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Perspective

Balance and Energy Use of Biogas in Poland: Prospects and Directions of Development for the Circular Economy

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Abstract: The production of biogas from biodegradable waste generated in all sectors of the economy in Poland is a key issue for the diversification of energy sources and climate neutrality. The biogas balances presented in the literature based on bio-waste often contain overly optimistic data, which in reality only represent the theoretical potential of biogas in Poland. The pragmatic approach presented in this study fills a gap in research by presenting a technical balance of biogas (real potential) that can be realistically achieved. The objective of the work was to perform a biogas balance in the context of electricity and heat generation in cogeneration units. The tests made it possible to estimate the technical potential of biogas, depending on the source of its generation, the possibility of its conversion to biomethane and biohydrogen and the methods of its use. The research results showed a 30% increase in biogas potential on an annual basis compared to the current state, resulting in a 29% increase in electricity production and a 28% increase in heat production. The technical potential of biogas was estimated at 2186.62 million m^3, which would allow for the production of 4627.06 GWh of electricity and 1869.64 TG of heat. The technical balance of biogas and the potential energy production can serve as input material for developing plans and strategies for the development of renewable energy sources in Poland. The work is consistent with the issues of balancing the renewable energy resources from biogas and the methods of conversion into other energy carriers using sustainable energy transformations in order to optimise energy production processes.

Keywords: biowaste; biogas balance; biomethane; biohydrogen; cogeneration

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1. Introduction

Biomass is a source of renewable energy. It is available in various forms and is used in various ways to convert chemical energy into other energy carriers. The definition of biomass provided in the Directive 2009/28/EC states that "biomass is the biodegradable part of products, waste or residues of biological origin from agriculture (including plant and animal substances), forestry and related industries, including fisheries and aquaculture, and also the biodegradable part of industrial and municipal waste [1]". One of the ways of converting biomass into other energy carriers is the process of anaerobic digestion. It is carried out in dedicated bioreactors (except landfill gas). The process yields biogas containing mainly methane, carbon dioxide, nitrogen, hydrogen sulphide, ammonia, sulfur and silicon compounds as other trace pollutants [2].

According to the Act on Renewable Energy Sources, biogas is defined as gas obtained from biomass, mainly from animal or plant waste processing installations, sewage treatment plants and landfills. In addition, the act also specifies agricultural biogas, which is defined as gas obtained in the process of methane fermentation of agricultural raw materials, agricultural by-products, liquid or solid animal manure, by-products, waste or residues from the processing of agricultural products or forest biomass [3].

In Poland, it has been adopted to classify the type of biogas based on substrates used for its production, which means that the following types of biogases are in operation: landfill, sewage sludge, agricultural, other as well as municipal biogas, which has been gaining in popularity in recent years. Landfill gas (LFG) produced in waste deposits is characterised by a diverse chemical composition resulting from the deposited waste's morphology [4]. Due to the content of the main parameters, which are methane (40–60%) and carbon dioxide 25–45%, as a type of greenhouse gas, it is a potential threat to the environment and people. Therefore, in this case, it is crucial to manage it through controlled intake, treatment and use for energy purposes [5]. Sewage treatment plants in mechanical and biological processes generate waste constituting sewage sludge, which contains significant amounts of biodegradable fractions [6]. Sewage sludge subjected to the fermentation process in separate fermentation chambers becomes a source of biogas (BSS), which mainly contains approximately 55–70% methane of and 27–44% carbon dioxide [7,8]. Biogas produced in sewage treatment plants is used for energy purposes, heat generation in gas boilers, or in cogeneration systems, generating electricity and heat, which are primarily used for the needs of treatment plants [9]. Biomass wastes derived from plant or animal production remains are the basic substrates for the production of agricultural biogas (AB) in fermentation chambers. The agricultural biogas produced in this process contains 50–75% methane and 24–45% carbon dioxide, as well as other impurities, including hydrogen sulphide, nitrogen and others in trace amounts [10].

