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Management of Biodegradable Waste Intended for Biogas Production in a Large City

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Abstract: Biodegradable waste from households, companies, and gastronomy is not utilized in large Polish agglomerations for the production of biogas. Determining the biogas production potential in a selected agglomeration will enable the implementation of circular economy goals and sustainable development objectives. Once appropriate odor neutrality standards are met, biogas plants could be constructed around large cities, supplying both energy and heating systems to nearby housing estates or production facilities. This article aims to assess the potential of biodegradable municipal waste collected in a large city for the production of energy in specialized municipal biogas plants. The following analytical study focuses on Krakow and its surrounding municipalities. Because of its geographical location, Krakow is exposed to smog, and every action limiting the usage of carbon-based materials for heating will have a positive impact on the air quality. A biogas plant powered by municipal waste would present a viable opportunity to limit urban smog. It is also crucial that a biogas plant can store energy as it is equipped with methane tanks. Both renewable and other energy sources are still awaiting functional technical solutions that would allow for optimal energy storage.

Keywords: biogas plants; renewable energy sources (RES); energy management; circular economy; municipal biogas plant

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1. Introduction

The European Union has defined the framework for the energy and climate policy. The goals adopted in March 2007 covering the period until 2020 assumed the reduction of carbon dioxide emissions, increased use of renewable energy resources, and improved efficiency of energy use [1]. Following these assumptions, a climate and energy package was introduced in April 2009, imposing on the member states the obligation to reduce GHG emissions by 20% by 2020 compared to 2005, and to increase the production of energy from renewable sources to 20%, and biofuels up to 10%. The Directive on the Community Emissions Trading Scheme [2] is of key importance for greenhouse gas emissions, as it assumes that from 2013 all CO_2 emission allowances will be available only through auctioning. The directive requires member states to introduce effective instruments supporting the development of renewable energy infrastructure [3]. During the negotiations on the directive's final shape, Poland committed to achieving the target of 15% in 2020, and by 2030—no less than 23% of the share of renewable energy sources (RES) [4]. The climate and energy framework introduced by the European Commission in January 2014 will be in place until 2030 [5].

The sources of RES in the power industry are the sun, wind, water, biomass, and biogas. The climate changes which are observable today cause instability of hydropower and render the management of wind and solar energy supply problematic. For these reasons, "the use of biogas will be particularly useful in the combined production of electricity and heat". The advantage this approach offers is the possibility to store energy in biogas, which can be used for control purposes. In economic terms, "biogas is an added value, as it enables the management of particularly onerous waste, e.g., animal waste, landfill gases" [5].

The Act on renewable energy sources of 20 February 2015, in point 1 of Article 2, provides a general definition of biogas as "gas obtained from biomass, in particular from animal or plant waste processing installations, sewage treatment plants, and landfills" [6].

Produced through anaerobic fermentation of organic matter, biogas is a mixture of methane (40–80%), carbon dioxide (16–48%), and other gases (water vapor and hydrogen sulfide). The methane content in biogas is affected by the type of organic substance (substrate) used in the fermentation process [7,8]. Methane is also released from hard coal deposits during mining [9] and can be produced through anaerobic fermentation of organic matter generated in agricultural production, food production and processing, and municipal waste. Its emission to the atmosphere can be reduced by subjecting organic matter to controlled fermentation in specialized chambers in installations called biogas plants. Methane released into the atmosphere is very harmful to the environment as it has a CO_2 equivalent of 25 times [10]. Methane obtained in closed installations can be used not only for energy purposes. Purified to the parameters of natural gas, it can become a raw material in the production of nitrogen fertilizers and plastics. For example, Grupa Azoty's installations need approximately 850–900 m^3 of natural gas to produce 1 ton of ammonia [11]. With the development of photovoltaics combined with energy storage and heat pumps, the importance of biogas for the energy sector may decrease, but it will increase for the chemical industry, especially in situations where an embargo on natural gas supplies from countries that treat natural gas as a policy tool is introduced. Of all RES, only biogas will prove useful in such a scenario.

Large amounts of biomass are generated in agriculture and agri-food processing as well as from municipal biowaste. The requirement for using this type of waste for the production of biogas is proper handling. Producing biogas from biodegradable waste generated in large cities would be beneficial for the sustainable development of modern cities [12–15].

Previous scientific works have addressed the general concept and conditions for the use of municipal waste for the production of biogas in cities. The studies presented possibilities for collecting, neutralizing, and using biodegradable waste for energy purposes [12,16,17]. Since no data on waste categories were gathered, the calculations required to ascertain the generation potential for a specific city were not conducted. This data is necessary to take action leading to the construction of a biogas plant in a city.

The construction of a Centralized Anaerobic Digestion plant (CAD) could help achieve this goal for a large city. The construction of this type of biogas plant is based on the concept of a large central biogas plant to which organic waste from the agricultural industry, food industry, and biodegradable household waste is transported by trucks. In CAD biogas plants, all stages of biogas production, from the transport of substrates, through the fermentation process, to the collection of digestate, take place in hermetic installations [18,19]. This technology was successfully used in Denmark already in the 1980s, significantly reducing the cost of biogas production compared to the system of German biogas plants based mainly on targeted crops (e.g., corn) [20]. For biowaste to become a source of energy (and a chemical raw material—authors' note), it should be collected, segregated, and processed biologically (through methane fermentation) [21].

This article consists of Section 1, which describes the most important legal framework for energy and environmental protection in the EU as well as general information about biogas plants. Section 1.1. describes the current state of the biogas industry in Poland. Section 1.2. describes the management of biodegradable waste in Poland. Section 1.3. presents the object of research. Section 2 presents the materials and methods based on the calculations in Section 3. Section 4 describes the discussion of the methods used and the results obtained. The article ends with substantive conclusions.

This article aims to assess the potential of biodegradable municipal waste (kitchen and green waste) from a large European city (around one million inhabitants) to produce energy in municipal biogas plants. Krakow and its surrounding municipalities were chosen for this research given the poor air quality caused by urban smog. A transition to other house heating systems which is possible through access to heat and electricity obtained from a biogas plant has the potential to improve the air quality in the city, which will directly translate into health benefits for its inhabitants.

This goal is achieved through the analysis of statistical data, as well as data obtained from the Ministry of Climate and Environment and municipalities (regarding the amounts of biowaste collected in 2021). These sources became the basis for calculations for different options of utilizing biowaste for the production of biogas as well as its adoption in the cogeneration process allowing for the production of electricity and heat.

