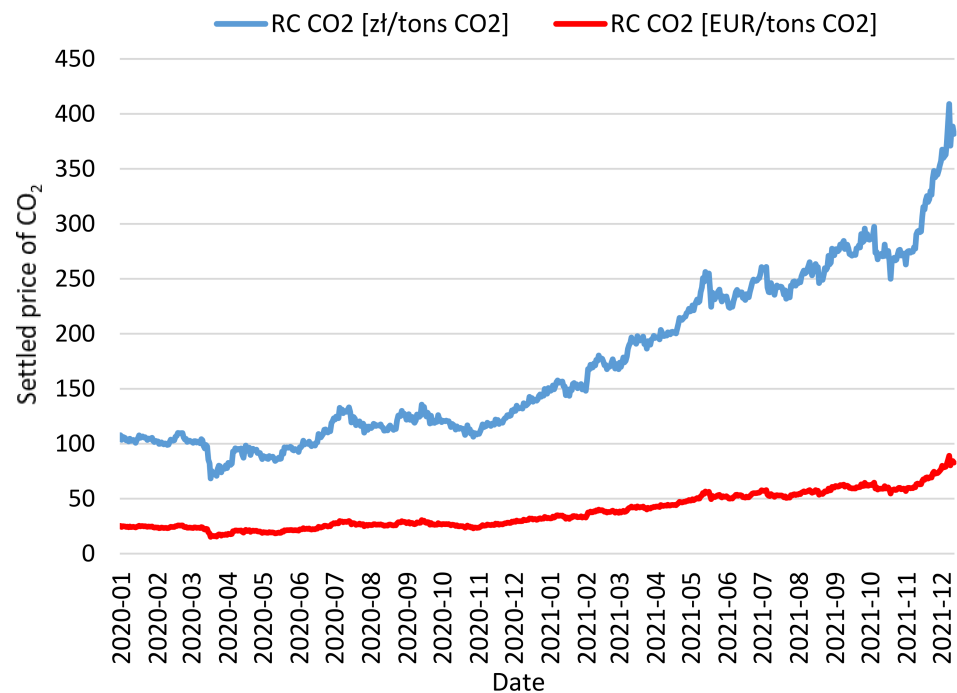


Figure 1. Settlement price of CO₂ emission allowances in 2020 and 2021. Source: Own study based on [32].

The prices of CO₂ emissions significantly affect the prices of electricity [33–35]. Figure 2 shows how the average prices of 1 MWh changed in Poland between 2010–2021. In 2010, the price amounted to 45.95 EUR/MWh and increased to 55.93 EUR/MWh in 2021. The price of electricity increased to a lesser extent than the price of CO₂ emission allowances, which, as shown in Figure 3, is the result of almost unchanged coal prices between 2007–2020.

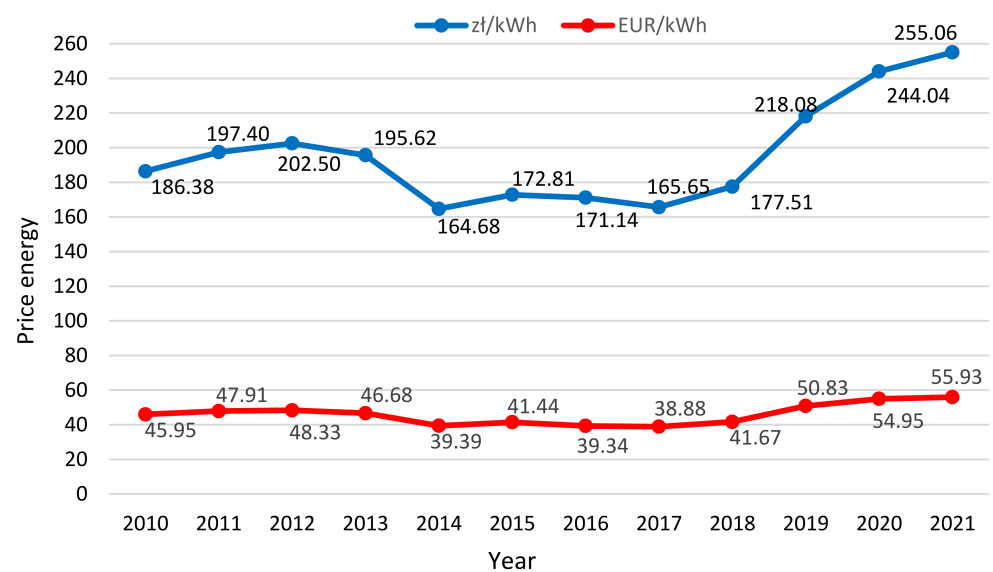


Figure 2. Average annual electricity price. Source: Own study based on [36,37].

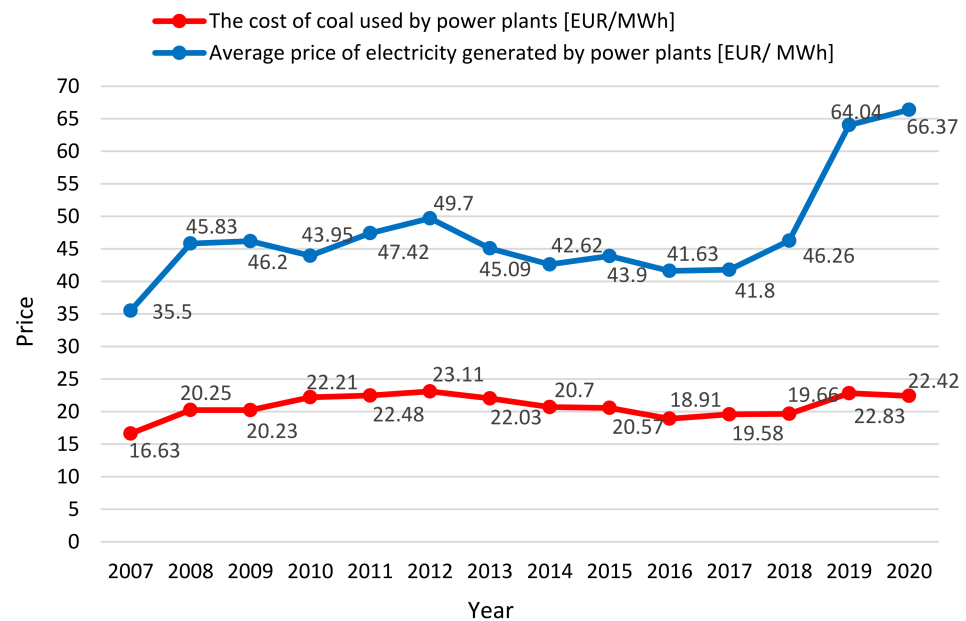


Figure 3. Average price of coal consumed by centrally dispatched generating units and average price of electricity generated by producers operating centrally generated generating units. Source: Own study based on [34,38].