In order for biogas to be used for energy purposes, especially in the cogeneration process, it should be purified, which will ensure the failure-free operation of gas engines. The generated heat is used for process purposes, while electricity is consumed in the facility, and the surplus is transferred to the external power grid [11]. The generated municipal waste contains a significant amount of biodegradable fraction, which, when collected selectively or separated from the stream of mixed municipal waste, becomes a source for the production of municipal biogas (MB) [12]. The available technologies allow us to carry out of these processes properly after prior preparation of the bioreactor feed, ensuring appropriate humidity and process temperature [13]. The resulting municipal biogas with the parameters of the main components (methane 50–60% and carbon dioxide 25–42%) is most often stored, cleaned and applied as a fuel for gas engines that are installed in cogeneration installations and used for work with generators, producing electricity and recovering heat that is primarily used for their own needs. Electricity, as a renewable energy, that is sent to the power grid is an important element of integrated energy systems in local as well as global terms [14].

Wastes generated in slaughterhouses, breweries and food industries, collected in a selective manner, become the input material for biogas production directly at the facilities where they have been produced or in dedicated fermentation installations. The biogas produced in this process, for the purposes of this work, referred to as residual biogas (RB), contains methane in the amount of 55 to 65% and carbon dioxide in the amount of 25 to 42% as the main components of the biogas [15]. The produced biogas is used in cogeneration systems, but also in trigeneration or polygeneration systems to produce chill and steam for technological purposes [16]. Such a method of waste management constitutes a process of biological recycling, which closes up the waste loop, and the produced energy is renewable energy, constituting a significant share of the balance of production plants [17].

The production of biogas from various fractions of biowaste is a key aspect in the context of waste management, especially in terms of its conversion into other energy carriers. Biogas, as a source of renewable energy, can contribute to the energy transformation of countries that have energy production equally based on fossil fuels, which generates the high emissivity of this sector [18]. The procurement of biogas and its energy use corresponds with the activities carried out as part of the European climate policy, aimed at achieving a modern green and climate-neutral economy based, among others, on renewable energy sources [19].

The biogas balances presented in the literature are based on outdated data and require updating in terms of potential bio-waste streams as well as the possibilities of applying new biogas conversion technologies. The approach presented in this study fills a gap in research by balancing the technical potential of biogas (real potential) that can be realised through the application of cogeneration and alternative technologies, such as the conversion of biogas to biomethane and biohydrogen. The aim of the study is to provide a technical balance of biogas (real potential) as a source of knowledge for developing plans and strategies for the development of renewable energy sources in Poland.

To perform the biogas balance, a method of document analysis, diagnostic survey, and statistical analysis was applied. The data used in the study were mainly obtained from publicly available statistical data, reports published by central administration bodies, reports from organisations responsible for energy management in Poland and the latest literature publications.

2. Biogas—Current State

The source of biomass production is targeted products, dedicated crops and waste, which should be collected in a selective manner and managed in accordance with the waste management hierarchy. One of the types of waste generated in connection with human activity is biowaste, generated in households but also in the services sector and during various production processes [20]. The Waste Act defines biowaste as: biodegradable waste from gardens and parks; food and kitchen waste from households; gastronomy, including restaurants, canteens and mass caterers; offices, warehouses and retail units; as well as similar waste from plants producing or providing food on the consumer market [21]. The physicochemical properties of such wastes make them biodegradable wastes that undergo aerobic or anaerobic decomposition with the participation of microorganisms, constituting a basic substrate for the production of biogas and compost. Figure 1 shows the sources of biowaste generation, their types, management methods and products that can be manufactured [22].

The final product of biowaste treatment will depend on the type of technology used. Most frequently, such processes yield energy in the case of thermal transformation, organic fertiliser in the case of composting, and biogas, which is a source of renewable energy produced in methane fermentation processes [23].

The production of energy from renewable sources in individual countries of the European Union (EU) has become a priority in the energy transformation processes of national economies. In 2021, the share of energy from renewable sources in total primary energy in Poland amounted to 21.12%, with the EU average being 40.7%. Moreover, the share of biogas in the structure of energy acquisition from renewable sources in 2021 in Poland amounted to 2.59%, with the EU average being 6.3% [19].

At the end of 2021, there were 265 landfills in Poland accepting municipal waste, with a total area of 1667.2 ha. Out of the collected 13,673,583.14 Mg of municipal waste, 5,295,791.6 Mg was deposited in landfills, which accounted for 38.7% of the total mass of collected municipal waste. Out of the total number of active landfills, 249 were equipped with degassing installations, which accounted for 94.0% of all active landfills where municipal waste was deposited. The number of installations at landfills where gas produced in waste deposits was disposed of with heat recovery accounted for 7.4%, while 19.7% of the installations were those where landfill gas was used to produce electricity. In 2021, with the effect of the disposal of landfill gas and its use for energy purposes, 207.4 GWh of electricity and 778.9 TJ of heat were produced [19].