1.1. Biogas Production in Poland

The data from the Energy Regulatory Office (Table 1) shows that the number of all biogas installations increased by 35 (from 301 to 336) in 2018–2020, and the installed capacity of power generators increased by 18.67 MW (from 235.32 MW to 253.99 MW). This slight increase in the number of installations and the power of aggregates results solely from the development of agricultural biogas plants, of which five were added in the discussed period. The power of their generators increased by 15.29 MW. The amount of electricity generated from biogas reached the highest levels in 2018, but it did not exceed 1 GWh. Electricity generated from biogas had a very small share in the production of electricity from all RES, which amounted to 21.617 TWh in 2018, 25.354 TWh in 2019, and 28.227 TWh in 2020 [22].

Table 1. Electricity production in Polish biogas plants in 2018–2021.

Biogas Plants	Year	Number of Installations	Installed Power [MW]		Energy Sold [MWh]	Usage of Installed Power [%]
			Whole	Mean		
Landfills	2018	97	62.35	0.643	128,729	23.57
	2019	98	59.39	0.606	65,173	10.32
	2020	102	61.19	0.600	44,528	8.31
Sewage treatment plants	2018	109	70.28	0.661	249,443	40.52
	2019	113	72.11	0.638	279,741	44.29
	2020	114	74.82	0.656	247,990	37.84
Agricultural	2018	95	102.69	1.081	567,099	64.74
	2019	105	112.16	1.068	562,303	64.19
	2020	120	117.98	0.983	508,381	49.19
Combined	2018	301	235.32	-	945,570	-
	2019	316	243.66	-	907,218	-
	2020	336	253.99	-	800,899	-

Own study based on materials from [21].

The fewest installations receiving biogas are located in municipal waste landfills, and they sold the smallest amount of energy. In 2021, 265 municipal waste landfills were active in Poland.

The number of biogas plants installed in these facilities provided in Table 1 is similar to the number of Polish cities with over 40,000 inhabitants (108 at the end of 2021). This means that all these cities already have such biogas plants, and their number is unlikely to increase in the coming years [22].

Agricultural biogas plants have a great development potential estimated at 1.7 billion Nm^3. The use of this amount of biogas for the production of electricity and heat would make it possible to evade the costs of the right to emit 3.4 million tons of CO_2 (ETS emission rights) [23,24]. Meanwhile, at the end of 2020, the annual production capacity amounted to 476,539,626 Nm^3 of biogas, and the installed power generators reached 124,742 MW [25].

This result does not indicate an overestimation of the possibilities of agricultural biogas production provided in the aforementioned document, given that slurry from herds of more than 20 dairy cows alone can produce 573,137,100 Nm^3 of biogas containing 343,882,260 Nm^3 of methane. With such an amount of biogas, 874,078 MWh of electricity and 961,436 MWh of heat (after deduction of the heat needed in the fermentation process) can be produced [26].

Among the main factors hindering the development of agricultural biogas plants are the provisions of the Spatial Planning and Spatial Development Act. The Act does not impose an obligation to adopt local spatial development plans for the entire area of a municipality [27]. This leads to the dispersion of residential constructions, which makes it difficult to locate biogas plants that must be built at a significant distance from residential buildings. In this situation, the construction of agricultural biogas plants is only possible in sparsely populated municipalities where large farms predominate [28].

The production potential of agricultural biogas plants would increase if the plants were powered by biodegradable municipal waste.

1.2. Biowaste Used for the Production of Biogas

Segregation and collection of biodegradable waste from households, especially kitchen waste, remains a big problem. The waste is often thrown into the mixed category, contaminating it, which hinders its disposal and poses a threat to people and the environment [29]. Proper segregation of this type of waste is of fundamental importance because it allows for its mechanical and biological processing in composting facilities or biogas plants [30]. Through proper segregation, the risks associated with the uncontrolled decomposition of organic matter are eliminated. The use of biodegradable waste as a substrate for the production of biogas can reduce the operating costs of the waste management system in municipalities [29]. It would also allow for the recovery of valuable minerals (nitrogen, phosphorus, potassium), which are lost in the case of incineration of a stream of contaminated mixed municipal waste [31]. Biodegradable waste poses several challenges: it needs to be protected against rodents and insects and emits odors during collection. A solution to this problem was proposed in Sweden, where waste is collected in airtight paper bags [32].

The amount of biodegradable municipal waste generated and collected depends on the number of inhabitants of the municipality, their eating habits, ecological awareness, and the type of buildings in the area. A study conducted by the World Bank has shown that around 50% of household organic waste could be used to produce biogas. In 2025, approximately 50% of the waste generated by residents will consist of biodegradable waste [33].

1.3. Research Object

Krakow was selected for the analysis of the production and usage potential of biogas obtained from biodegradable waste. In 2021, 782,000 people lived in the city. The inhabitants of the Krakow and Wieliczka municipalities are also connected with the city through work, studies, and services. In 2021, these poviats (administrative divisions) were inhabited by 283,812 and 132,364 people, respectively. In total, 1,198,315 people lived in the Krakow agglomeration in 2021 [22] (see Figure 1).

Figure 1. Municipalities belonging to the so-called "Krakow agglomeration". Own study based on [34].

The city of Krakow has an integrated municipal waste management system, managed by Municipal Cleaning Company Sp. z o.o. This company owns a Municipal Waste Landfill and a Thermal Waste Treatment Plant. A Regional Municipal Waste Processing Installation, a biogas collection facility, and a composting plant operate at the landfill [35]. When determining the potential for biogas production, data on the amount of biodegradable waste generated in Krakow and the municipalities surrounding it, which are popularly called the "Krakow agglomeration", were used. The agglomeration consists of 14 municipalities, four of which are urban-rural (Świątniki Górne, Skawina, Niepołomice, and Wieliczka), and the rest are rural (Zielonki, Michałowice, Kocmyrzów-Luborzyca, Igołomia-Wawrzeńczyce, Biskupice, Mogilany, Czernichów, Liszki, Zabierzów, Wielka Wieś). These municipalities are inhabited by a total of 300,676 people.

2. Materials and Methods

The studies carried out so far in Poland focused only on determining the total amount of biodegradable waste generated in cities such as Krakow, Białystok, and Koszalin [30]. However, an analysis of the possibilities for the agglomeration of a large city in terms of biogas production from municipal bio-waste has not been carried out. The Krakow agglomeration seems to be a good object for research because, apart from a large amount of waste, it has land reserves in industrial zones and a network of roads enabling the transport of substrates to biogas plants.

The following research focuses on the calculation of the energy potential of biodegradable municipal waste collected in 2021 from homes and companies producing or selling food products in Krakow and its surrounding municipalities.

