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Analysis of biogas from sewage sludge digestion in terms of diversification in the natural gas production structure in Poland

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ABSTRACT

The intensive development of sewerage networks and municipal wastewater treatment plants observed in Poland in recent years has led to the generation of large quantities of municipal sewage sludge. At present, only nearly 140 out of about 2,500 wastewater treatment plants have full sludge digestion facilities. This means that only 6% of wastewater treatment plants operating in Poland produce biogas that can be used for energy purposes. The total volume of digesters at all wastewater treatment plants is estimated at 800,000–900,000 m^3. The aim of this paper is to analyse the energy potential of biogas generated in the processes of methane fermentation of sewage sludge in the context of the EU energy and climate policy while strengthening national energy security. Thus the following research questions have been formulated: To what extent can biogas support the implementation of the EU energy and climate policy in Poland? What are the barriers to biogas development from sewage sludge digestion in Poland? The research hypothesis was defined that the production of biogas from sewage fermentation will contribute to increasing the energy security of the country by diversifying the natural gas production structure and increasing the stability of the energy system.

Keywords: Biogas; Methane fermentation; Natural gas; Climate policy; Energy security

1. Introduction

In the process of energy transformation, one of the main goals of which is to reduce greenhouse gas emissions and neutralise the correlation between economic development and the use of high-carbon fossil fuels, renewable energy sources and alternative fuels play an important role [1–3].

One such fuel is biogas, that is, a renewable energy carrier created as a result of organic matter degradation by natural micro-organisms under anaerobic conditions. As a low-carbon substitute for fossil natural gas, biogas can be used to generate electricity, heat or, for example, as a biofuel in transport. The implementation of various support systems, the use of renewable resources, promotes the development of biogas plants [4].

Analysing the development potential of the biogas market in Poland so far in relation to the structure of substrates used, it is formed as follows: agricultural waste has by far the biggest potential, much smaller, decreasing landfill waste, and a relatively small but constantly increasing potential is shown by sewage sludge [5,6]. The dominance of waste biogas technology in Poland is the subject of many scientific studies [5,7–12]. The volume of organic

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waste from agricultural activities is highly diversified and relatively abundant, and Polish agriculture is currently undergoing a transformation process in line with the European climate policy [13–15]. There is a research gap in the scope of scientific studies related to biogas production from sewage sludge, whose potential is constantly increasing due to the dynamic development of water and sewage infrastructure [16]. There are some analyses concerning the optimisation of biogas production in Polish wastewater treatment plants [17]; however, there is a lack of current research concerning the development of this kind of infrastructure, in the aspect of revealing the barriers to its development and supporting the implementation of the EU energy and climate policy. Considering the above aspects, the following research questions were formulated. To what extent can biogas support the implementation of the EU energy and climate policy in Poland? What are the barriers for biogas development from sewage sludge digestion in Poland? At the same time, a research hypothesis was formulated that the production of biogas from sewage fermentation will contribute to increasing the energy security of the country by diversifying the natural gas production structure and increasing the stability of the energy system.

2. Determinants of the European Union's energy and climate policy

The EU energy sector, for years based on centralised, conventional sources of energy production, is characterised by high import dependence, insufficient diversification of energy supply and production sources, low rate of progress in energy efficiency, relatively high and unstable energy prices, the need for greater transparency in energy markets, and insufficient development of energy interconnections between Member States [18]. Therefore, it affects the environment and has insufficient system stability due to the development of renewable energy sources [19,20]. The growing ambitions of the EU's energy and climate policy are forcing EU countries to implement the energy transition. This means not only moving away from fossil fuels to renewable energy sources, but also leads to a change in thinking and management of the energy sector, with the simultaneous development of distributed generation and a greater role for society not only as a consumer, but also as an energy producer [21,22]. Nowadays, a special emphasis in political activities carried out in the European Union is placed on pro-climate conditions. The culmination of the move towards a carbon-free energy industry and related markets is the Communication from the Commission to the European Parliament, the Council of Europe, the Council of the Economic and Social Committee, and the Committee of the Regions – "A European Green Deal", published at the end of 2019. It assumes that by 2050 Europe (including the European Union Member States and the European countries aspiring to join the EU which cooperate with them within the framework of programmes for harmonisation of climate and energy activities, as well as other third countries) will achieve 100% net zero-emission status, becoming the first continent in the world to be completely climate-neutral [23].

