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Management of Bio-Waste Generated in the Krakow Metropolitan Area in the Context of Circular Economy Strategies for Residential Heating

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Abstract

The article assesses the energy potential of biodegradable municipal waste in the Krakow Metropolitan Area, analyzing the feasibility of using derived biomethane for residential heating by 2050. Framed within the circular economy and the European Green Deal, the study highlights a significant technological gap in Poland, contrasting it with successful models in Austria, Germany, and Italy. Empirical data from 2023–2024 indicate that kitchen waste (code 20 01 08) is an optimal feedstock for methane fermentation due to its stable annual flow, whereas green waste (code 20 02 01) presents challenges due to high seasonality. Simulation modeling suggests that annual biomethane production from kitchen waste could range from approximately 1.23 million m^3 (Variant 3) to over 1.42 million m^3 (Variant 4). A key finding is the synergy between waste-to-energy transformation and building thermal modernization. By reducing energy demand, the consistent volume of kitchen waste processed from 2024 could potentially supply heating for between 4928 and 8180 apartments by 2050. Ultimately, the research underscores the role of metropolitan integration in achieving sustainable development goals, enhancing regional energy security, and reducing emissions.

Keywords: waste management; biomethane; waste-to-energy strategies; sustainability

1. Introduction

One of the key foundations of the European Green Deal is the transition from a linear economy to a circular economy model [1]. In this model, waste is no longer a problem and becomes an essential raw material. This necessitates increasing the level of municipal waste segregation and minimizing the mixed waste stream. These efforts should focus on maximizing resource utilization in line with the 6R concept, which encompasses—among other things—reduction, reuse, and recycling [2]. The EU strategy on biodegradable waste management plays a key role in the future sustainability of the EU economy—an economy based on the use of natural resources to provide food, energy, and materials, while simultaneously strengthening the Community's resource independence and competitiveness. Municipal Waste Europe (MWE), the European Compost Network (ECN), and the European Biogas Association (EBA) support this strategy, as it represents a significant step toward achieving a circular economy in Europe [3,4].

The disposal of biodegradable waste leads to a reduction in greenhouse gas emissions such as carbon dioxide, methane, and water vapor. This waste is utilized systematically

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to generate renewable energy in facilities such as biogas and biomethane plants, which can be integrated with other renewable energy installations [5,6]. According to the European Biomethane Map, Europe is a major player in the biomethane market, having reached an installed production capacity of 6.4 billion m^3 of biomethane per year; 81% (5.2 billion m^3) of this capacity is accounted for by plants located within the European Union. The highest numbers of biogas and biomethane plants are located in Germany, Italy, and Austria—countries highlighted in the context of the potential to produce biogas and biomethane from the waste materials analyzed in this article [7]. A well-organized waste management system encourages waste generators to handle waste properly and fosters the development of numerous biomethane production facilities. The volume of collected biodegradable waste is steadily rising, leading to a consistent increase in the number of biogas and biomethane production plants. Improvements are being made to existing waste segregation rules to further enhance the efficiency of the biodegradable waste collection system [8–13].

Germany leads the way in implementing circular economy principles and developing biogas and biomethane plants. In 2025, the country operated over 11,000 biogas plants and 272 biomethane plants, injecting 1.4 billion cubic meters of biomethane into the grid annually. Germany has set an ambitious target of producing 35 billion cubic meters of biomethane by 2030, a key element of the country's decarbonization strategy. This goal can be achieved by converting existing biogas plants—which currently generate electricity and heat via cogeneration—into biomethane plants that feed gas into the local gas network [14–16]. Meanwhile, there are around 350 biogas plants operating in Austria, and biogas meets approximately 2% of the country's total gas demand. Plans are in place to increase biogas production in the near future, with a tenfold increase targeted by 2030 [17]. Vienna is an example of a city where biodegradable waste management is conducted in line with circular economy principles. The Austrian capital is home to the Simmering biogas plant, which operates in conjunction with the district heating network. Additionally, a facility producing biomethane from kitchen waste operates in the Simmering district. The biomethane produced is fed into Vienna's gas grid. The plant generates approximately 1 million cubic meters of CO_2-neutral biomethane annually, utilizing around 22,000 tonnes of kitchen bio-waste. This biomethane supplies energy to approximately 900 households in Vienna, resulting in an annual reduction of 3000 tonnes of CO_2 emissions [18]. The results achieved have led Vienna to plan a doubling of the Simmering plant's capacity to between 34,000 and 50,000 tonnes of biodegradable waste per year [19]. The planned increase in biomethane production aims to achieve climate neutrality for Vienna by 2040 [20]. Italy is another country implementing circular economy principles. Legislation there is fostering the growth of the biogas market, driven by the MITE Decree of 15 September 2022, which introduced a plan to reduce natural gas consumption [21]. This document has created better opportunities in Italy for the construction of new biomethane production facilities, with the biomethane being injected into the gas grid or used to fuel vehicles [22]. Italy is currently undergoing an energy transition, shifting from the generation of electricity and heat in biogas plants to the production of biomethane with specifications matching high-methane natural gas. In 2025, there were 137 biomethane plants and biomethane production capacity reached approximately 873 million cubic meters per year [23,24].