The initial data obtained determined the amounts of biodegradable green waste (code 20 02 01) and kitchen waste (code 20 01 08) collected. The data was obtained from the city halls and municipal offices detailed in the chapter "Research Subject". The information on the amounts of waste collected from companies was obtained from The Ministry of Climate and the Environment of Poland. The data includes information on the following waste types: 16 03 80; 02 02 03; 02 02 02; 02 02 80; 02 01 02. Table 2 presents a list of biodegradable waste which can be used for the production of biogas.

Table 2. Biodegradable waste for biogas production.

Waste Code	Type of Waste
02 01 02 [1]	Animal tissue waste
02 02 02 [2]	Animal tissue waste
02 02 03	Raw materials and products unsuitable for consumption and processing
02 02 80	Animal tissue waste with hazardous properties
16 03 80	Expired or unsuitable for consumption food products
20 01 08	Biodegradable kitchen waste
20 02 01	Biodegradable waste

[1] Code 02 01 02—from subgroup 02 01—waste from agriculture, horticulture, hydroponics, forestry, hunting, and fishing. [2] Code 02 02 02—from the subgroup 02 02—waste from the preparation and processing of food products of animal origin. Source: [36].

The production potential for biogas, electricity, and heat energy was calculated based on the collected data. To that end, a simulation showing the energy potential of biodegradable waste collected in Krakow and its surrounding municipalities was run for biogas plants powered in four different variants. The results of the calculations were used to determine the number of houses that can be powered with the electric and heat power generated in a cogeneration process at a biogas plant.

2.1. The Production Potential of Biogas in Krakow and Surrounding Municipalities

Two main types of waste are generated in households, i.e., biodegradable kitchen waste (code 20 01 08) and biodegradable waste (code 20 02 01). Kitchen biowaste (code 20 01 08) is organic waste generated at home from vegetable and fruit leftovers (peelings, spoiled fruit, etc.), food leftovers (without meat and bones), coffee grounds and tea bags, eggshells, groats, pasta, and rice. The second type of biowaste is green waste from home gardens (code 20 02 01), i.e., grass, leaves, flowers and stems, branches, etc. Both types of waste (except branches) are collected by their producers into brown bags or containers of the same color and picked up by companies collecting mixed municipal waste [37,38]. Branches are transported by waste producers to special locations and placed in suitable containers. Information on the amounts of biodegradable waste collected in 2021 is presented in Table 3.

Table 3. Amount of waste in tons collected in households in the city of Krakow and the surrounding municipalities in 2021.

Municipality	Amount of Waste [Mg]	
	Code 20 02 01	Code 20 01 08
Świątniki Górne	492.2	0
Mogilany	185.0	969.56
Skawina	1005.2	84.12
Czernichów	679.5	0
Liszki	129.2	594.78
Zabierzów	3049.3	3.16
Wielka Wieś	1090.7	0
Zielonki	38.0	1226.77
Michałowice	451.5	0
Kocmyrzów-Luborzyca	1484.2	0
Igołomia-Wawrzeńczyce	0	0

Table 3. *Cont.*

Municipality	Amount of Waste [Mg]	
	Code 20 02 01	**Code 20 01 08**
Niepołomice	4169.1	0
Biskupice	480.9	0
Wieliczka	1080.0	0
Total municipalities surrounding Krakow	1433.7	2878.4
Krakow	49,826.0	19,003.3
Together with Krakow	64,160.7	21,881.7

Own study based on [39–53].

Households in the "Krakow agglomeration" produce the largest amounts of biodegradable waste code 20 02 01. The greatest amount of this type of waste was collected in the Niepołomice municipality. The city's most common buildings are single-family houses on small plots of land where biowaste cannot be composted. In Niepołomice, due to the compact size of plots, home composters are a rarely used solution. The rural area of the Niepołomice municipality is characterized by single-family houses, where biodegradable waste is composted on-site. The second in terms of the amount of waste code 20 02 01 collected is the Zabierzów rural municipality. In Zabierzów, single-family housing predominates, and it is also not possible to compost biodegradable waste. This type of waste was not collected at all in the Igołomia-Wawrzeńczyce municipality, due to the predominantly agricultural nature of the area [39–53].

The second type of waste produced in 2021 in households of the municipalities above is categorized as biodegradable kitchen waste with code 20 01 08. The largest amount of biowaste of this type was collected in the following municipalities: Zabierzów, Mogilany, and Liszki. Much of it is wasted food. In Poland, it amounts to about 90 kg/person annually.

Biowaste for use in biogas plants can also come from stores and food production companies. Biodegradable waste in the former comes from food products that are expired or unsuitable for consumption (code 16 03 80). These include spoiled vegetables and fruit, stale bread, meat, and sausages, expired dairy products, food in opened packages, or frozen food subjected to temperatures exceeding the safe limit for storage. Animal tissue waste (code 02 01 02 and code 02 02 02), raw materials, and products unsuitable for consumption and processing (code 02 02 03) originate from food processing plants [36].

Table 4 shows the data on the amount of biodegradable waste generated in 2021 in companies operating in the municipalities of the "Krakow agglomeration". It shows that the largest amount of biodegradable waste was generated by companies in the Niepołomice municipality. This waste was predominantly "raw materials and products unsuitable for consumption and processing" (code 02 02 03) and "expired or unsuitable for consumption food products" (code 16 03 80). Similar results can be observed in other municipalities.

Table 4. Amount of waste in tons collected in companies in Krakow and the surrounding municipalities in 2021.

Municipality	Waste Code				
	16 03 80	**02 02 03**	**02 02 02**	**02 02 80**	**02 01 02**
Krakow	553.56	0	0	0	0
Zielonki	0.02	0.53	0	0	0
Michałowice	84.31	0	0	0	0
Kocmyrzów-Luborzyca	0	0.09	0	0	0
Igołomia-Wawrzeńczyce	0	0	0	0	0

Table 4. *Cont.*

Municipality	Waste Code				
	16 03 80	02 02 03	02 02 02	02 02 80	02 01 02
Niepołomice	217.98	3840.95	0	0	0
Biskupice	0	0	0	0	0
Wieliczka	286.04	0	0	0	0
Świątniki Górne	21.19	0	0	0	0
Mogilany	66.64	0	0	0	0
Skawina	142.25	0	4.19	0	0
Czernichów	27.46	0	0	0	0
Liszki	463.10	0	0	0.87	0
Zabierzów	227.79	0.21	0	0	2.28
Wielka Wieś	102.26	56.91	0	0	0
Total	2192.58	3898.68	4.19	0.87	2.28

16 03 80—Expired or unsuitable for consumption food products. 02 02 03—Raw materials and products unsuitable for consumption and processing. 02 02 02—Animal tissue waste. 02 02 80—Animal tissue waste with hazardous properties. 02 01 02—Animal tissue wasteOwn study based on [54].