In order to achieve these ambitious climate and energy targets, almost all sectors of the European economy will be transformed. According to the recommendations of the "European Green Deal" strategy, the priority towards decarbonisation will be the transformation of heavy energy-intensive industries, resource-intensive sectors, digital technologies, construction, heating, transport, agriculture, and electricity and heat generation structure [23,24].

In the process of diversification of energy production sources, renewable energy sources will play an important role, including: wind energy, solar radiation, geothermal energy, ambient energy, tidal and wave energy, hydropower, and biomass and biogas [25].

3. Importance of natural gas for EU countries

At present, in many regions of Europe, the technologies ensuring continuity of energy supply are high-emission coal-fired power plants; low-emission nuclear power plants, which cause social controversy; and gas-fired power plants, which are much less harmful to the environment compared to other conventional power plants [26–28]. In the transition period, during the shift from high-carbon conventional energy towards less carbon-intensive unconventional sources, natural gas and its synthetic substitute forms will most probably constitute an element of transition fuel in the process of European energy transformation [29,30]. Natural gas in the EU Member States will potentially contribute to increasing the efficiency of the energy production process and also support the reduction of pollutant emissions, in the transport sector, for example [31,32]. The literature emphasises that infrastructure, which in the short term will bring many benefits both in terms of security, finance and climate conditions, in the long term may prove to be disadvantageous, maintaining the operation of the fossil fuel market and thus limiting the development of the RES market [30]. With regard to natural gas, certain political and strategic conditions also speak against it. The European natural gas sector is characterised by: growing demand for the raw material – a 2018–2019 increase of 4.2% and particularly unfavourable, low, satisfying about 20% of the demand, constantly decreasing production – a 2018–2019 decrease of about 11% and also a high rate of imports – a 2018–2019 increase of 4.2%, including nearly half from the east [33,34] – which in the past has been associated with unexpected interruptions in energy supply, and also in many cases results in prices unrelated to current market determinants [35,36].

In addition, the growing demand for transitional blue fuel, resulting from the desire to stabilise the energy system, despite the implementation of a policy of diversification of supply sources, support from the Connecting Europe Facility and similar programmes, as well as the continuous development of the LNG infrastructure, will continue to direct European countries to depend on supplies from third countries [37]. It will also affect the competitiveness of the European economy and, above all, make it less secure. The shift away from fossil fuels towards renewable energy, which is in line with the "European Green Deal", also creates a risk of so-called "stranded assets". The extensive gas infrastructure in an era of transitioning away from fossil fuel natural gas will potentially remain completely abandoned and may be highly capital- and time-consuming to modernise [38,39].

4. Role of biogas in the transformation of the European energy sector

As demonstrated in the Green New Deal strategy, in parallel with the exploitation of fossil natural gas, actions will be taken across the EU to support the decarbonisation of the gas sector, including through increased support for the development of low-carbon gases, the development of a far-reaching concept for a competitive carbon-free gas market, and tackling harmful methane emissions [23].

One renewable gas that perfectly fits into the assumptions of the European strategy for green transformation is biogas, which is produced as a result of the transformation of organic compounds by anaerobic micro-organisms in methane fermentation [40–44]. Suitable conditions for proper biogas formation are constant optimum temperature, anaerobic conditions, and sufficient availability of organic matter [43]. Biogas is a mixture of gases whose proportions fluctuate considerably. It consists mainly of methane, carbon dioxide and small amounts of hydrogen sulphide, nitrogen, oxygen and hydrogen [45–48] (Table 1).

As a biofuel produced by processing used organic matter coming from, among other things, agricultural waste, landfill gas recovery and sewage sludge, as a component of a closed-cycle economy, it shows favourable energy properties. The calorific value of biogas can be compared to that of coal, which means that it is possible to replace part of the energy production with solid fuels and use biogas obtained in an environmentally friendly way. Table 2 presents the basic fuels used for energy production and their calorific values and conversion of these values in relation to biogas [44,49].