According to statistical data, in 2021, there were 3276 municipal wastewater treatment plants operating in Poland, including 8 mechanical treatment installations, 819 with increased biogenic removal and 2449 treatment plants that made use of biological wastewater treatment processes. In that period, municipal sewage treatment plants served 28,511,915 inhabitants, which accounted for 75.2% of the population in Poland. On an annual basis, 1,367,110.9 [dam^3] of wastewater was treated, producing 584,754 Mg of sewage sludge. In 2021, 100 sewage treatment plants were equipped with sewage sludge fermentation installations, which resulted in the production of 367.8 GWh of electricity and 1471.27 TJ of heat [19].

At the end of 2021, there were 128 installations in Poland which had been entered into the register of agricultural biogas producers. The production capacity of biogas plants was 513 million m^3 of agricultural biogas per year, while the cogeneration modules installed in the biogas plants had a total electric power output of 125.323 MW. In the analysed period, over 4.9 million tons of raw materials were used for methane fermentation, and with the effect of these processes, 342.913 million m^3 of agricultural biogas was obtained, which meant that an amount over 335.335 million m^3 was used for the generation of electricity and heat from cogeneration units. The remaining part was burned in gas boilers and torches. In total, 2971.78 TJ of heat and 732.645 GWh of electricity were produced from agricultural biogas, whereof approximately 607.708 GWh was transferred to the external power grid, and the remaining amount was used for the needs of the facilities [24].

The mass of collected municipal waste intended for composting and fermentation in 2021 amounted to 1,824,323.2 Mg, which accounts for 13% of the total mass of collected municipal waste. In 2021, there were nine municipal waste fermentation installations operating in Poland with a total capacity of 189,000 Mg/year, whereof eight installations processed biodegradable waste separated from the stream of mixed municipal waste and one installation processed biowaste collected selectively. The installed electrical capacity of these installations is 6.22 MW. In 2021, 33.26 GWh of electricity and 132.35 TJ of heat were generated in biofermentation installations [25].

Another biogas is produced in the process of the anaerobic fermentation of biomass from food industry waste generated in slaughterhouses, breweries and other food industries. The volume of electricity and heat production for this industry was estimated on the basis of statistical data and the Register of Energy Producers available at the Energy Regulatory Office in Poland, and it involves waste not transferred to other recipients. In 2021, in effect of methane fermentation, 6.80 GWh of electricity and 28.74 TJ of heat were produced. Due to the specificity of the industry, a significant amount of produced biogas was used for the needs of the facilities and for technological processes [19,26]. The volume of electricity and heat production from biogas in 2021 in Poland is presented in Table 1.

Table 1. Production of electricity and heat from a specific type of biogas [19,24,26].

Type of Biogas	Biogas Stream [mln m^3]	Amount of Produced Electricity [GWh]	Amount of Produced Heat [TJ]
Landfill	107.43	204.70	778.86
From sewage sludge	153.74	367.80	1471.27
Agricultural	342.91	732.60	2971.78
Municipal	15.65	33.62	132.82
Other	3.25	6.86	28.74
Total	622.98	1345.58	5383.47

Electricity produced from a given type of biogas was primarily used to meet the energy needs of the facilities, and its surplus was transferred to the grid as a sale, based on signed contracts with a selected grid operator. The heat produced from a given type of biogas was primarily used for technological purposes (heating the feed in fermentation chambers) and then for social and living or technological purposes on the premises of the remaining facilities and installations.

Based on the data contained in Table 1, the total amount of energy obtained from biogas in 2021 was 10,227.17 TJ. Out of this amount, 7522.08 TJ (73.55%) was used as input for energy transformations (processing into other energy carriers), while 2705.09 TJ (26.45%) was the end use by consumers (industry, services sector, households) for their technological, production and living needs. The end use does not include processing into other energy carriers.