2.2. Possibilities of Producing and Utilizing Biogas from Biodegradable Waste

The assessment of the potential of biogas production is based on the information on the amounts of substrates available for biogas plants in the city of Krakow and the municipalities of the "Krakow agglomeration". The simulation was carried out in four variants:

Variant 1—production of biogas from waste with codes 20 01 08 and 20 02 01 collected from households in municipalities from the "Krakow agglomeration" (Figure 2). In this variant, the total amount of substrates collected in 2021 reached 17,213 tons, including 14,335 tons of code 20 02 01 waste, and 2878 tons of code 20 01 08 waste (Table 3).

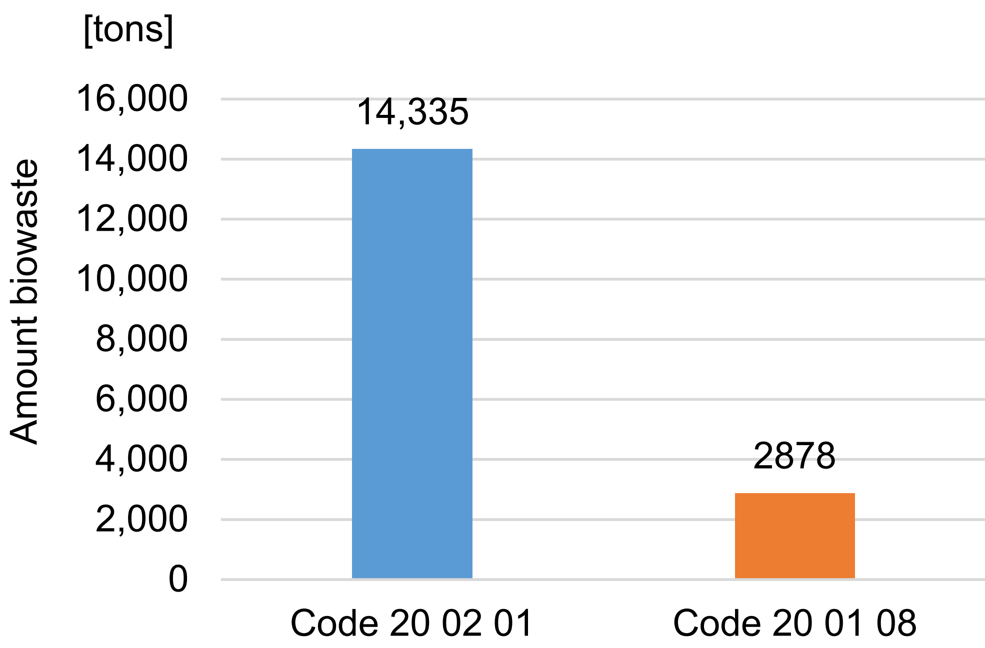

Figure 2. Amount of biowaste collected in Variant 1.

Variant 2—production of biogas from waste with codes 20 01 08 and 20 02 01 collected from households in Krakow and municipalities from the "Krakow agglomeration"

(Figure 3). In this variant, the total amount of waste collected in 2021 reached 86,043 tons, including 64,161 tons of code 20 02 01 waste and 21,882 tons of code 20 01 08 waste.

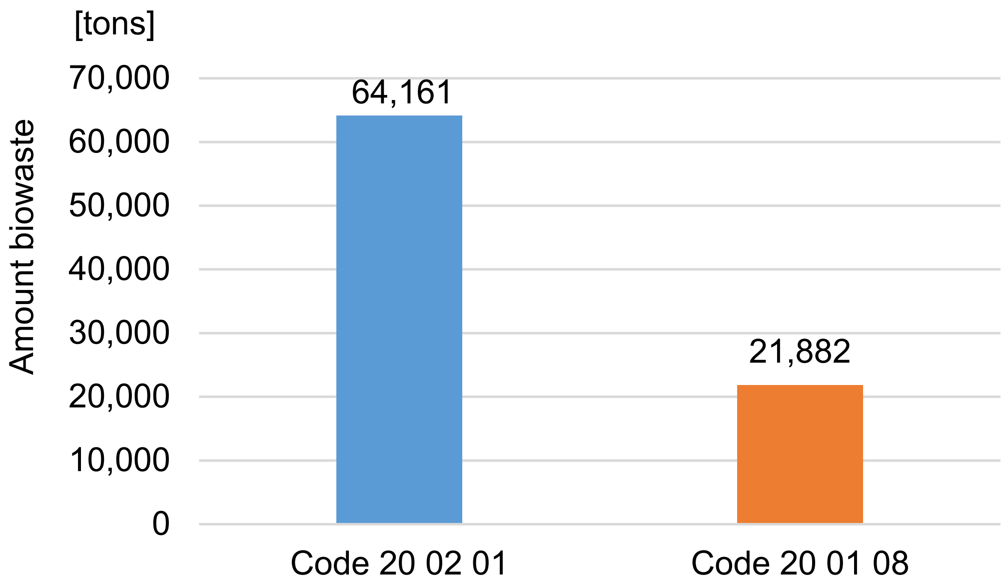

Figure 3. Amount of biowaste collected in Variant 2.

Variant 3—production of biogas from waste with codes 20 01 08 and 20 02 01 collected from households in Krakow (Figure 4). In this variant, the total amount of waste collected in 2021 reached 68,829.3 tons, including 49,826.0 tons of code 20 02 01 waste and 19,003.3 tons of code 20 01 08 waste.

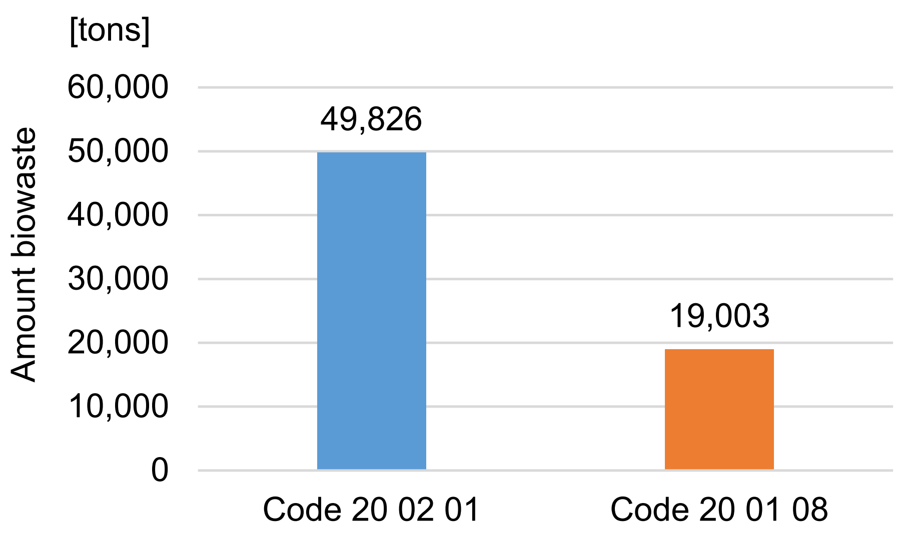

Figure 4. Amount of biowaste collected in Variant 3.