The physical and strategic conditions of biogas make it an excellent substitute for fossil natural gas. First of all, in comparison to conventional fuels, the use of renewable gaseous fuel is characterised by significantly lower pollutant emissions (according to the European Biogas Association, the biogas sector may contribute to a reduction in global greenhouse gas emissions by about 10%–13%) [50]. In addition, from a climate-neutral perspective, the environmental priority of biogas production is to reduce emissions of methane, a highly damaging gas that has a strong greenhouse effect. In addition, biogas upgrading yields biomethane, which due to its purity can be injected into the grid and used as a renewable substitute for natural gas [51,52]. It also justifies the current extension of the gas infrastructure and eliminates the possibility of generating so-called "stranded assets" resulting from potential abandonment of the use of blue fuel. Biogas also benefits from the structure of the products used in its production process, which makes it a versatile raw material and independent of the abundance of natural resources. This promotes domestic production of gaseous fuel, reduces the level of dependence on imports from outside the country, and increases the energy security of a given region, which particularly applies to the importing countries and is part of the structure of trade in natural gas on the European gas market [53].

The European Union is the world leader in biogas production, in 2019 the total volume of biofuel produced in member countries reached 164 TWh [54] (Table 3). However, this volume is only marginal compared to the EU's demand for gas. In the process of implementing the assumptions set out in the European Green Deal strategy, the need to develop the potential of the renewable gas market is therefore evident.

Significant potential connected with biogas production exists in Poland [5,7–12]. In 2019, the volume of (primary) energy generated from biogas in this country relative to total domestic energy production was nearly 0.5%. With regard to electricity, a total of 1,162 GWh of energy (2019) was produced from biogas (an increase of 22% compared to 2015 – 906.4 GWh), including 350.8 GWh from wastewater treatment plants; 178 GWh from landfill gas; and 633.2 GWh from other sources (including agricultural biogas). A relatively large increase, more than doubling the share of energy from biogas in 2019, also occurred in thermal energy production, 2015 (436 TJ)–2019 (1,004.2 TJ). Of this, 35.5 TJ of energy came from landfills; 105.6 TJ from wastewater treatment plants; and 863.2 TJ from other

Table 1
Composition and selected properties of biogas generated by methane fermentation [47]

Parameter	Unit	Value
Methane	% vol.	50–75
Hydrogen	% vol.	<1
Carbon dioxide	% vol.	25–45
Carbon monoxide	% vol.	<0.3
Nitrogen	% vol.	<2
Oxygen	% vol.	<2
Hydrogen sulfide	mg/L	<1,000
Ammonia	mg/L	<100
	MJ/Nm^3	23
Typical caloric value	kWh/Nm^3	6.5
	MJ/kg	20.2
Fuel equivalent	0.6–0.65 dm^3 oil/m^3 biogas	
Explosive limit	6%–12% biogas in air	
Flash-point	650°C–750°C	
Critical pressure	75–89 bar	
Critical temperature	–82.5°C	
Density	1.2 kg/Nm^3	

Table 2
Calorific value of biogas and comparison to other energy carriers [49]

Fuel type	Calorific value	Conversion ratio to 1 m^3 biogas with a calorific value of 26 MJ/m^3
Biogas	20–26 MJ/m^3	1 m^3
Natural gas	33.5 MJ/m^3	0.77 m^3
Diesel	41.9 MJ/dm^3	0.62 m^3
Hard coal	32.4 MJ/kg	1.1 kg
Rapeseed biofuel	36.5 MJ/kg	0.7 kg
Ethanol	29.6 MJ/kg	0.85 kg
Firewood	8–18 MJ/kg	2 kg

generation sources. Thus, when analysing the development of the biogas market in Poland, a constant upward trend is noticeable (an increase of 20% between 2015 and 2019) [6].

Currently, in Poland during the period of expansion of the national water and sewage infrastructure, a large development potential is shown by underutilised sewage sludge resources [56,57]. The development of renewable biofuel production in wastewater treatment plants can help to generate benefits: environmental (reduction of methane emissions), energy (creation of self-sufficient wastewater treatment plants) and economic (lower cost of internal energy supply) [58–62].