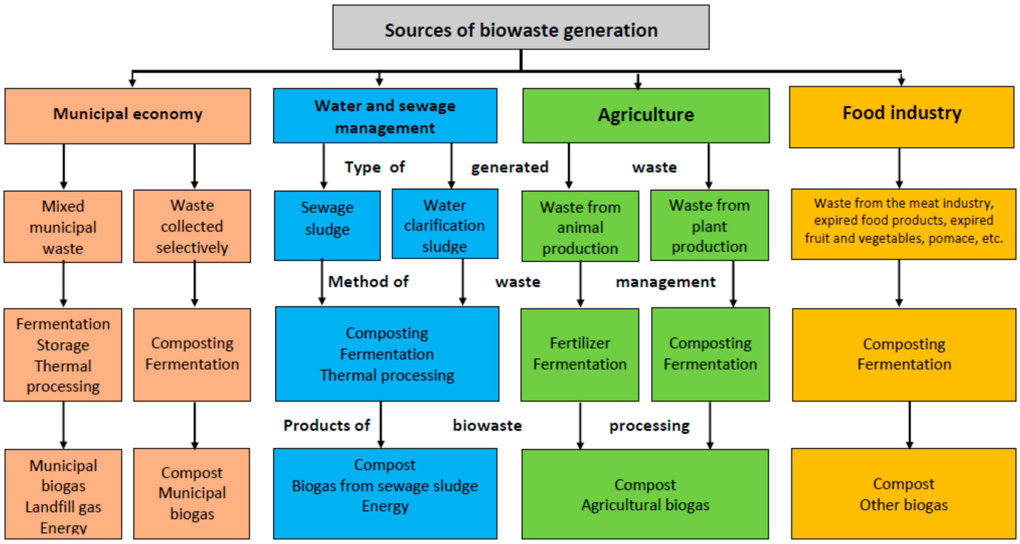

Figure 1. Types and methods of biowaste management [24,25,27].

The installed electric power of all power plants that used biogas to generate electricity from biogas in 2021 amounted to 256.5 MW. Considering the scope of the installed electric power and the amount of electricity produced from biogas amounting to 1345.58 GWh, the average productivity of biogas plants from the installed 1 MW of electric power was 5235.3 MWh. This value is less than 59.8% of the theoretical productivity of 8760 MWh for 1 MW [27]. The actual technical availability of the cogeneration installation, taking into account maintenance and emergency shutdowns, oscillates between 8000–8500 h/year.

3. Prospects—The Technical Potential of Biogas and Energy Production

The paper estimates the technical balance of biogas (real potential) possible to be generated from biodegradable waste in Poland. The carried-out tests and analyses carefully estimate the amount of biogas in relation to the theoretical balance provided in the literature, which, depending on the publication, may be up to eight times higher than the technical balance of biogas provided in the paper. Each type of biogas should be treated individually due to the properties of individual substrates, various fermentation processes, purification, storage and energy use in cogeneration units.

The generation of energy in the combined process guarantees high energy efficiency in the range of 80–85%. Obviously, it does not close the path to another conversion of biogas, e.g., into biomethane in the form of bioCNG and/or bioLNG with optional bioCO_2 production. These are relatively new technologies, but they already have numerous applications on an industrial scale. In the future, biohydrogen can be produced (vehicle propulsion, injection into the natural gas network, storage facility), but it requires significant investments in this area and refinement of the technology.

3.1. Landfill Biogas

The Regulation of the Minister of Economy of 16 July 2015 on the admission of waste to landfills in Poland [28], based on Council Decision No. 2003/33/EC of 19 December 2002 [29], introduced a ban on landfilling of waste with a calorific value above 6 MJ/kg. This applies to strictly defined types of waste with the codes 19 08 05, 19 08 12, 19 08 14 and 19 12 12 and to all waste from group 20. This is tantamount to a ban on landfilling of the biodegradable fraction, which was included in the waste groups listed above. This fact will result in a significant reduction in the amount of biogas produced in landfills in the near future.

Another factor is the life cycle of landfills, which are systematically being closed and subjected to reclamation. The analysis of statistical data for the last 10 years showed that at the end of 2011, there were 578 active landfills accepting municipal waste, while at the end of 2012, there were 265 of them. In terms of the technical aspect, the number of landfills as potential sources of biogas production is decreasing; within the analogous period of time, the number of landfills equipped with degassing installations decreased from 428 to 249 [30]. When estimating the potential of biogas that can be obtained from landfills, the productivity of the waste deposit should be taken into account, which will be different depending on the morphology of the stored waste and its compression [31,32]. Based on the age of the landfills, the current methanogenic activity and the amount of biogas currently obtained, the potential of available landfill biogas was estimated to be around 276.24 million m^3. In the estimation process, it was assumed that the current biogas stream would increase by 33% due to intensified biogas acquisition at landfills which are no more than 20 years old, and the biogas production curve is still rising. The estimated stream of biogas will allow for the generation of 524.85 GWh of electricity and 1889.34 TJ of heat in cogeneration units [33].