Variant 4—production of biogas from waste with codes: 16 03 80, 02 02 03, 02 02 02, 02 02 80, 02 01 02 generated in companies in Krakow and municipalities from the "Krakow agglomeration" (Figure 5). In this variant, the total amount of waste collected reached 6098.65 tons.

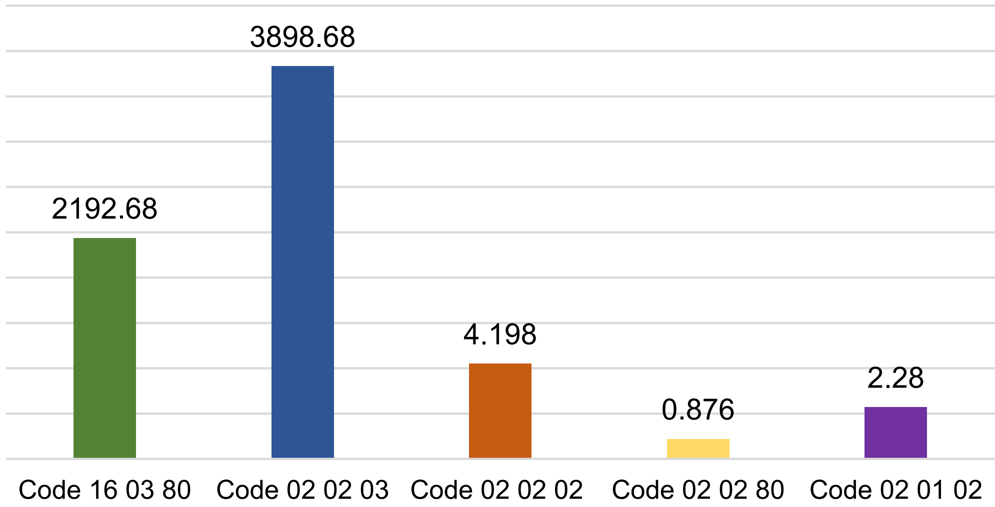

Figure 5. Amount of biowaste collected in Variant 4.

Figure 6 shows the total amount of biowaste collected for individual variants.

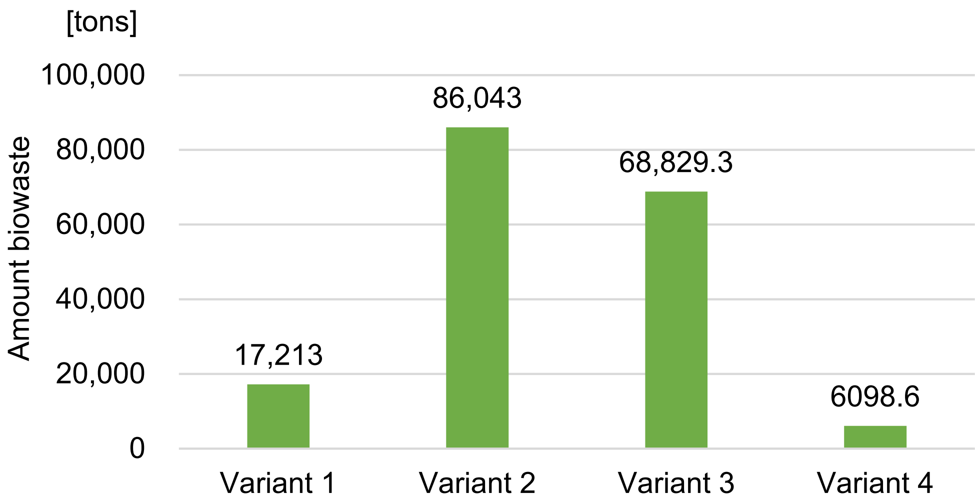

Figure 6. Total amount of biowaste collected for specific variants.

The collected data did not include information on the content of dry matter in the waste used to power the biogas plant, so for the calculations, a biogas yield corresponding to 1 ton of fresh mass ($\mathbf{t_{fm}}$) was assumed. The following biogas yield was assumed for municipal waste code 20 02 01: $\boldsymbol{V_{bg}}$ = 250 Nm^3/$\mathbf{t_{fm}}$, code 20 01 08: $\boldsymbol{V_{bg}}$ = 250 Nm^3/$\mathbf{t_{fm}}$, codes 1*–5*: $\boldsymbol{V_{bg}}$ = 500 Nm^3/$\mathbf{t_{fm}}$. The yields proposed were taken from the references below [7]. Assuming the biomethane content of $\boldsymbol{C_{bm}}$ (from Table 5) in biogas produced from 1 ton of specific waste, the heating value of biomethane $\boldsymbol{V_{bm}}$ $\boldsymbol{W}$ Nm^3/$\mathbf{t_{fm}}$ was calculated using the following formula:

$$\boldsymbol{V_{bm}} = \boldsymbol{V_{bg}} \cdot \frac{\boldsymbol{C_{bm}}}{100} \tag{1}$$

Assuming the heating value of biomethane of $\boldsymbol{W}$ = 9.3 kWh/Nm^3 (Figure 5), the total energy $\boldsymbol{E_t}$ found in biomethane obtained from 1 $\mathbf{t_{fm}}$ of biowaste was calculated with the following Formula (2):

$$\boldsymbol{E_t} = \boldsymbol{V_{bm}} \cdot W \tag{2}$$

Electricity E_e and heat energy E_h obtained from 1 $\mathbf{t_{fm}}$ of substrate was calculated with Formulas (3) and (4):

$$E_e = E_t \cdot \frac{\eta_e}{100} \quad (3)$$

$$E_h = E_t \cdot \frac{\eta_t}{100} \quad (4)$$

where: η_e—electricity yield, η_t—heat energy yield.

The electric power of the generator P_e was calculated with the following Formula (5):

$$P_e = \frac{E_e}{T_w} \quad (5)$$

where T_w—generator runtime.

The thermal power of the generator P_h was calculated with the following Formula (6):

$$P_h = \frac{E_h}{T_w} \quad (6)$$

Table 5. Values adopted for the calculation of yields of biogas, biomethane, electricity, and heat.