Table 3
Primary production from biogas in the European Union in 2019 (in ktoe) [55]

EU country	Total biogas production	Biogas production from sewage sludge
Germany	7,547.5	487.2
Italy	1,828.0	50.0
France	976.6	44.6
Czech Republic	581.2	43.6
Denmark	396.6	29.8
Netherlands	356.0	62.7
Poland	298.5	120.2
Spain	260.3	64.4
Belgium	231.9	26.4
Austria	214.4	33.7
Finland	189.7	37.8
Sweden	181.5	77.8
Slovakia	143.3	12.8
Greece	125.0	20.0
Hungary	83.1	25.8
Latvia	80.6	2.1
Croatia	80.2	3.5
Portugal	80.1	6.4
Bulgaria	51.0	8.3
Ireland	50.0	11.2
Lithuania	39.0	6.8
Slovenia	22.2	1.2
Romania	20.7	0
Luxembourg	18.0	1.8
Cyprus	14.0	0.7
Estonia	13.9	7.6
Malta	1.6	1.0

5. Biogas production at wastewater treatment plants in Poland

A rational way to treat sewage sludge is to use it as a substrate for biogas production in the methane fermentation process [63,64]. Biogas from sewage sludge can be used to produce heat, mechanical energy, and electricity. Typical biogas utilisation methods include: (1) combustion in heating boilers with the generation of heat used for heating purposes, (2) combustion in gas engines coupled to generators that produce mechanical energy to directly drive pumps, or (3) combustion in gas engines or gas turbines coupled to generators that produce electricity for power equipment at the wastewater treatment plant, with each of the above methods also generating additional thermal energy that can be used for technological needs (e.g., the maintenance of proper temperature in the separated digesters in the wastewater treatment plant, or for the needs of preparing domestic hot water (CHP Process – Combined Heat and Power) [47,65–68]. Biogas production from sewage sludge for energy production is justified in large wastewater treatment plants with an average capacity of more than 8–10,000 m^3/d. The suitability of biogas for energy purposes is determined by its properties, primarily its methane content. Sewage sludge biogas has a relatively stable methane content, which translates into a relatively high calorific value compared to agricultural or landfill biogas (Table 4).

In recent years, Poland has witnessed dynamic growth in the construction and expansion of sewerage networks and municipal wastewater treatment plants, leading to the generation of large quantities of municipal sewage sludge. According to the statistical data, in 2003 Poland produced 447 thousand Mg s.m. of municipal sewage sludge, while in 2019 this amount was already 574.6 thousand Mg s.m. [16]. There are nearly 2,500 wastewater treatment plants operating in Poland, with only 140 having sewage sludge digestion facilities (Fig. 1).

Table 4
Average biogas composition according to source [69]

Component	Unit	Landfill gas	Sewage sludge gas	Agricultural biogas
Methane	%	44–64	57–67	53–72
Carbon dioxide	%	24–34	32–41	14–39
Oxygen	%	<3.0	<1	<1
Nitrogen	%	10–20	0.2–0.7	0.5–7.5
Hydrogen sulfide	ppm	15–427	23–8,000	10–30,000
Ammonia	mg/m^3	<100	<100	50–400
Calorific value	MJ/m^3	15.8–23.0	20.5–23.9	18.8–25.8
	kWh/m^3	4.4–6.5	5.7–6.5	5.2–7.2