The situation differs in countries that joined the EU after 2004. Above all, there are significant differences in the efficiency of the separate collection of biodegradable waste. Poland is one such country. Waste management regulations are aligned with EU directives. The Polish waste management system is based on several key legal regulations, one of which is the Waste Act [25], according to which waste management should be conducted in a manner that ensures the protection of human life and health as well as the environment.

The Act also contains guidelines regarding the handling of specific types of waste and the obligations of entities that generate and collect waste [26]. This Act establishes the framework for the recycling of biodegradable waste, mandating its separate collection for recovery processes (composting and fermentation). National Waste Management Plans are developed based on the Waste Act; these plans support efforts to achieve the objectives and meet the requirements set out in EU waste management legislation [27]. Another important document is the Act on Maintaining Cleanliness and Order in Municipalities. It defines the specific tasks of the municipality and the obligations of property owners, and regulates, among other things, the conditions for collecting municipal waste from property owners and the management of such waste [28]. Another important document regulating waste management procedures is the Waste Catalogue [29]. Municipal waste, including separately collected fractions, is classified under the final category: Group 20. This group includes biodegradable waste collected from households, such as biodegradable kitchen waste (code 20 01 08) and biodegradable waste (code 20 02 01). Waste management in Poland is based on the Unified Waste Segregation System (JSSO). Introduced in 2017, this system applies nationwide. Since then, municipal waste has been collected in five main fractions using color-coded containers: paper (blue), metals and plastics (yellow), glass (green—or, if the fraction is separated into clear and colored glass: clear glass [white] and colored glass [green]), bio-waste (brown), and mixed waste (black) [30]. The method of waste segregation is also regulated by the Regulation of the Minister of Climate and Environment on the method of selective collection of selected waste fractions, which precisely specifies the types of waste collected selectively [31].

A significant issue within the Polish bio-waste management system is the lack of municipal biogas and biomethane plants that utilize green bio-waste (code 20 02 01) and kitchen waste (20 01 08) for biogas production in large and medium-sized cities. Currently, the municipal biodegradable waste stream is processed primarily into compost. Poland does have facilities for agricultural biogas production, as well as biogas plants at wastewater treatment plants and landfills [32]. Data for 2025 show that the Polish biogas sector surpassed a total of 400 installations (including agricultural and municipal biogas plants, as well as those at wastewater treatment plants and landfills). According to the National Support Centre for Agriculture (KOWR) registry, 210 large agricultural biogas installations were operating in Poland in 2025. Of these, two produced biomethanes while the remainder produced biogas used for the combined generation of electricity and heat. Estimates by the Energy Regulatory Office and market reports indicate that the rest of the market (approximately 120–130 installations) consisted of biogas plants at wastewater treatment plants and landfill gas recovery facilities. Additionally, 79 agricultural micro-biogas plants were in operation [32]. Poland lacks municipal biogas plants that utilize green and kitchen bio-waste collected in urban areas. This stands in stark contrast to European standards, where the processing of urban bio-waste in dedicated municipal biogas plants is common practice, enabling the effective implementation of circular economy principles [33].

In 2025, the first biomethane production facilities began operating in Poland. Unlike standard biogas plants, where the produced biogas is burned, these facilities purify the gas to meet the specifications of high-methane natural gas and inject it directly into the gas grid. The absence of municipal biogas and biomethane plants means that Polish cities are irretrievably losing the energy contained in organic waste. Poland's current waste management structure reveals a significant technological gap in the municipal sector; namely, that urban bio-waste management systems remain technologically outdated.

The purpose of this article is to analyze the biodegradable waste management system as well as to estimate the general energy potential and feasibility of generating energy from household kitchen bio-waste collected in Krakow and the municipalities of the Krakow

Metropolitan Area within the context of residential space heating. This objective was achieved by conducting a comprehensive literature review, evaluating industry portals and local government resolutions, and utilizing data for the year 2024 provided by the Marshal's Office of the Malopolskie Voivodeship.