3.2. Biogas from Sewage Sludge

In effect of the cyclical connection of new sewage producers, municipal sewage treatment plants already have large energy potentials now and will have so in the future. In 2021, 1,367,110 [dam^3] of municipal wastewater was treated, including 1,135,776 [dam^3] of biologically treated wastewater and with increased removal of nutrients, suitable for use in sludge fermentation, which accounts for 83% of the total volume. Assuming that 1000 m^3 of treated wastewater can generate an average of 0.8 MWh of electricity, the potential for electricity production from biogas in wastewater treatment plants can be estimated at approx. 908.62 GWh per year. Taking into account the above-mentioned calculations, in 2021, wastewater treatment plants used the potential of resources in terms of electricity generation at a rate of 40.48% [27,31,33].

Considering the fact that the full potential of sewage sludge, due to technical reasons of sewage treatment plants, cannot be fully used for energy purposes, energy use of sludge resources was adopted at the level of 70%. For this reason, biogas production can be expected at the level of 408.87 million m^3 per year, which will allow for the production of electricity in the amount of 899.53 GWh and heat in the amount of 3885.98 TJ, assuming that the energy will be generated in cogeneration. Attaining 899.53 GWh per year at the scale of electricity generation in wastewater treatment plants opens up the possibility of building new cogeneration installations for electricity and heat generation, which will significantly contribute to the rise in the self-consumption of energy and a greater urge for the energy self-sufficiency of wastewater treatment plants.

3.3. Agricultural Biogas

The production sector for agricultural biogas is currently one of the most developing sectors in Poland. Between 2012–2021, a rise in the number of biogas plants from 28 to 128 installations was reported. The installed electrical capacity increased by 69.5%, the amount of produced biogas increased by 78.6%, while the production of electricity increased from 141.8 GWh in 2012 to 732.6 GWh in 2021. Based on statistical data [19,33], publications [34–36] and reports [24,25,27], the potential of agricultural biogas in Poland was estimated. Waste in the form of natural fertilisers from animal production, waste from plant production, waste from the agricultural and food industry as well as raw materials from special purpose crops were adopted as substrates for the agricultural biogas production process. In the research, variants constituting estimates viewed as average and realistic for acquisition were analysed. The biogas potential estimated in Poland, produced from the substrates listed above, was referred to as the technical potential, and it amounts to 1295.61 million m^3 of biogas per year. Assuming that agricultural biogas will be used as fuel for cogeneration units, the estimated amount of generated electricity will come to 2850.32 GWh and heat to 10,926.77 TJ.

3.4. Municipal Biogas

Biowastes from the stream of municipal waste collected selectively (green waste from gardens, parks and cemeteries, waste from marketplaces, kitchen waste and waste from gastronomy) were adopted as potential substrates for the production of municipal biogas. The balance of biowaste obtainable from the stream of collected municipal waste was estimated on the basis of statistical data [19,30,33], reports [25,27] and literature [34,35,37,38]. Currently, a significant part of biowaste still ends up in mixed municipal waste, but over time, along with the improvement of selective collection, the stream of biowaste collected selectively will be augmented [39]. Considering the fact that in 2021, 1824.3 thousand Mg of municipal waste was collected and transferred to biological treatment processes (composting and/or fermentation), which constitutes 13% of the entire collected stream of municipal waste, the estimation assumes that the level of collection of this waste will increase to 20%. Accordingly, the estimated stream of biodegradable waste will amount to 2735.2 thousand Mg, and when assuming the technical potential of this stream intended for the methane fermentation process will be at the level of 70%, we obtain the quantity of 1,914,000.64 Mg. The use of such a waste stream during fermentation will allow us to produce about 191.4 million m^3 of biogas, which, when fed to cogeneration units, will yield 421.22 GWh of electricity and 1819.64 TJ of heat.

3.5. Other Biogas

The potential of the remaining biogas produced from waste from the food industry was estimated on the basis of statistical data [19,27,30], literature [31,32,37] and reports [25]. For the estimation, we adopted waste that was not transferred to agricultural biogas plants but was used directly on the premises of the producer, i.e., at slaughterhouses, breweries and in other food industries. The estimated theoretical potential was 57.8 million m^3, while the estimated technical potential will amount to 14.45 mln m^3, which is 25% of the theoretical potential. The estimated biogas potential will allow for the production of approximately 31.79 GWh of electricity and 137.32 TJ of heat, assuming that energy production is carried out in a cogeneration system.