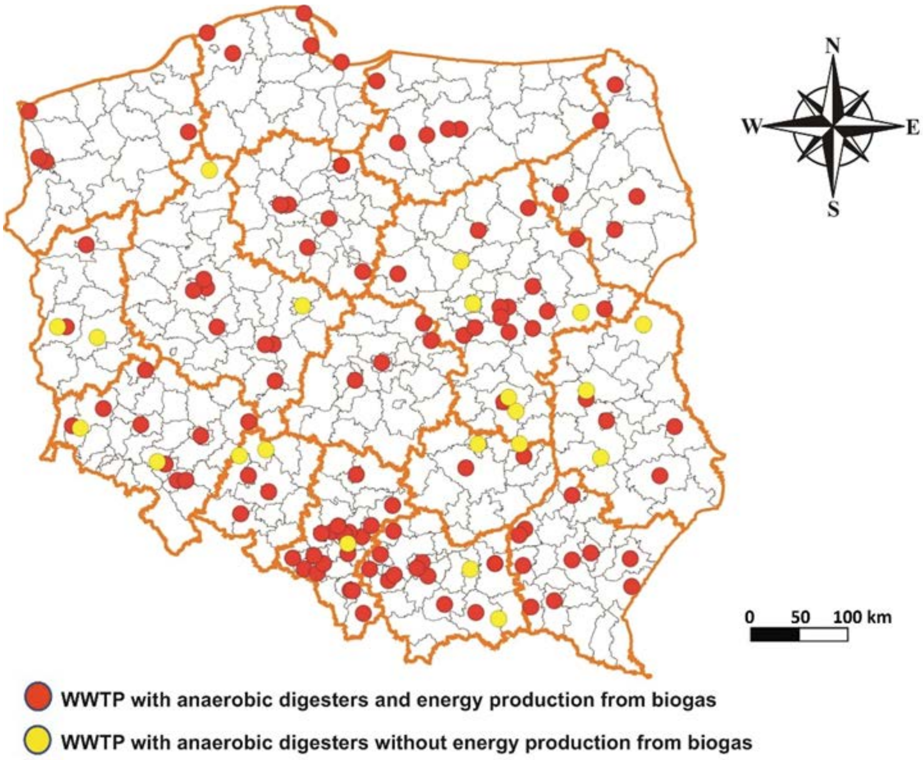

Fig. 1. Wastewater treatment plants in Poland using anaerobic digestion of sewage sludge [57].

Only 6% of wastewater treatment plants operating in Poland currently produce biogas. The total volume of digesters at all wastewater treatment plants is estimated at 800,000–900,000 m^3. However, not all wastewater treatment plants produce heat and/or electricity from the biogas produced. Only 112 wastewater treatment plants have installed biogas generators, one steam turbine, and one thermoelectric generator to produce electricity from exhaust gas (flue gas energy) [70]. The total installed capacity of the electric generators at the wastewater treatment plants in Poland is 74 MWel (Fig. 2).

Electricity and heat production at wastewater treatment plants is currently 350.8 GWh and 105.6 TJ, respectively (Figs. 3 and 4). For comparison, the total electricity demand in Poland is 169.4 TWh/y (data for 2019) [6].

When analysing the quantities of sludge processed in anaerobic digestion processes, it can be concluded that the energy potential inherent in sludge is used in less than 40%. [57]. For comparison, in Croatia, about 30% of sewage sludge is converted to biogas through fermentation [71]. It is estimated that as many as 170 installations for biogas production from sewage sludge in treatment plants can still be built in Poland [57]. The calculation indicates that it may be more than 1% of the energy production in Poland. It is estimated that as much as 0.5–0.7 billion Nm^3 of biogas can be produced from sewage sludge in the coming years [70], which, compared to domestic natural gas production (4.6 billion Nm^3 in 2018) [72], represents a significant amount of gaseous fuel used for energy purposes. The potential for electricity generation from biogas

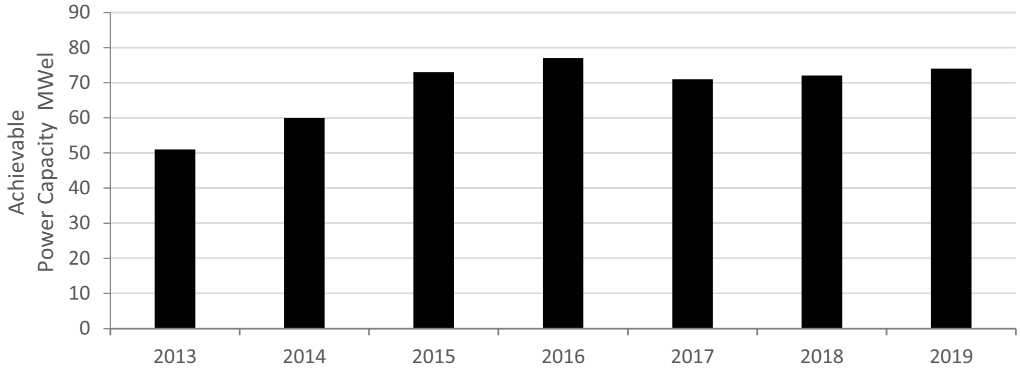

Fig. 2. Power of electrical installations for biogas combustion in wastewater treatment plants.