In Poland, the price of electricity for households is regulated by the Energy Regulatory Office. As shown in Figure 4, in the years 2012–2018, the price remained at an almost constant level of approximately 0.12 EUR/kWh to drop to 0.1131 EUR/kWh in 2019 and increase to 0.1208 EUR/kWh in 2020. Forecasts for 2021 and beyond predict further growth, which may cause energy exclusion of a large group of lower-income families.

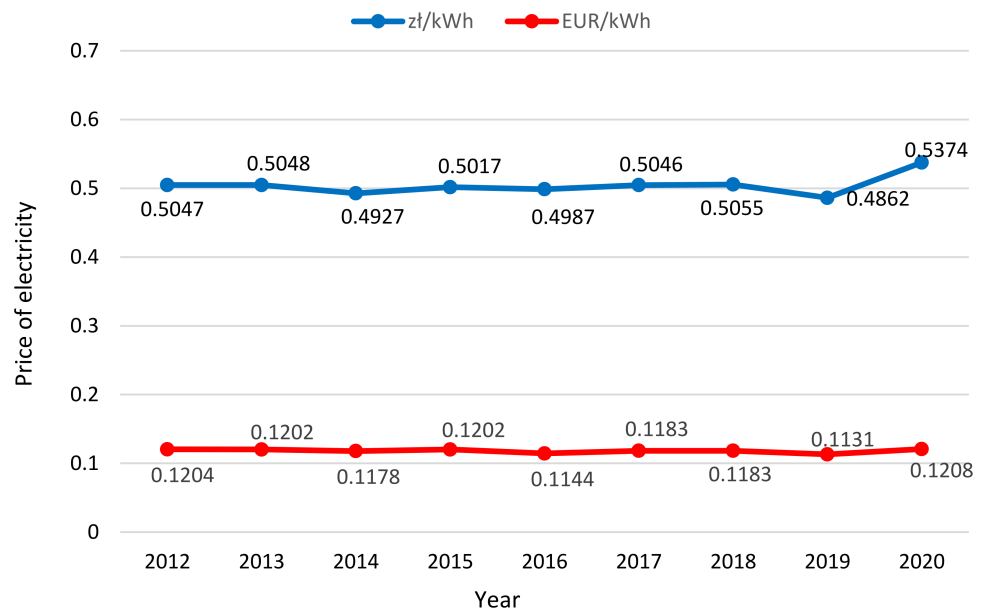


Figure 4. Average price of electricity for a household consumer, including the fee for the provision of electricity distribution services. Source: Own study based on [34,39].

In the EU countries, the price of electricity becomes more dependent on the price of CO₂ emission allowances than on the prices of energy resources such as coal and natural gas. The prices of allowances will increase because the climate package of the European Commission “Fit for 55” assumes that in 2030 CO₂ emissions will be reduced by 55%.

compared to 1990. In order for energy prices not to grow at such a rapid pace, all renewable energy sources should be used, with particular emphasis on biogas plants. They transform biodegradable waste, which is burdensome for people and the environment, into energy that does not increase the level of carbon dioxide in the atmosphere.

3. Biogas Plants in Europe

The biggest number of biogas plants can be found in Asia [9,17]. The plants there are usually small installations that provide an alternative source of energy for cooking and lighting in rural areas [40]. According to Pathak, a farm in India with four cows produces 2300 m³ of biogas, which replaces 316 L of kerosene and 5535 kg of hardwood, whose global warming potential (GWP) is 762 and 10,571 kg of CO₂, respectively [41]. In Poland, as in other EU countries, biogas is mainly used to produce electricity, which must have parameters that allow it to power professional energy networks. Therefore, the further part of the study will only consider the operating conditions of biogas plants in Poland and other EU countries.

The majority of biogas is produced in biogas plants from a variety of substrates. It is also collected in landfills. Biogas is a renewable energy source. It can be used in various ways, as shown in Figure 5. It is most often burned in cogeneration units with 35% electrical efficiency and 55% thermal efficiency. In the absence of heat recipients, a better way to use biogas could be its purification to the high-methane gas parameters specified in the standard [42] and injection into a gas network, compression allowing for the use in vehicle propulsion, or the production of hydrogen after reforming [43–47].

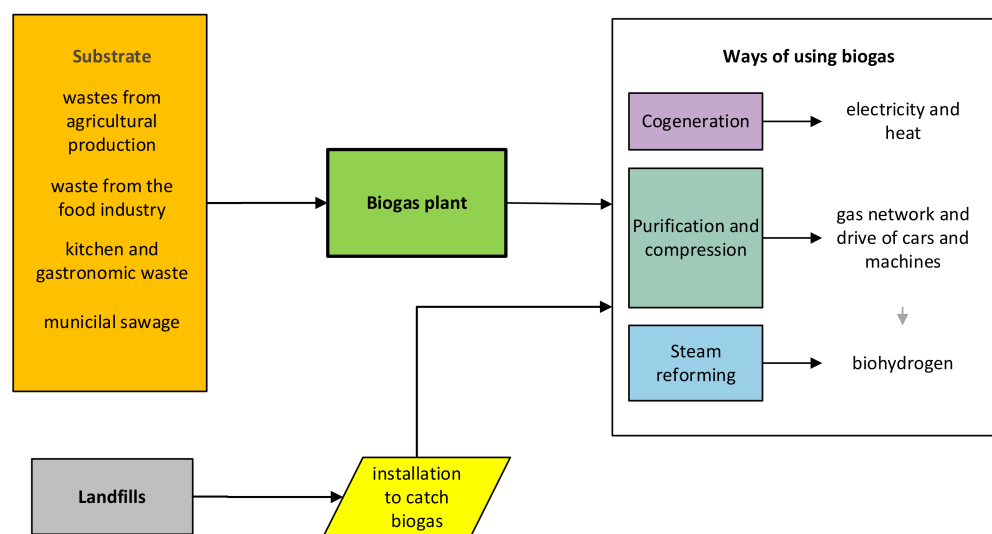


Figure 5. Sources of biogas and methods of its use.

Due to the substrates used, biogas plants are divided into [8]:

- agricultural—using biomass from target crops, manure from farm animals,
- waste from the agri-food industry,
- in sewage treatment plants—using organic waste separated from municipal sewage,
- on landfills—collecting biogas generated in landfills,
- municipal—processing selectively collected biodegradable municipal waste,
- mixed (other).

At the end of 2019, there were 18,943 biogas plants in Europe, which generated 167 TWh of electricity from 15.8 billion m³ of biogas [48]. Figure 6 shows that the majority of new biogas plants were built in 2010—4281, and 2015—2319.