The estimated value of the technical potential of biogas in Poland applicable in cogeneration units for the production of electricity and heat is presented in Table 2.

Table 2. The estimated technical potential of biogas in Poland and energy production [30–34].

Type of Biogas	Biogas Stream [mln $m^3 \cdot year^{-1}$]	Production of Electricity [$GWh \cdot year^{-1}$]	Production of Heat [$TJ \cdot year^{-1}$]
Landfill	276.24	524.85	1889.34
From sewage sludge	408.87	899.53	3885.68
Agricultural	1295.61	2850.32	10,962.77
Municipal	191.46	421.22	1819.53
Other	14.45	31.14	137.32
Total	2186.62	4627.06	18,694.64

The estimation of the technical potential was made primarily in order to determine the balance of electricity and heat possible to be generated from biogas in cogeneration units. Currently, in Poland, this method is the most popular and optimal in terms of energy efficiency and is economically acceptable. Occasionally, there are trigeneration installations that use waste heat in an absorption refrigeration unit to produce cold for household and/or technological purposes. The demonstrated technical potential of biogas is realistic to obtain, and the quoted amounts of electricity and heat produced in cogeneration units are potentially obtainable. The comparison of the balance of biogas produced in 2021 to the estimated technical potential in Poland is shown in Figure 2.

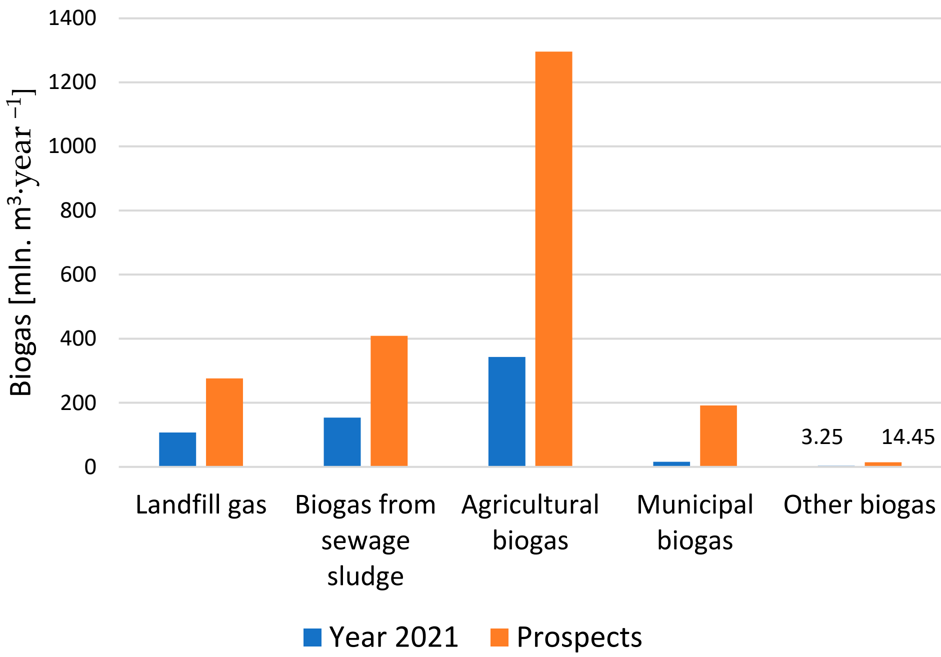

Figure 2. Current status and prospects of biogas balance [19–27,30–37].

The performed estimation of the technical potential of biogas that can be produced in Poland is more than three times higher compared to the amount of biogas used in 2012. In the prepared biogas balance, the highest estimated increase was recorded for municipal biogas, demonstrating a larger than 12-fold increment as compared to that from 2021. Additionally, the smallest increase was estimated for landfill biogas, which demonstrated a larger than 2.5-fold increment, which is related to the gradual elimination of biogas activity of landfills. In terms of quantity, the largest share is reported for agricultural biogas, with an estimated amount of 1295.61 mln m^3 of biogas able to be produced. The estimated amount of electricity and heat able to be produced in cogeneration units compared to the current state in Poland is shown in Figure 3.