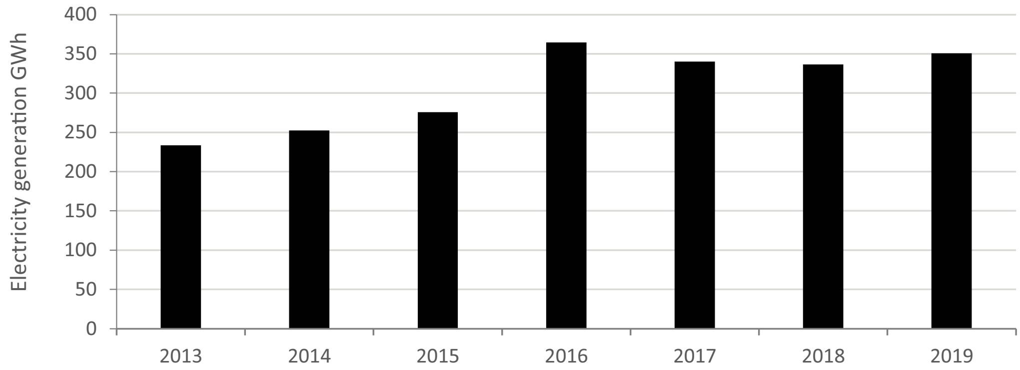

Fig. 3. Electricity production from biogas in wastewater treatment plants in 2013–2019 according to statistical data.

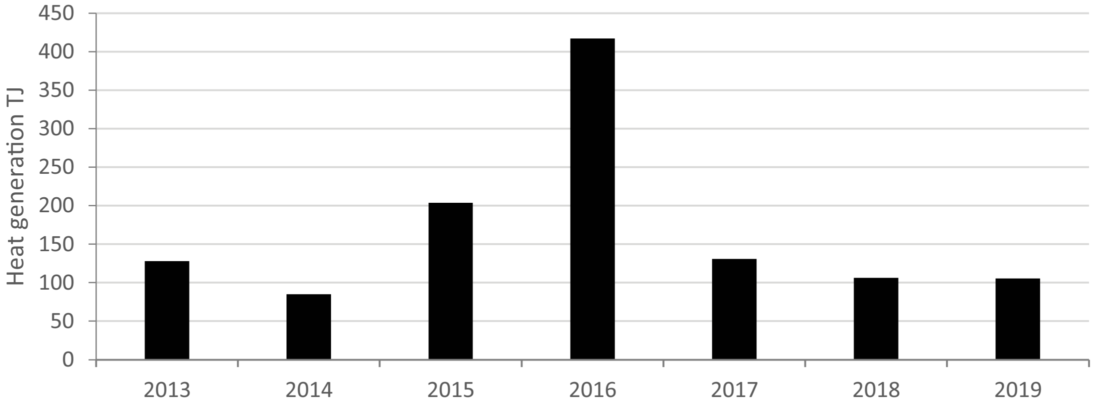

Fig. 4. Thermal energy production from biogas in wastewater treatment plants in 2013–2019 according to statistical data.

in Polish wastewater treatment plants is high. The study showed that depending on the type of technological system, the efficiency of electricity production from biogas ranges from 0.36 to 4.8 kWh/Nm^3 (Table 5).

Assuming that 1 m^3 of biogas yields an average of 2 kWh/Nm^3, it is possible to generate as much as 1,400 GWh of electricity, a more than 4-fold increase compared to current levels. The analysis of the topic indicates that the biogas potential of wastewater treatment plants in Poland can easily be increased by using new technologies, which enable the intensification of biogas production, for example, by using co-fermentation of sewage sludge with other organic waste, so-called co-substrate [68,81–84] or sludge disintegration [85–87].

6. Barriers to biogas market development in Poland

In spite of the expected large production opportunities, the biogas sector, including the sphere of exploiting substrates coming from wastewater treatment plants, considered in the study encounters a number of barriers, significantly slowing down the development of this branch of the renewable energy sources infrastructure.

The development of sewage sludge biogas plants requires considerable financial outlays, which in many cases makes it difficult or even impossible to invest in such technologies (Table 6).