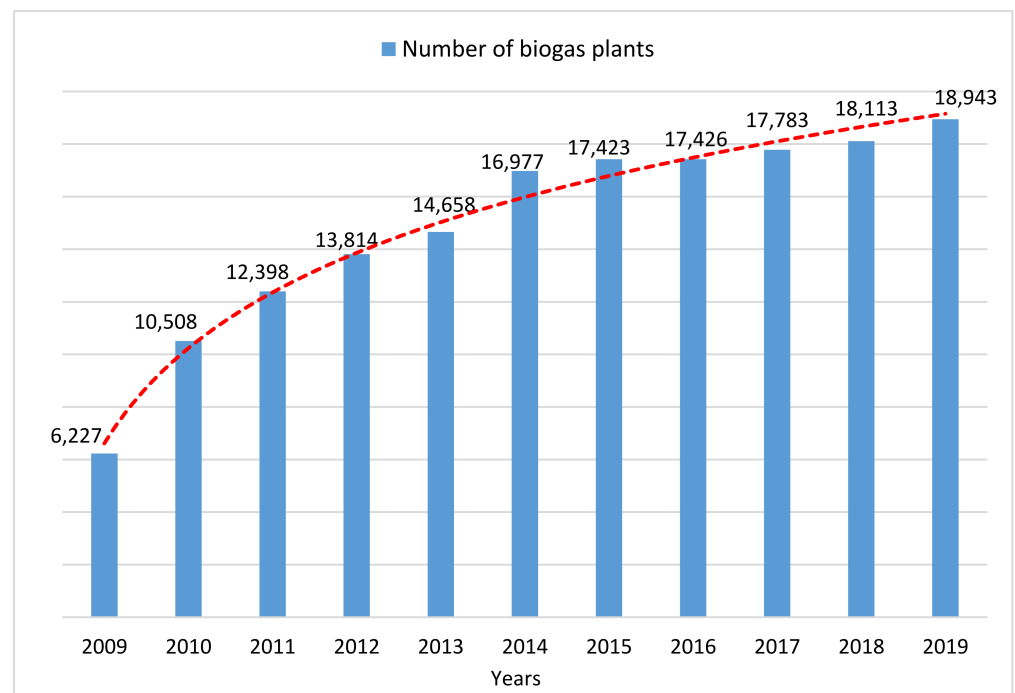


Figure 6. Number of biogas plants in Europe built in 2009–2019. Source: own study based on [49].

The largest biogas producer is Germany, where 11,454 biogas plants of all types were operating in 2018 (see Figure 7). The second country in terms of the number of biogas plants is Italy with 1620 installations. In other EU countries, there were fewer than 1000 biogas plants.

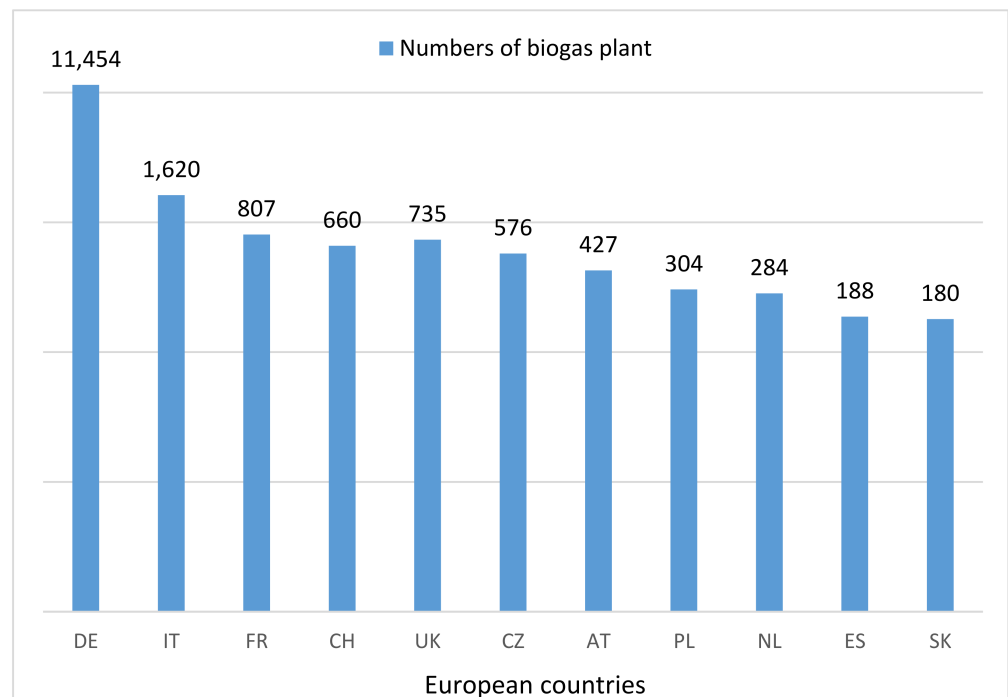


Figure 7. The number of biogas plants in 2018 in selected EU countries. Source: own study based on [50,51].

In 2020, biogas plants in Germany had a total capacity of 9.301 MW [52]. For the production of biogas in this country, very large amounts of maize silage are used, which

makes it possible to obtain large amounts of ethane biomass per mass unit of this substrate. This resulted in a reduction in the production of plants for animal feed and food for humans. As a result, food had to be imported from neighboring countries such as Poland. From the beginning of the 90s, mainly high-power biogas plants were established in Germany, which also caused soil sterilization and degradation of the natural environment. Since 2009, subsidies for small biogas plants have increased. New forms of bonuses for biogas plants producing biogas from manure were also introduced. As a result of this tactic, the deliberate cultivation of maize was limited and the variety of crops intended for energy purposes increased [53,54].

In Austria, the climatic conditions are similar to those in Germany. 427 biogas plants were operating there in 2019, including 190 agricultural plants, 100 at sewage treatment plants, and 15 landfills. The total reported energy production was 1.487 GWh. Since 2003, thanks to the Green Electricity Act, there has been an increase in biogas production on the Austrian market. Many installations were built between 2003 and 2005 and subsidies for their operation were granted for a period of 13 years [48].

In Italy, 2.5 billion m³ of biogas is produced in nearly 1600 biogas plants, which use waste and side products from the agri-food sector as substrates [55]. The oldest biogas plants in Italy are high power (over 5 MW). They are usually located in landfills and generate landfill gas. Most of them are agricultural biogas plants with a capacity of up to 1 MW. There is also a new type of installation powered by biodegradable waste, which most often has a capacity of up to 0.3 MW [56]. In Italy, 67% of biogas is produced from animal excrement and agricultural and forestry activities, the rest is biogas produced from sewage sludge. Most installations produce biogas which is burned in cogenerators. There are also drying and CO₂ biogas purification installations which produce biomethane with a composition similar to that of natural gas. The upgraded biogas is then injected into a natural gas grid or sent to a standalone compressed natural gas (CNG) distribution system. Italy is one of the few European countries where biomethane can be injected into the public gas grid (Green Gas Grids). According to Gatti et al., such a solution is more economically viable than the production of electricity and heat in the cogeneration process [57]. However, despite political incentives to promote the production of biomethane, such a solution is not very popular.