Quantity	Symbol	Unit	Waste Codes		
			20 02 01	20 01 08	1*–5*
Amount of biogas	V_{bg}	m^3/t	250	180	500
Biomethane content in biogas	C_{bm}	%	56	60	65
Calorific value	W	kWh/Nm^3	9.3	9.3	9.3
Electricity yield	η_e	%	35	35	35
Heat energy yield	η_h	%	55	55	55
Generator runtime	T_w	h/year	8000	8000	8000

1*. Code 16 03 80—Expired or unsuitable for production food products. 2*. Code 02 02 03—Raw materials and products unsuitable for consumption and processing. 3*. Code 02 02 02—Animal tissue waste. 4*. Code 02 02 80—Animal tissue waste with hazardous properties. 5*. Code 02 01 02—Animal tissue waste. Own study based on [7].

3. Results

For the calculations of the annual yield of biogas, biomethane, electricity, and heat, values from Table 5 were adopted.

Microsoft Excel was used for all four calculation variants for the amounts of biowaste assuming the values presented in Table 5. Table 6 presents amounts of biogas, biomethane, electric power, and heat energy which can be generated.

Table 6. Possible production of biogas, biomethane, and energy from biodegradable waste generated in households in 2021.

Item	Symbol	Unit	Variant 1	Variant 2	Variant 3	Variant 4
Waste code 20 02 01	-	tons/year	14,335	64,161	49,826	-
Waste code 20 01 08	-	tons/year	2878	21,882	19,003.3	-
Waste with codes 1*–5*	-	tons/year	-	-	-	6099
Total waste	-	tons/year	17,213	86,043	68,829	6099
Amount of biogas	V_{bg}	$m^3/year$	4,101,790	19,979,010	15,877,094	3,049,325

Table 6. *Cont.*

Item	Symbol	Unit	Variant 1	Variant 2	Variant 3	Variant 4
Amount of biomethane	V_{bm}	m^3/year	2,317,724	11,345,796	9,027,996.4	1,982,061
Total energy	E_t	MWh/year	21,555	105,516	83,960	18,433
Electricity	E_e	MWh/year	7544	36,931	29,386	6452
Power electricity of the generator set	P_e	MW	0.9	4.6	3.7	0.8
Heat energy from cogeneration	E_h	MWh/year	10,822	58,034	39,354	10,138
Heat energy for fermentation	E_h	MWh/year	3247	17,410	11,806	3041
Heat energy for sale	E_h	MWh/year	7575	40,624	27,548	7096
Power heat of the generator set	P_h	MW	1.35	7.2	4.9	1.2

1*. Code 16 03 80—Expired or unsuitable for consumption food products. 2*. Code 02 02 03—Raw materials and products unsuitable for consumption and processing. 3*. Code 02 02 02—Animal tissue waste. 4*. Code 02 02 80—Animal tissue waste with hazardous properties. 5*. Code 02 01 02—Animal tissue waste.

Nearly all obtained electricity can be sold to a power system operator, as can about 70% of the heat energy. The remaining 30% is allocated to sustain the methane fermentation process.

Based on the data from Table 6, Figure 7 shows the potential for biogas and biomethane production from 1 ton of biodegradable waste (originating from home gardens—code 20 02 01), kitchen waste (code 20 01 08) and waste from food production and distribution companies (codes: 16 03 80, 02 02 03, 02 02 02, 02 02 80, 02 02 01). Figure 7 shows that the greatest amount of biogas can be produced from waste generated by companies. However, this kind of waste contains a large amount of protein and fats (nitrogen compounds). It is, therefore, important to keep the C:N (carbon to nitrogen) ratio between 10:1 to 25:1 [55].

From the above-mentioned waste, it is possible to obtain approximately 43,382 MWh/year of energy and heat in excess of 68,172.04 MWh/year, of which 47,720 MWh/year is intended for sale (the rest of the heat is needed for technological processes at the biogas plant). Figure 8 details the calculations.

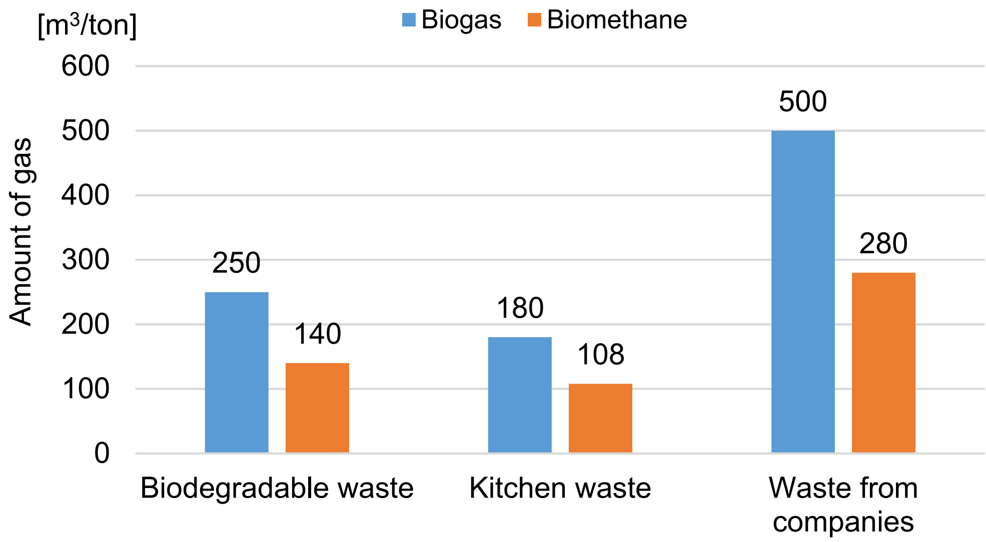

Figure 7. Potential biogas and biomethane production [m^3] from 1 ton of biowaste generated in households and by companies in 2021.