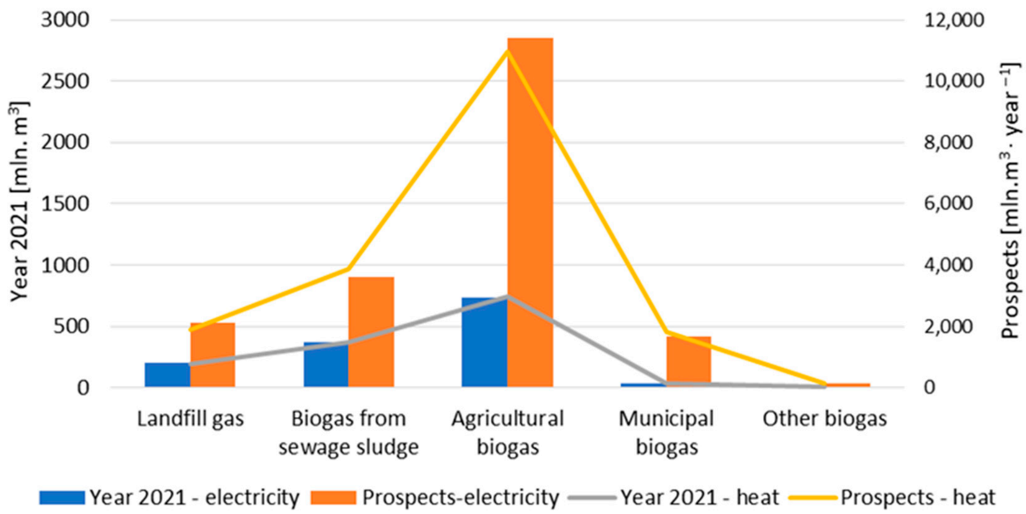

Figure 3. Current state and prospects of energy production in cogeneration units [19–27,30–37].

The largest increment in energy production from biogas, based on the estimation in relation to the state from 2021, was reported for municipal biogas, where a 12-fold increase in electricity and a 13-fold increase in heat production were reported. In terms of quantity, the greatest value of energy can be produced from agricultural biogas, which for electricity accounts for 45.7% of the total electricity and 42.7% of heat. This is a significant volume of energy in the entire energy balance of biogas.

4. Recommendations for Biogas

The European Union's strategy to reduce methane emissions, announced on 14 October 2020 by a communication from the European Commission to the European Parliament and the European Council, is consistent with the issue involving the acquisition and use of biogas, and thus the use of methane as the second most important gas after carbon dioxide responsible for global warming [40].

Consequently, there are plans to strive for climate neutrality in the European Union, which is to be achieved through a deep transformation of many sectors of the economy. This process opens up great opportunities for the production of renewable gases, including biogas. The general assumptions of the EU climate strategy expressed in the European Green Deal create a general framework for the development of biogas production, favouring its much broader use in the economic cycle (not only electricity and heat). In this aspect, an available alternative to cogeneration should also be considered, consisting of the conversion of biogas to biomethane and/or the production of biohydrogen from biogas [41]. Figure 4 shows the available methods of converting biogas into other energy carriers that can be implemented in Poland.