4. Biogas Plants in Poland

Poland is a European country with a high potential for biogas production, where three types of biogas plants operate: agricultural biogas plants, biogas plants in sewage treatment plants, and biogas plants in landfills. Almost all biogas produced is burned in cogeneration units producing electricity and heat. Electricity is sold to a power grid, while heat is used for fermentation processes, and the surplus is sold to consumers.

According to the data of the Energy Regulatory Office in Table 2, in 2018 there were 301 biogas plants in Poland (95 agricultural, 109 in sewage treatment plants, and 97 in landfills). The total capacity of cogeneration units installed totaled 235.317 MW. Over the two-year period, the number of biogas plants increased to 336 (agricultural plants 120, sewage treatment plants 114, landfills 102). In 2020, the installed capacity of cogeneration units stood at 254 MW. The increase in the number of biogas plants was not accompanied by an increase in the amount of energy produced. While in 2018 biogas plants produced 945,570 MW of electricity, in 2020 the amount reached only 800,899 MW. The largest decrease occurred in biogas plants in landfills (from 128,729 MW to 44,528 MW). In these biogas plants, the utilization rate of the installed capacity decreased from 23.57% in 2018 to 8.31% in 2020. This decrease can be associated with the effect of the obligation to collect biodegradable municipal waste in force since 2017 [58]. Biogas plants in wastewater treatment plants maintained fairly stable electricity production levels and the installed capacity utilization ratio oscillated around 40%. In the period discussed, the largest increase (25) occurred in agricultural biogas plants. The energy production in 2018 and 2019 was similar and exceeded 0.56 GWh. However, in 2020, it dropped to the level of 0.508 GWh.

Also, the power utilization ratio, which in agricultural biogas plants in 2018 and 2019 exceeded 64%, in 2020 decreased to 49.19% [59]. The difference in the amount of electricity produced may be related to the quantitative changes in the substrates used, as shown in Table 3. Differences in consumption may result from a different structure of crops and their different productivity. The reason for this may be that some substrates can be used more efficiently for other purposes (e.g., beet pulp can become feed for cattle).

Table 2. Summary of changes in the volume of electricity produced by biogas plants.

Biogas Plants	Year	Number of Installations	Installed Power [MW]		Energy Produced [MWh]	Use of Installed Power [%]
			Whole	Mean		
agricultural	2018	95	102.688	1.081	567,099	64.74
	2019	105	112.158	1.068	562,303	64.19
	2020	120	117.980	0.983	508,381	49.19
in sewage treatment plants	2018	109	70.281	0.661	249,443	40.52
	2019	113	72.108	0.638	279,741	44.29
	2020	114	74.820	0.656	247,990	37.84
in landfills	2018	97	62.348	0.643	128,729	23.57
	2019	98	59.396	0.606	65,173	10.32
	2020	102	61.195	0.600	44,528	8.31
together	2018	301	235.317	-	945,570	-
	2019	316	243.662	-	907,218	-
	2020	336	253.995	-	800,899	-

Sources: Own study based on [58].

Table 3. Consumption of substrates in agricultural biogas plants in 2018–2020.

No.	Substrates	Amount of Substrates Consumed [tons]		
		2018	2019	2020
	Distillation decoction			
1.	Fruit and vegetable residues	839,983	817,199	759,774
2.	Slurry	770,953	768,890	706,945
3.	Maize silage	757,555	733,452	759,774
4.	Beet pulp	482,427	420,712	491,870
5.	Technological sludges from the agri-food industry	291,648	251,507	209,816
6.	Dairy industry waste manure	179,801	187,812	227,148
7.	Manure	107,972	125,141	132,911
8.	Expired food	85,422	84,923	91,681
9.	Post-slaughter waste	73,610	98,406	117,184
10.	Food processing waste	66,847	104,438	85,777
11.	Plant waste mass	66,356	120,602	344,329
12.	Green fodder	54,657	42,114	42,247
13.	Fruits and vegetables	40,715	33,060	43,691
14.	Grass and cereal silage	38,397	30,350	45,926
15.	Poultry manure	25,419	22,334	26,708
16.	Gastric contents	22,525	19,741	27,532
17.	Cereal, grain waste	18,387	10,607	11,348
18.	Sludge from processing plant products	13,137	7346	18,971
19.		13,046	16,732	21,090
20.	Forage	12,879	8216	20,066
21.	Fats	11,909	14,602	25,580
22.	Straw	6849	4193	7753
23.	Fatty sediments	5171	4395	3462
24.	Catering waste	4920	6196	1528
25.	Protein waste, fat waste	3590	4120	3036
26.	Coffee	2224	10	3
27.	Liquid wheat residues	1436	1203	1101
28.	Yeast sediments	865	-	-
29.	Waste from plant oil production	616	10,129	12,232
30.	Glycerine	357	348	415
31.	Plant oils	204	6131	3891
32.	Production washings	150	419	1215
33.	Fusel oils	140	163	248
34.	Lecithin and soap mixture	40	1485	181
35.	Post-extraction pulp from the production of herbal pharmaceuticals	40	35	-
Total		4,000,249	3,957,741	4,409,055

Sources: Own study based on [60].

Table 3 shows that Polish agricultural biogas plants mainly process waste and maize silage from special purpose crops and it is about 10% of the mass of all substrates. The consumption of maize silage in 2018–2020 was almost unchanged as compared to 2016 when it stood at 439 tons [61]. In the discussed period, the share of out-of-date food in agricultural biogas plants increased by 62.8%, fat by 46.6%, and the amount of processed technological waste from the agri-food industry by 23%.

In Polish biogas plants, biogas is almost exclusively burned in cogeneration units, which produce electricity and heat. Between 2011–2015, agricultural biogas producers were required to provide the National Center for Agricultural Support with information on the amount of heat generated. This obligation was lifted by the provision of the Act of February 20th, 2015 on renewable energy sources [62]. The amounts of energy produced from biogas are very small. It is estimated that about 5 billion m³/year of biogas with the parameters of high-methane natural gas can be produced from waste generated in agriculture and the agri-food industry [63]. The number of launched biogas plants is small in relation to the assumptions adopted in 2010 in the document of the Council of Ministers entitled “Direction of Development of Agricultural Biogas Plants in Poland in 2010–2020” [64].