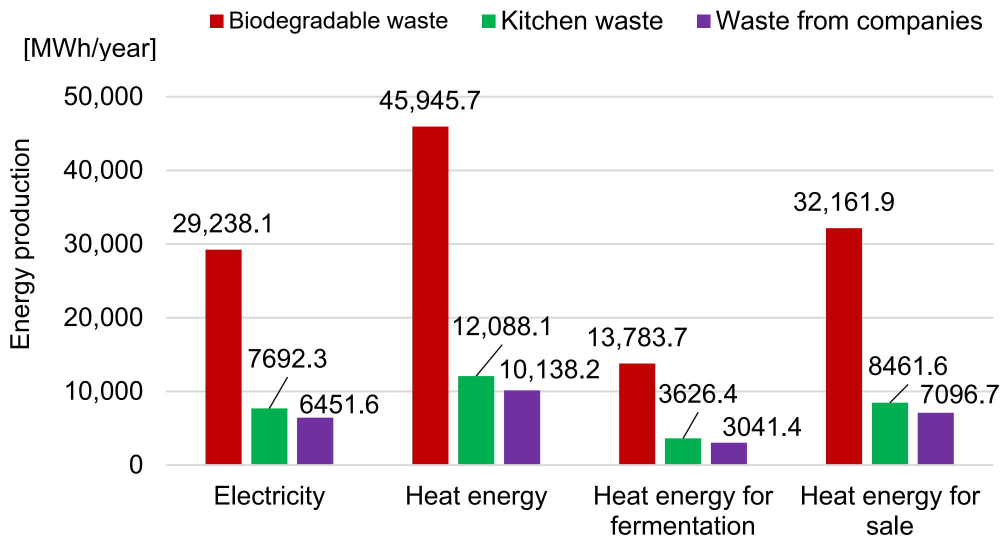

Figure 8. Production of electricity and heat [MWh/year] from the waste collected from households and companies in the city of Krakow and the "Krakow agglomeration".

Such an amount of energy can be used to power and heat houses and buildings in cities. As was mentioned previously, biogas is largely combusted in cogeneration units which generate electricity and heat. For this analysis, we assumed the energy demand of a single-family house without a basement, with a usable area of 110 m^2, well-insulated, and without a garage. The house is heated with a modern dual-function gas boiler with 98% efficiency. The annual energy consumption for space heating and domestic hot water reaches e_t = 7.5 MWh/year. The electric energy usage of such a house is assumed to be e_e = 3 MWh/year. Assuming the numbers for electricity E_e and heat power for sale E_{ts}, we can calculate the number of houses N_e and N_t which can be powered by the energy generated by the studied biogas plant. For that purpose, we are using the following Formulas (7) and (8).

$$N_e = E_e / e_e \tag{7}$$

$$N_t = E_{ts} / e_t \tag{8}$$

The results of these calculations are presented in Table 7. From the data presented in that table, it becomes clear that Variant 2 allows for the heating of 5416 houses and can supply energy to 13,541 houses. Another great set of results can be found in Variant 3, where the generated energy can heat 3673 houses and supply electric power to 9182 houses. These results are also presented in Figure 9.

Table 7. The possibility to cover the electricity and heat energy needs for houses based on analyzed variants.

Details	Symbol	Variant 1	Variant 2	Variant 3	Variant 4
Number of houses powered with electricity	N_e	2 525	13 541	9 182	2 150
Number of houses powered with heat energy	N_t	1 010	5 416	3 673	946

Once treated, the biomethane contained in biogas can also be compressed and used to fuel cars, tractors, or other machines [8,56–59]. Assuming a single filling of a cylinder with compressed biomethane at 200 Nm^3, the produced amount of biogas would suffice to fill 11,588 such cylinders in Variant 1, 56,729 in Variant 2, 45,140 in Variant 3, and 9910 in Variant 4.

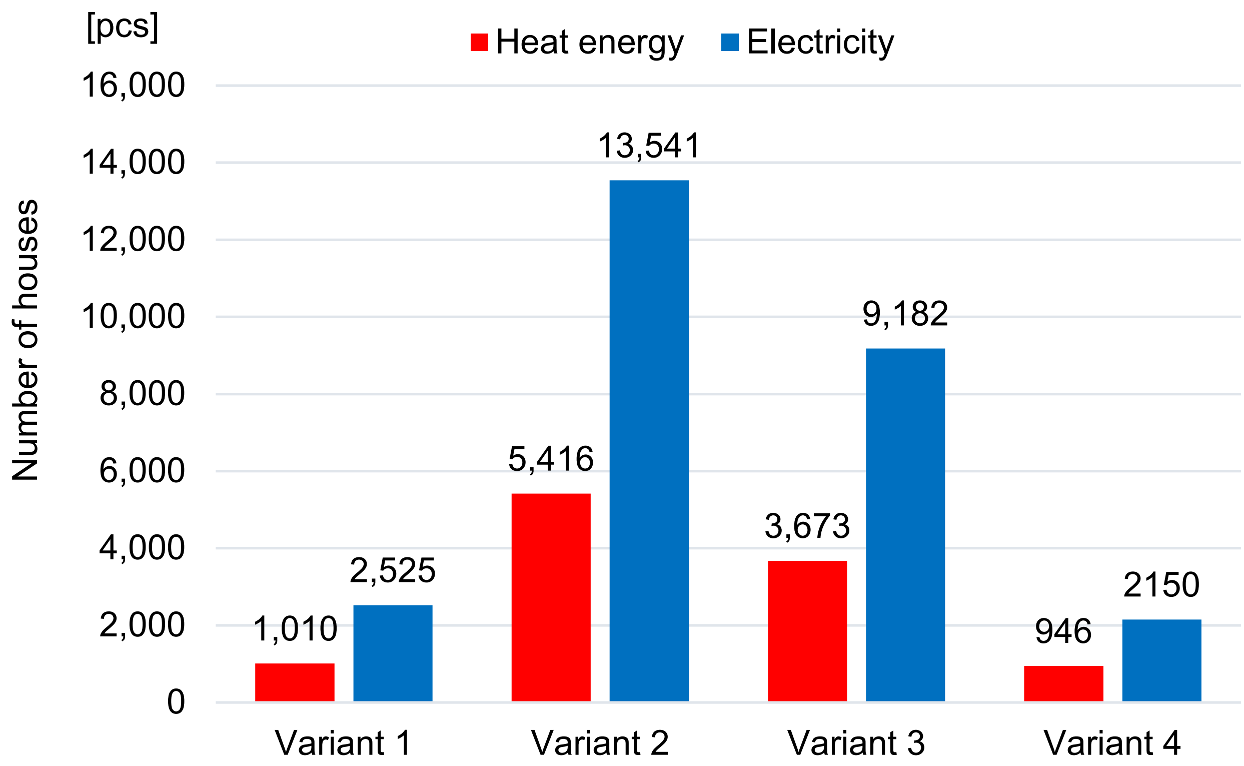

Figure 9. Number of standard houses that can be supplied with electricity and heat from biogas produced from waste for the four studied variants.