The use of biogas installations in sewage treatment plants is due to a number of conditions – financial and technological. The technologies of sewage sludge treatment applied by sewage treatment plants depend partly on the country or region and their location; however, the size of the plant is of greatest importance (Fig. 5). Although many technologies can be used in treatment plants of different sizes (especially in combination with other technologies), composting, drying, anaerobic digestion (fermentation) and incineration are applicable and possible only in larger treatment plants. The use of sludge methane digestion for biogas production is considered financially feasible for treatment plants of at least 20,000 RLM [89].

In the case of sewage treatment plants of <20,000 RLM, with a capacity of 500–2,500 m^3/d, it becomes possible to centralise the process of sewage sludge fermentation and biogas production in one facility, to which sewage sludge can be brought from neighbouring sewage treatment plants, for example, from a distance of up to 50 km, justified by financial reasons. The use of a group installation with anaerobic chambers will enable rational processing of sewage sludge into biogas and production of electrical and thermal energy. In addition, co-fermentation of sewage sludge with other organic waste can be used, which increases the biogas yield. Nevertheless, it becomes necessary to determine the technological and financial calculation in this regard.

The development of the biogas market in Poland is still hindered by the use of conventional fuels, which are highly price-competitive with renewable gas fuels. The average reference price of electricity for installations using biogas from sewage sludge, according to the regulation of the Polish Minister of Climate of 24 April 2020, is 447.5 PLN/MWh [90], with the average price of electricity in Poland (Q4 2020) being 247.48 PLN/MWh [91].

The large increase in biogas production, aimed not only at ensuring the self-sufficiency of treatment plants but also at managing energy surpluses, is also hampered by the lack of specialised transport infrastructure and the low demand for this type of fuel resulting from the deficit of distribution points and the low popularity of developing low-emission transport [17,92]. Introduction of gaseous biofuels to the national energy system is also held back by lack of biomethane production facilities [93].

The increase in the number of biogas plants in Poland is further complicated by the current administrative and legal conditions. Poland's highly centralised energy market, based mainly on fossil fuels, has only been undergoing a profound transformation for a few years. The programmes introduced for the development of renewable energy sources infrastructure have so far been used to a limited extent, mainly due to the lack of appropriate legislative solutions guaranteeing stable market development. However, the current government is working on updating legislation to introduce renewable fuels into the system, an example of which is the work carried out on updating the regulation on detailed conditions for the operation of the gas system

Table 5
Electricity production in selected wastewater treatment plants in Poland

Studied facilities	Electricity production from biogas (kWh/Nm^3)	References
The Mielec WWTP	1.9–4.8	[73]
The Krosno WWTP	3.82–4.51	[74]
The Rzeszów WWTP	2.02–2.48	[75]
The Debica WWTP	0.36–2.13	[76]
The Tarnów WWTP	1.62	[70]
The Zamość WWTP	1.16–2.21	[77]
The Opole WWTP	0.95–2.18	[78]
The Iława WWTP	2.15–2.41	[68]
The Łańcut WWTP	1.89–2.19	[79]
The Hajdów WWTP	1.42–2.07	[80]

Table 6
Forecast of investment costs of generation technologies in 2030, 2050 (EUR/kWe) [88]

Generation technologies	2030	2050
Gas turbine	530	570
Combined cycle power plant	860	940
Hard coal	1,625	1,725
Lignite	1,875	1,975
Nuclear	5,000	5,000
Wind onshore	1,300	1,200
Wind offshore	2,500	1,950
Photovolatic	600	475
Hydro RoR	3,600	3,600
Biogas	3,100	2,900
Biomass/waste	3,100	3,100