The document states that by the end of 2020 there will be an average of one biogas plant in each commune. The program failed as there are approximately 2200 municipalities in Poland. This situation in the development of agricultural biogas plants is caused by the low profitability of investments and their long cycle. Low profitability results, among other factors, from the adopted definition of agricultural biogas, which makes it difficult to use municipal biodegradable waste. The long cycle of investments is related to the problems of locating large biogas plants in provinces with a high percentage of small farms [63]. Changing the definition of agricultural biogas and increasing the number of small and agricultural micro-biogas plants is necessary to increase the production of biogas and to obtain biomethane from it. It would reduce the costs of electricity production caused by the need to purchase CO₂ emission rights. The potential of biogas production from farm waste.

In 2020, 508,381 MWh of electricity was obtained from biogas produced in agricultural biogas plants from 4,409,055 tons of substrate mass, as shown in Table 2. The substrates included 759,774 tons of slurry and 91,681,445 tons of manure. There is no information in Table 3 whether it was cattle or pig faeces. This is an important piece of information because Table 4 shows that the yield of biogas from 1 tons of pig manure is over 25% higher than that of 1 tons of cattle manure. Assuming that animal faeces used in 2020 were 50% from cattle and 50% from pigs, they allowed for the production of 32,165,138 m³ of biogas containing 19,299,083 m³ of biomethane. Combustion of this amount of gas in cogeneration units allowed for the production of 65,600,578 MWh of electricity, i.e., 12.9% of electricity generated in biogas plants.

The share of animal excrements in the total mass of substrates was very small because in 2020 the livestock bred in Poland counted 6,278,896 heads for cattle and 11,727,410 for pigs. It is not possible to estimate the amount of manure and slurry produced precisely because there are different types of barns and pigsties, and some cattle are grazed on pastures in summer. Furthermore, it is not possible to use 100% of the manure and slurry produced. On farms with several cows or several dozen porkers, the construction of a biogas plant would be an economic absurdity. The transport of manure from small farms to biogas plants installed on larger farms would be uneconomical due to transport costs and burdensome for the environment due to odors.

In order to estimate the supply of cattle manure that can be used in agricultural biogas plants, the population of dairy cows was analyzed. Due to the feeding method (feeding with Total Mix Ration mixtures) and milking technology, the herds of such cows spend most of their time in barns. In 2020, there were 2,125,694 such cows. In 2020, there were 2,125,694 such cowsheds with more than 20 heads house 1,482,747 cows, i.e., 69.75% of the dairy cows’ population. Cowsheds of this size have a litter-free system that allows them to collect the slurry. Using the data contained in Table 4, the potential possibilities

of biogas, biomethane, and energy production from slurry from barns with more than 20 dairy cows were assessed. The results of the calculations are summarized in Table 5. It shows that only the slurry produced in cowsheds with more than 20 dairy cows had the potential to produce 874,078 MWh of electricity. Such an amount is much more than what the agricultural biogas plants produced in 2020 from all substrates. By burning biogas in cogeneration units, it is also possible to obtain a net 961,436 MWh of thermal energy. In total, the slurry from these barns can be used to obtain 1,835,514 MWh of electricity and heat. The production of biogas (and thus electricity and heat) may be higher because the barns, apart from dairy cows, also house heifers and calves which are not included in a dairy cow herd.

Table 4. Potential for the production of biogas, electricity, and heat from 1 ton of biodegradable waste.

Substrate	Biogas Yield [m ³]	Methane Content [%]	Biomethane Yield [m ³]	Electricity Yield [kWh]	Amount of Heat [kWh]		
					Produced	On Fermentation	For Sale
Cattle slurry	27	60	16.20	52.73	82.86	24.86	58.00
Pig slurry	45	65	29.25	95.21	149.61	44.88	104.73
Cattle manure	45	60	27.00	87.89	138.11	41.43	96.67
Pig manure	60	60	36.00	117.18	184.14	55.24	128.90
Chicken manure	80	60	48.00	156.24	245.52	73.66	171.86
Maize silage	185	55	101.75	331.20	520.45	156.14	364.32
Grass silage	185	55	101.75	331.20	520.45	156.14	364.32
Food remnants and expired food products:	Min. 50	55	30.00	97.65	153.45	46.04	107.42
	Max 480	55	264.00	859.30	1350.36	405.11	946.25
Grocery store waste	Min. 45	65	29.25	95.21	149.61	44.88	104.73
	Max. 110	65	71.50	232.70	365.72	109.72	256.01
Stomach content of pigs	40	65	26.00	84.63	132.99	39.90	93.09
Content of the rumen of cows	40	60	24.00	78.12	122.76	36.83	85.93
Mown grass	175	60	105.00	341.78	537.08	161.12	375.95

Source: Own study based on [65].

Table 5. Potential for biogas, biomethane and energy production from cattle slurry.

Description	Unit	Amount
Number of cows in barns	item	1,482,747
Weight of slurry produced per cow/year	ton	25
Annual mass of slurry produced	ton	16,576,482
Biogas yield from slurry	m ³ /ton	27
Annual biogas production	m ³	414,412,060
Methane content in biogas	%	60
Annual production of methane	m ³	248,647,236
Electricity yield	kWh/ton	52.73
Annual electricity production	kWh	874,077,916
	MWh	874,078
Thermal energy yield	kWh/ton	82.86
Annual production of thermal energy	kWh	1,131,603,768
	MWh	1,131,604
Thermal energy for fermentation	MWh	170,168
Thermal energy for sale	MWh	961,436

In Poland, the Emissions Trading System is serviced by the National Center for Emissions Management (KOBIZE). It publishes data on the calorific value and the CO₂ emission factor which are used for reporting under the Emissions Trading Scheme. These data relate to fossil fuels used in various activities. The emission factors for fuels used in utility

power plants and CHP plants are as follows: hard coal-93.63 kg/GJ (337.04 kg/MWh = 0.33704 ton/MWh), lignite-107.15 kg/GJ (385, 71 kg/MWh = 0.38571 ton/ MWh), natural gas 55.41 kg/GJ (199.46 kg/MWh = 0.19946 ton/MWh) [66]. For the calculations, the price of CO₂ emission allowances was adopted, which on 12 December 2021 amounted to PLN 381.78/ton (82.76 EU/ton). Table 6 presents the calculated amount of reduction of the production costs of such amount of electricity and heat for sale that can be obtained from biogas produced from slurry from the analyzed dairy herds (see Table 5).

Table 6. Reduction of the costs of electricity and heat production from biogas in relation to fossil fuels.