4. Discussion

Based on the simulations conducted for described variants of powering for a biogas plant it is possible to determine the optimal power of such a plant. The best option is a plant with an installed capacity of 1 MW which utilizes about 30 tons of biowaste per year [60]. It is also important to consider the potential location of a biogas plant. To determine one, it is advised to consider the possibility to obtain substrates from producers of biodegradable waste, such as households, food producers, gastronomy, school canteens, preschools, and hospitals [61]. An important factor that should inform the decision on the localization is the vicinity of suppliers of substrates used for biogas production, as well as the possibility to manage the post-fermentation mass locally by urban green services or farmers. According to the circular economy assumptions promoted in the EU, digestate should be viewed as fertilizer rather than a troublesome waste [62].

Despite the numerous benefits of digestate, a challenge may arise in fully utilizing the large quantities produced after substrate fermentation. Additionally, there is a potential concern regarding the presence of heavy metals in the digestate, which could result from using grass clippings from urban green spaces as a substrate. In such cases, the digestate may not be suitable for agricultural use as a fertilizer. However, it can still be employed to fertilize urban green areas, roadside greenery, and the remediation of post-industrial sites [63–65].

Once utilized as fertilizer, the digestate mass can replace chemical fertilizers, improving the quality of soil and lowering emissions of odors [66]. The possibility to incorporate the electrical systems into the energy network is yet another beneficial aspect of the proposed solution. It requires the decision of a local distribution network operator following the analysis of system parameters [67]. Managing the substantial amounts of heat generated during the cogeneration process could pose a challenge. Any unused heat would be released into the atmosphere, leading to increased warming. It is worth considering the construction of heating networks in newly developed single-family housing estates or integrating new sections into the existing heating infrastructure to address this issue [68,69].

Biogas plants are economically cost-effective and technologically feasible given the current state-of-the-art knowledge. The production of energy in such installations leads to the reduction of costs of waste management. Total savings can contribute to annual income, improving the economic results of the investment [70]. From the economic perspective, a constant technological process is crucial, so the best variant would be to generate electricity and heat energy through cogeneration processes. The surplus of heat energy can be sold or distributed to nearby houses [71]. Substrates should be stored in airtight containers at the investment area to prevent potential odor emissions [72].

The undertaking does not lead to a significant, negative impact on local communities and the environment. Long-term, the biogas plant will contribute locally to the improvement of air quality, reducing the popularity of fossil fuel-based heating sources. It will lead to lowered CO_2 emissions [73], and the generated energy will not be subjected to emission-related fees imposed by the European Union [26]. A biogas plant directly contributes to Sustainable Development Goals. The production of biogas will contribute to the realization of the seventh SDG goal, namely "Affordable and Clean Energy". This will be realized through the increased involvement of RES in the energy mix as well as through the development of infrastructure empowering rural areas [74] to benefit from modern and sustainable energy solutions. A biogas plant would also contribute to the thirteenth SDG—"Climate Action"—through proper biowaste segregation and fermentation in municipal biogas plants. Biogas generated in them is a renewable energy source that does not pollute the air in the cities [75]. Municipal biogas plants are important for the realization of the assumptions of circular economy as they can transform burdensome waste into an energy resource, downscaling the usage of fossil fuels.

Lack of progress in the buildout of municipal biogas plants may cause difficulties in realizing the Energy Policy of Poland until 2030 relating to the development of the renewable energy sector. It may also hinder the progress towards achieving the goal of the Directive of the European Parliament 2009/28/WE on promoting the usage of energy obtained from renewable sources [4,76]. To realize the Sustainable Development Goals, as well as the EU and Polish policies, the community should be engaged in putting them into action. To achieve that, it is necessary to begin from the basics: proper biowaste segregation and the introduction of a system that would allow for the collection and utilization of waste in biogas plants [12,77,78].

5. Conclusions

Biodegradable waste subjected to methane fermentation in biogas plants is a renewable source of energy that is more stable than the sun and wind. Biogas obtained through this kind of fermentation can be directly used to produce electricity and heat.

Currently, agricultural biogas plants in Poland produce biogas from agricultural, livestock farming, and agri-food industry waste, and to a small extent—waste from targeted crops. This is due to the government of the Republic of Poland granting them a special status ensuring higher profitability. Biogas plants operating at municipal sewage treatment plants and installations collecting biogas at municipal waste landfills also exist. Biogas from all installations is burned in cogeneration units. The amount of electricity produced is less than 1 TWh and constitutes an insignificant portion of the energy produced via all RES.

There are no biogas plants in Poland utilizing municipal biowaste from households and green areas within cities. According to simulation studies carried out for the city of Krakow and the surrounding municipalities, this kind of waste has a significant biogas production potential. It can provide the raw material for one or several biogas plants with a total installed capacity of about 5 MW. With such power, the production of electricity could reach 37 GWh per year, and the sale of heat energy to the municipal network—about 41 GWh. Given the development of the Krakow metropolis and the potential of other municipalities of the Krakow and Wieliczka municipalities, the production of electricity and heat could even double.

For a biogas plant utilizing municipal waste to function properly, efficient waste collection and transport systems need to be developed. The waste should be collected frequently (several times a week) and in airtight containers. This would ensure the residents would not have to bear the inconvenience of waste-related odors.

The use of biodegradable municipal waste can reduce the operating costs of waste management, and thus reduce the fees for their production. To succeed, the project would have to receive financial support in the form of the funds allocated for the energy transformation devised by the European Union.

The analysis described in this article allows us to determine that large cities have the potential to use the so-called municipal waste for the production of electricity via cogeneration processes. As a production facility, a biogas plant offers the possibility to utilize municipal waste, protect the natural environment of a city, reduce the costs borne by a city on currently available waste utilization, and can be an efficient source of heat and electricity. Heat and electricity generated in a biogas plant have the potential to significantly change the predominant methods used for house heating as they eliminate the combustion of coal, petroleum, and natural gas. A change in the technology used to heat housing estates will lead to a significant improvement in the air quality in the cities. The technological process of a biogas plant is run on commonly available input materials and would grant energy security to the country.

Production of biogas from municipal waste supports the realization of the circular economy assumptions, which is why the National Fund for Environmental Protection and Water Management launched a program called "The development of cogeneration based on municipal biogas plants" in 2023. The program grants financial aid to local governments willing to build out municipal biogas plants. The program is expected to receive about PLN 1.5 billion in funding [79].

The current technological process makes it possible to store biogas. It is a crucial point given how volatile and unpredictable other energy production sources can be. Biogas plants are equipped with modern technical solutions which ensure that any odors remain contained within, making it possible for the biogas plants to be built in the vicinity of cities.

The realization of the assumptions of biodegradable waste management used for the production of biogas can be supported by the smart city 3.0 concept. The concept assumes systemic management over particular elements of the infrastructure, taking into account balanced economic development and pro-ecological social and financial solutions in the EU. Rational waste management as presented by the smart city 3.0 concept requires planning, execution, and motivation [80].

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