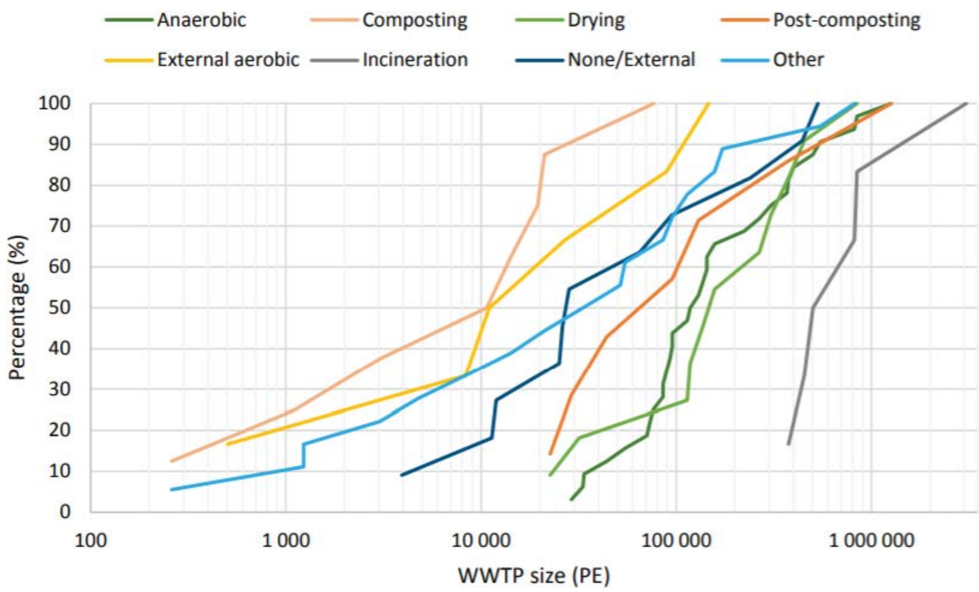

Fig. 5. Correlation between sludge treatment technologies and wastewater treatment plant (WWTP) sizes in PE (66 WWTPs, 99 technological steps). Shown on a cumulative frequency graph with %ages referring to total number of WWTPs in the sample. Lime stabilization, humification and external aerobic added to the "Other" section [89].

to contribute to the development of the renewable gas market [94]. In the Polish Energy Policy until 2040, by the end of this decade it is assumed that the capacity for transporting the fuel mixture containing about 10% of decarbonised gases through gas networks will be achieved [95].

There are also problems associated with low public awareness of the possibility of using municipal waste to generate closed-loop energy and the resulting lack of adequate levels of knowledge, which creates public controversy over the large financial outlays – for an uncertain, potentially inefficient market for gaseous renewable fuels [96,97].

7. Summary

As far as technical issues are concerned, the dynamically developing water and sewage infrastructure in Poland favours the construction of biogas plants which use sewage sludge as a substrate. By creating the potential to replace carbon-intensive fossil fuels with low-emission, equally high calorific value, renewable gases. In addition, biogas facilities at wastewater treatment plants can serve as pumped peak storage plants as a result of the easy storage of biogas, since its production is stable and conditioned by the economic activity in urban areas that produces wastewater.

The analysis of the impact of the development of biogas infrastructure on the implementation of the energy transition process while simultaneously strengthening energy security reveals a positive impact in the main areas directly related to the Polish energy sector. Increasing biogas production will contribute to diversification of the natural gas production structure and thus increase Poland's self-sufficiency in energy and reduce dependence on the import of this energy raw material. Since biogas production in Poland would be free of the risk of fuel supply disruption, it would increase system stability and reduce transmission losses if produced by distributed generation in different locations throughout the country. The potential transport of surplus biogas also constitutes an alternative to the constantly expanding infrastructural regasification components. If fossil natural gas is phased out and injected into the system (as biomethane), it could enable the continued use of gas networks in the future, neutralising the possibility of stranded assets.

Despite the barriers to the development of biogas technology in Poland, as shown in the study, given the currently planned and ongoing activities of the European Union in cooperation with representatives of the Polish government and business, based on strategies developed by these institutions that meet the requirements for sustainable energy transition, we can expect a gradual increase in the level of investment for the development of the Polish biogas market, which is already the second largest in the EU (EU-27) in terms of production volume.

8. Conclusions

In 2019, the volume of (primary) energy generated from biogas in Poland relative to total domestic energy production was nearly 0.5%.

In total (2019), 350.8 GWh of electricity and 105.6 TJ of heat were produced from biogas plants at wastewater treatment plants.

There are nearly 2,500 wastewater treatment plants operating in Poland, with 140 having sewage sludge digestion facilities.

In the case of sewage treatment plants of <20,000 RLM, with a capacity of 500–2,500 m^3/d, it becomes possible (if justified by financial and technological reasons) to centralise the process of sewage sludge fermentation and biogas production in one facility, to which sewage sludge can be brought from neighbouring sewage treatment plants.

A steady upward trend has been observed towards the expansion of the domestic biogas market (growing at 20% during 2015–2019).

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