Description	Unit	Coal	Lignite	Natural Gas
CO ₂ emission factor	ton/MWh	0.33704	0.38571	0.19946
Electricity				
Production	MWh	874,078	874,078	874,078
CO ₂ emissions	ton	294,599	337,141	174,344
Cost of CO ₂ emission allowances	zł	112,472,101	128,713,548	66,560,899
	EUR	24,381,034	27,901,758	14,428,676
Thermal energy for sale				
Production	MWh	961,436	961,436	961,436
CO ₂ emissions	ton	324,042	370,835	191,768
Cost of CO ₂ emission allowances	zł	123,712,903	141,577,569	73,213,196
	EUR	26,817,748	30,690,344	15,870,722

The reduction of electricity production costs shown in Table 6 is possible under the current legal status. The reduction of heat production costs will be possible after the obligation to provide the National Agricultural Advisory Center with information on the amount of heat produced, which was abolished in 2015, is restored [63]. The level of thermal energy cost reduction will also depend on whether all the heat generated is used. Due to the fact that all types of biogas plants are located away from human settlements, there are problems with using all thermal energy from cogeneration.

5. Conclusions

The role of renewable energy sources in the energy mix must increase. The growing demand for electricity and heat cannot be met only by fossil fuels, the combustion of which increases the amount of CO₂ in the atmosphere. Renewable energy sources such as solar and wind have enormous potential, but due to their volatility, they must be supplemented by energy storage and more stable sources. Biogas plants, in which the biogas produced can be burned on an ongoing basis in the cogeneration process, but also stored, purified to the parameters of natural gas, or converted into hydrogen (biohydrogen) in reforming processes, are considered to be a stable source. Purified biogas can be compressed and used in combustion engines of agricultural vehicles and agricultural machines. Biohydrogen could be used for the same purposes as well as in zero emission fuel cells.

In Polish conditions, agricultural biogas plants located on farms engaged in animal husbandry have the greatest potential to increase biogas production. In such biogas plants, manure is transported directly from the barns to the installation, which reduces the costs of waste transport and odor emissions. The production of electricity and heat in combination with the production of electricity from photovoltaic panels can make a livestock farm self-sufficient in terms of energy and even bring additional income from their sale. Operating and servicing a biogas plant is also an opportunity to increase non-agricultural employment in rural areas.

The possibility of further development of biogas plants and the increase of the production of biogas depend largely on the change of regulations. Currently, they do not allow agricultural biogas plants to use municipal kitchen waste as substrates. Their addition to

the slurry would increase the biogas yield (see Table 4). This solution is used, for example, in Denmark in Central Anaerobic Digestion (CAD) biogas plants.

The production of biogas, a renewable energy carrier, from biodegradable waste can also solve the problem of waste management, becoming the best example of a circular economy.

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References

1. Jeon, E.C.; Myeong, S.; Sa, J.W.; Kim, J.; Jeong, J.H. Greenhouse gas emission factor development for coal-fired power plants in Korea. *Appl. Energy* **2010**, *87*, 205–210. [CrossRef]
2. Dieterich, B.; Finnan, J.; Hochstrasser, T.; Müller, C. The greenhouse gas balance of a dairy farm as influenced by the uptake of biogas production. *BioEnergy Res.* **2014**, *7*, 95–109. [CrossRef]
3. Jeffry, L.; Ong, M.Y.; Nomanbhay, S.; Mofijur, M.; Mubashir, M.; Show, P.L. Greenhouse gases utilization: A review. *Fuel* **2021**, *301*, 121017. [CrossRef]
4. Horowitz, C.A. Paris Agreement. *Int. Leg. Mater.* **2016**, *55*, 740–755. [CrossRef]
5. United Nations. Paris Agreement. In *Proceedings of the 21st United Nations Framework Convention on Climate Change, Paris, France, 30 November–13 December 2015*; United Nations: New York, NY, USA, 2016.
6. Kreidenweis, U.; Breier, J.; Herrmann, C.; Libra, J.; Prochnow, A. Greenhouse gas emissions from broiler manure treatment options are lowest in well-managed biogas production. *J. Clean. Prod.* **2021**, *280*, 124969. [CrossRef]
7. Dictionary of Environmental Protection. Available online: <https://www.teraz-srodowisko.pl/slownik-ochrona-srodowiska/> (accessed on 15 October 2021).
8. Nikiciuk, M. Ecological and Progrowth Potential of Agricultural Biogas Sector in Podlaskie Voivodship. In *Współczesne Problemy Ekonomiczne w Badaniach Młodych Naukowców. Analizy Makro-i Mezoekonomiczne*; Polskie Towarzystwo Ekonomiczne: Białystok, Poland, 2019; Volume 3, pp. 98–117.
9. Tagne, R.F.T.; Dong, X.; Anagho, S.G.; Kaiser, S.; Ulgiati, S. Technologies, challenges and perspectives of biogas production within an agricultural context. The case of China and Africa. *Environ. Dev. Sustain.* **2021**, *23*, 14799–14826. [CrossRef]
10. Biznez Alert. Metan z Kopalni w Brzeszczach Będzie Źródłem Prądu i Ciepła. Available online: <https://biznesalert.pl/metan-brzeszcze-energia-cieplo> (accessed on 17 October 2021).
11. Kwaśny, J.; Banach, M.; Kowalski, Z. Technologies of biogas production from different sources—A review. *Czas. Tech.* **2012**, *17*, 83–102.
12. Igliński, B.; Piechota, G.; Iwański, P.; Skarzatek, M.; Pilarski, G. 15 Years of the Polish agricultural biogas plants: Their history, current status, biogas potential and perspectives. *Clean Technol. Environ. Policy* **2020**, *22*, 281–307. [CrossRef]
13. Vlyssides, A.; Mai, S.; Barampouti, E.M. Energy Generation Potential in Greece From Agricultura Residues and Livestock Manure by Anaerobic Digestion Technology. *Waste Biomass Valorization* **2015**, *6*, 747–757. [CrossRef]
14. Augustyn, G.; Mikulik, J.; Rumin, R.; Szyba, M. Energy Self-Sufficient Livestock Farm as the Example of Agricultural Hybrid Off-Grid System. *Energies* **2021**, *14*, 7041. [CrossRef]
15. Zepter, J.M.; Gabderakhmanova, T.; Andreassen, K.M.; Boesgaard, K.; Marinelli, M. Biogas Plant Modelling for Flexibility Provision in the Power System of Bornholm Island. In *Proceedings of the 55th International Universities Power Engineering Conference (UIPEC), Turin, Italy, 1–4 September 2020*; Institute of Electrical and Electronics Engineers: Piscataway, NJ, USA, 2020; pp. 1–6.
16. Ramos-Suárez, J.L.; Ritter, A.; González, J.M.; Pérez, A.C. Biogas from animal manure: A sustainable energy opportunity in the Canary Islands. *Renew. Sustain. Energy Rev.* **2019**, *104*, 137–150. [CrossRef]
17. Duan, N.; Lin, C.; Wang, P.; Meng, J.; Chen, H.; Li, X. Ecological analysis of a typical farm-scale biogas plant in China. *Front. Earth Sci.* **2014**, *8*, 375–384. [CrossRef]
18. Balda, M.C.; Furubayashi, T.; Nakata, T. A novel approach for analyzing the food-energy nexus through on-farm energy generation. *Clean Technol. Environ. Policy* **2017**, *19*, 1003–1019. [CrossRef]
19. Otoma, S.; Diaz, R. Life-cycle greenhouse gas emissions and economic analysis of alternative treatments of solid waste from city markets in Vietnam. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 70–87. [CrossRef]