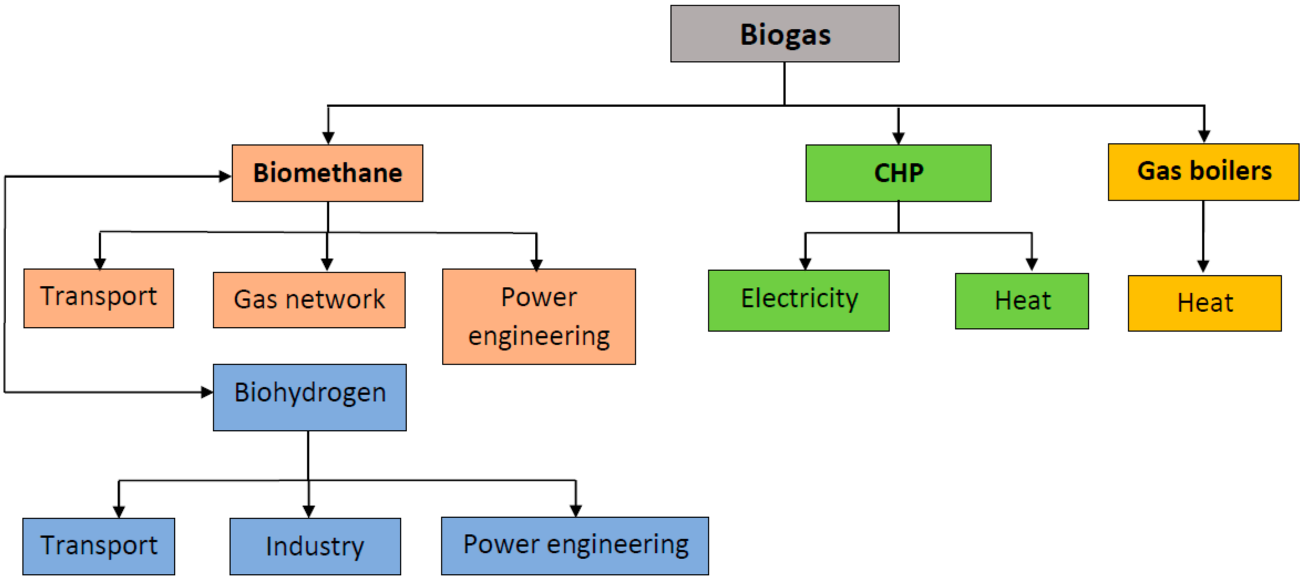

Figure 4. Conversion of biogas into other energy carriers [37,41,42].

The possibility of converting biogas into alternative energy carriers is limited by the available technology, the efficiency of this process and the costs of such an installation. In addition to the most popular methods of biogas application, such as combustion in gas boilers or energy production in cogeneration units, there are technologies available that allow, among others, the conversion of biogas to biomethane or biohydrogen [42].

The production of biomethane in dedicated installations requires that an appropriate technology is selected, and that appropriate management of the produced fuel be ensured. One of the ways to use biomethane is to inject it into the natural gas network as a source of renewable energy. Such solutions on an industrial scale are currently not used in Poland, which is mainly due to the lack of incentive effect for biomethane producers, the lack of favourable legal regulations and the need to introduce legal regulations in the context of decarbonisation of natural gas as a fossil fuel.

Upgrading biogas to meet biomethane parameters (quality of natural gas) is particularly visible and advisable in the context of energy transformation in Poland. In addition to legal and economic aspects affecting the creation of biomethane installations, a very important role is played by the technical aspect—the effective production of biomethane and its injection into local gas networks. The synergy of three entities, the legislative body, biomethane producer and gas network operator, is necessary to create a friendly formal and legal environment in order to jointly understand technical barriers and adapt the existing transmission infrastructure and quality requirements of biomethane expected from biomethane producers. The product co-produced with biomethane generated from biogas can also include bioCO_2, which is used, for e.g., in the food industry.

The biomethane obtained in the purification process can also be used locally. It can be used for transport as fuel for vehicles powered by CNG or LNG directly at the biomethane producer or in the distribution network at compressed gas refuelling stations.

Another alternative to diversify the use of biogas involves its conversion to biohydrogen and, in consequence, its storage as an energy resource to be used during periods of peak demand. Biohydrogen obtained from biogas in various technologies can be used as fuel for technological processes in the industry, for driving motor vehicles, or for generating electricity in hydrogen fuel cells.

5. Conclusions

The development of the biogas market in Poland is consistent with the circular economy system and the waste-to-energy trend. Owing to the use of various technologies for the production, conversion and management of biogas contributes to the climate neutrality and energy independence of the country. The technical balance of biogas in Poland presented in the work is one of the methods of estimating its resources and its use in cogeneration processes. The study presented in the paper was based on a practical approach to estimating the biogas potential, using document analysis consisting of the literature data, reports, current analyses and decarbonisation strategies of the energy sector. The direction chosen by the authors, the cogenerative use of biogas, is a generally accessible, low-cost solution that can be implemented in a short period of time, resulting in a large volume of energy from a renewable source. In this context, we should be open also to new biogas conversion technologies, e.g., to biomethane and biohydrogen, taking into account the sources of biogas production, its potential resources and ways of using it.

Regardless of the type of final energy carrier (biomethane, biohydrogen), biogas produced from biodegradable waste is the source of green energy which will dominate the energy balance of Poland in the coming years. When balancing energy generated from biogas and its transformation, energy losses occurring in energy conversion processes from one form to another should also be considered. Similarly, the associated additional environmental emissions must be considered.

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