20. Zhang, Y.; Banks, C.J.; Heaven, S. Anaerobic digestion of two biodegradable municipal waste streams. *J. Environ. Manag.* **2012**, *104*, 166–174. [\[CrossRef\]](#)
21. Barros, R.M.; Tiago Filho, G.L.; da Silva, T.R. The electric energy potential of landfill biogas in Brazil. *Energy Policy* **2014**, *65*, 150–164. [\[CrossRef\]](#)
22. Jeswani, H.K.; Smith, R.W.; Azapagic, A. Energy from waste: Carbon footprint of incineration and landfill biogas in the UK. *Int. J. Life Cycle Assess.* **2013**, *18*, 218–229. [\[CrossRef\]](#)
23. Glivin, G.; Sekhar, S.J. Waste potential, barriers and economic benefits of implementing different models of biogas plants in a few Indian educational institutions. *BioEnergy Res.* **2020**, *13*, 668–682. [\[CrossRef\]](#)
24. Wu, X.; Wu, F.; Tong, X.; Wu, J.; Sun, L.; Peng, X. Emergy and greenhouse gas assessment of a sustainable, integrated agricultural model (SIAM) for plant, animal and biogas production: Analysis of the ecological recycle of wastes. *Resour. Conserv. Recycl.* **2015**, *96*, 40–50. [\[CrossRef\]](#)
25. Kiselev, A.; Magaril, E.; Magaril, R.; Panepinto, D.; Ravina, M.; Zanetti, M.C. Towards circular economy: Evaluation of sewage sludge biogas solutions. *Resources* **2019**, *8*, 91. [\[CrossRef\]](#)
26. Kapoor, R.; Ghosh, P.; Kumar, M.; Sengupta, S.; Gupta, A.; Kumar, S.; Vijay, V.; Kumar, V.; Vijay, V.K.; Pant, D. Valorization of agricultural waste for biogas based circular economy in India: A research outlook. *Bioresour. Technol.* **2020**, *304*, 123036. [\[CrossRef\]](#)
27. Cruz, I.A.; Andrade, L.R.S.; Bharagava, R.N.; Nadda, A.K.; Bilal, M.; Figueiredo, R.T.; Ferreira, L.F.R. Valorization of cassava residues for biogas production in Brazil based on the circular economy: An updated and comprehensive review. *Clean. Eng. Technol.* **2021**, *4*, 100196. [\[CrossRef\]](#)
28. Moore, P.A.; Miles, D.; Burns, R.; Pote, D.; Berg, K.; Choi, I.H. Ammonia emission factors from broiler litter in barns, in storage, and after land application. *J. Environ. Qual.* **2011**, *40*, 1395–1404. [\[CrossRef\]](#)
29. Meyer-Aurich, A.; Schattauer, A.; Hellebrand, H.J.; Klauss, H.; Plochl, M.; Berg, W. Impact of uncertainties on greenhouse gas mitigation potential of biogas production from agricultural resources. *Renew. Energy* **2012**, *37*, 277–284. [\[CrossRef\]](#)
30. European Commission. Emissions Cap and Allowances. Available online: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_pl (accessed on 10 November 2021).
31. European Commission. Auctioning. Available online: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/auctioning_pl (accessed on 10 November 2021).
32. Polskie Sieci Elektroenergetyczne. Settlement Price of CO₂ Emission Allowances. Available online: <https://www.pse.pl/web/pse-eng/data/balancing-market-operation/basic-price-and-cost-indicators/settlement-price-of-co2-emission-allowances> (accessed on 10 November 2021).
33. Energy Regulatory Office. Średnia Kwartałna Cena Energii Elektrycznej Sprzedanej na Zasadach Innych Niż Wynikające z Art. 49a ust. 1 i 2 Ustawy—Prawo Energetyczne. Available online: <https://www.ure.gov.pl/pl/energia-elektryczna/ceny-wskazniki/7851,Srednia-kwartałna-cena-energii-elektrycznej-sprzedanej-na-zasadach-innych-niz-wy.html> (accessed on 14 November 2021).
34. Eur-Pln. Available online: <https://eur-pln.pl/> (accessed on 10 January 2022).
35. Centrum Informacji o Rynku Energii. Uprawnienia do Emisji CO₂ Stanowią Już 59% Cen Energii Elektrycznej. Available online: <https://www.cire.pl/artykuly/o-tym-sie-mowi/uprawnienia-do-emisji-co2-stanowia-juz-59-ceny-energii-elektrycznej> (accessed on 10 January 2022).
36. Energy Regulatory Office. Od Stycznia za Prąd Zapłacimy o 21 zł Więcej. Available online: <https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/9963,Od-stycznia-za-prad-zaplacimy-o-21-zl-wiecej.html> (accessed on 10 January 2022).
37. Woźniak, J. Influence of the cost of CO₂ emission allowance purchases on the increase in electricity prices in Poland. *Energy Policy* **2012**, *15*, 139–149.
38. Energy Regulatory Office. Średnioważony Koszt Węgla, Zużywanego Przez Jednostki Wytwórcze Centralnie Dysponowane Oraz Średnia Cena Energii Elektrycznej Wytworzonej Przez Wytwórców Eksploatujących Jednostki Wytwórcze Centralnie Dysponowane w Danym Roku. Available online: <https://www.ure.gov.pl/pl/energia-elektryczna/ceny-wskazniki/7854,Sredniowazony-koszt-wegla-zuzywanego-przez-jednostki-wytworcze-centralnie-dyspon.html> (accessed on 14 November 2021).
39. Energy Regulatory Office. Średnia Cena Energii Elektrycznej dla Gospodarstw Domowych. Available online: <https://www.ure.gov.pl/pl/energia-elektryczna/ceny-wskazniki/7853,Srednia-cena-energii-elektrycznej-dla-gospodarstw-domowych.html> (accessed on 14 November 2021).
40. Goel, S.; Sharma, R. Optimal sizing of a biomass-biogas hybrid system for sustainable power supply to a commercial agricultural farm in northern Odisha, India. *Environ. Dev. Sustain.* **2019**, *21*, 2297–2319. [\[CrossRef\]](#)
41. Pathak, H.; Jain, N.; Bhatia, A.; Mohanty, S.; Gupta, N. Global warming mitigation potential of biogas plants in India. *Environ. Monit. Assess.* **2009**, *157*, 407–418. [\[CrossRef\]](#)
42. PN-C-04750: 2011 Standard; Gaseous Fuels. Classification, Designation and Requirements. Polish Standardization Committee: Warsaw, Poland, 2011; ICS 75.160.30.
43. Aryal, N.; Kvist, T. Alternative of biogas injection into the Danish gas grid system—A study from demand perspective. *ChemEngineering* **2018**, *2*, 43. [\[CrossRef\]](#)
44. Fernández-González, J.M.; Martín-Pascual, J.; Zamorano, M. Biomethane injection into natural gas network vs composting and biogas production for electricity in Spain: An analysis of key decision factors. *Sustain. Cities Soc.* **2020**, *60*, 1–16. [\[CrossRef\]](#)

45. Persson, M.; Jönsson, O.; Wellinger, A. Biogas upgrading to vehicle fuel standards and grid injection. *IEA Bioenergy Task* **2006**, *37*, 102242.
46. Gregorie, E.F.; Lamb, J.J.; Lien, K.M.; Pollet, B.G.; Burheim, O.S. Hydrogen and Biogas. In *Micro-Optics and Energy*; Springer: Cham, Switzerland, 2020; pp. 131–155.
47. Nahar, G.; Mote, D.; Dupont, V. Hydrogen production from reforming of biogas: Review of technological advances and an Indian perspective. *Renew. Sustain. Energy Rev.* **2017**, *76*, 1032–1052. [CrossRef]
48. European Biogas Association. Available online: https://www.europeanbiogas.eu/wpcontent/uploads/2021/01/EBA_StatisticalReport2020_abridged.pdf (accessed on 12 November 2021).
49. European Biogas Association. Available online: <https://www.europeanbiogas.eu/wp-content/uploads/2021/01/Annual-Report-2020-new.pdf> (accessed on 16 November 2021).
50. Sustainable Agribusiness Forum. European Biogas Association Statistical Report. Available online: <https://saf.org.ua/en/library/989/> (accessed on 24 October 2021).
51. The World Bank. Available online: <https://datatopics.worldbank.org> (accessed on 24 October 2021).
52. Statista. Cumulative Capacity of Biomass Power Plants in Germany from 1990 to 2020. Available online: <https://www.statista.com/statistics/449300/biomass-plants-cumulative-capacity-germany/> (accessed on 12 November 2021).
53. Yang, X.; Liu, Y.; Thrän, D.; Bezama, A.; Wang, M. Effects of the German Renewable Energy Sources Act and environmental, social and economic factors on biogas plant adoption and agricultural land use change. *Energy Sustain. Soc.* **2021**, *11*, 6. [CrossRef]
54. Bischof, A. Insights to the internal sphere of influence of peasant family farms in using biogas plants as part of sustainable development in rural areas of Germany. *Energy Sustain. Soc.* **2012**, *2*, 2–9. [CrossRef]
55. Murano, R.; Maisano, N.; Selvaggi, R.; Pappalardo, G.; Pecorino, B. Critical Issues and Opportunities for Producing Biomethane in Italy. *Energies* **2021**, *14*, 2431. [CrossRef]
56. International Energy Agency. Biogas and Biometane in Italy. Available online: https://iea.blob.core.windows.net/assets/ced91034-a399-404e-b8be-dea83b9b3187/1.4_PelliniAlessandro_13Jul2021.pdf (accessed on 15 November 2021).
57. Bortoluzzi, G.; Gattia, M.; Sognia, A.; Consonnia, S. Bio-methane production from agricultural resources in the Italian scenario: Technoeconomic analysis of water wash. *Chem. Eng.* **2014**, *37*, 259–264.
58. Energy Regulatory Office Departament Komunikacji Społecznej. Available online: <https://www.ure.gov.pl/pl/urzed/informacje-ogolne/departamenty/6664,Departament-Komunikacji-Spolecznej.html> (accessed on 28 November 2021).
59. Internetowy System Aktów Prawnych. Regulation of the Minister of the Environment of 15 December 2017 on the Levels of Storage Limitations for the Mass of Biodegradable Municipal Waste. Journal of Laws of 2017, Item 2412. Available online: <http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20170002412/O/D20172412.pdf> (accessed on 16 November 2021).
60. Biuletyn Informacji Publicznej. Dane Dotyczące Działalności Wytwórców Biogazu Rolniczego w Latach 2011–2020. Available online: <https://bip.kowr.gov.pl/informacje-publiczne/odnawialne-zrodla-energii/biogaz-rolniczy/dane-dotyczace-dzialalnosci-wytworcow-biogazu-rolniczego-w-latach-2011-2020> (accessed on 12 November 2021).
61. Gradziuk, P. Potential and forecasts for the use of agricultural biogas in Poland. *Ann. Assoc. Agric. Agribus. Econ.* **2017**, *19*, 64–70. [CrossRef]
62. Internetowy System Aktów Prawnych. The Act of February 20, 2015 on Renewable Energy Sources. Journal of Laws of 2015, Item. Available online: <http://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20150000478/U/D20150478Lj.pdf> (accessed on 19 October 2021).
63. Szyba, M. Spatial planning and the development of renewable Energy sources in Poland. *Acta Innov.* **2021**, *39*, 5–14. [CrossRef]
64. Polska Izba Gospodarcza Energetyki Odnawialnej i Rozproszonej. Document of the Council of Ministers, Kierunki Rozwoju Biogazowni Rolniczych w Polsce w Latach 2010–2020 (Directions of Development of Agricultural Biogas Plants in Poland in 2010–2020), Warszawa, 2010. Available online: <https://www.pigeor.pl/media/js/kcfinder/upload/files/Kierunki-Rozwoju-Biogazowni-Rolniczych-w-Polsce-na-lata-2010--2020.pdf> (accessed on 21 October 2021).
65. Institute of Renewable Energy. Biogaz Produkcja Wykorzystywanie. Available online: https://www.ieo.pl/dokumenty/obszary_badan/Biogaz%20-%20Produkcja%20Wykorzystywanie.pdf (accessed on 15 November 2021).
66. The National Centre for Emissions Management (KOBIZE). Wartości Opałowe (WO) i Wskaźniki Emisji CO₂ (WE) w Roku 2018 do Raportowania w Ramach Systemu Handlu Uprawnieniami do Emisji za Rok 2021. Available online: https://www.kobize.pl/uploads/materialy/materialy_do_pobrania/monitorowanie_raportowanie_weryfikacja_emisji_w_eu_ets/WO_i_WE_do_monitorowania-ETS-2021.pdf (accessed on 10 November 2021).