2. Methods

2.1. Research Objective

The Krakow Metropolitan Area was selected to analyze the biodegradable waste management system and calculate the potential for biomethane production from bio-waste. It comprises Krakow and 14 municipalities, four of which are urban-rural municipalities (Swiatniki Gorne, Skawina, Niepolomice, and Wieliczka), and the remainder of which are rural municipalities (Zielonki, Michalowice, Kocmyrzow-Luborzyca, Igolomia-Wawrzenczyce, Biskupice, Mogilany, Czernichow, Liszki, Zabierzow, and Wielka Wies). At the end of 2023, the Krakow Metropolitan Area had a population of nearly 1.14 million. The largest municipality is Krakow, with 806,201 inhabitants, and the smallest is Igolomia-Wawrzenczyce with 7839 inhabitants, this is shown in Figure 1.

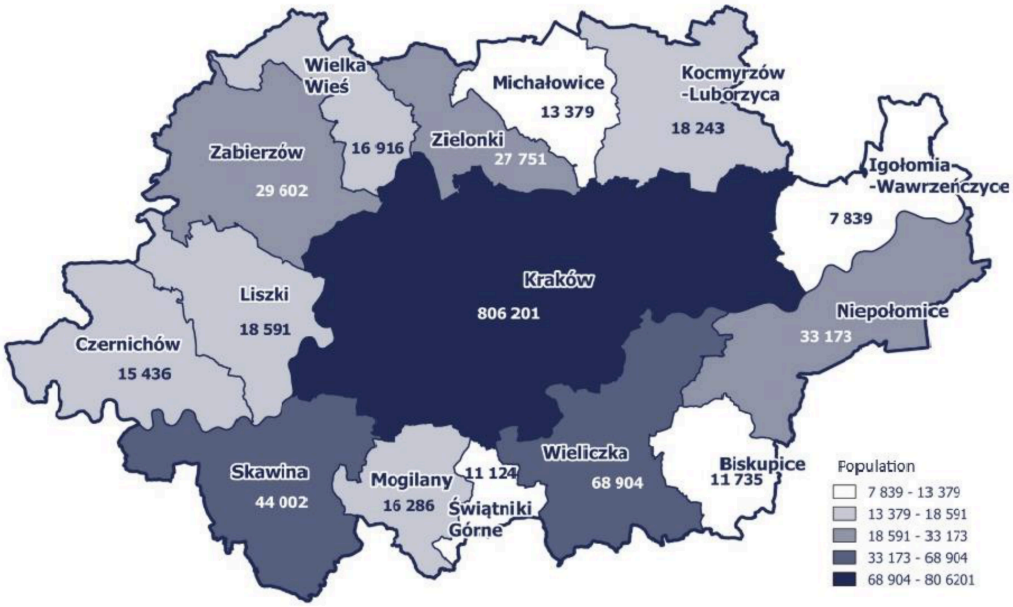


Figure 1. Population of the Krakow Metropolitan Area in 2023 [34] (The names of the municipalities are written in their original spelling).

Based on municipal resolutions on waste collection principles and methods of calculating fees, as well as information on municipal websites, a review of the most important activities in municipalities related to biodegradable waste management systems was conducted. These activities are presented in Table 1. Data on the amount of biodegradable waste collected in the Krakow Metropolitan Area was used to determine the potential for biomethane production. The data was provided by the Marshal's Office of the Malopolska Voivodeship.

Table 1 presents the principles of the waste collection system in Krakow and the municipalities of the Krakow Metropolitan Area, based on documents provided by individual municipalities, including resolutions of the Municipal Councils regarding detailed segregation methods and municipal waste collection rules. Waste collection schedules published for waste producers on the websites of individual municipalities are also included. All municipalities operate a five-fraction collection system: paper (blue), glass (green), metals and plastics (yellow), bio-waste (brown), and mixed waste (black).

Table 1. Operations within the waste collection system in Krakow and the Municipalities of the Krakow Metropolitan Area.

Activities	Municipalities
Increased fee for not sorting municipal waste	All municipalities
Reduced fee for composting biodegradable waste calculated as a lump sum per household	Niepolomice, Liszki, Wieliczka, Wielka Wies, Biskupice
Reduced fee for composting biodegradable waste per resident	Krakow, Czernichow, Igolomia- Wawrzenczyce, Kocmyrzow-Luborzyca, Mogilany, Michalowice, Skawina, Swiatniki Gorne, Zabierzow, Zielonki
Fixed fee for the collection of municipal waste from households per person	Krakow, Biskupice, Czernichow, Igolomia-Wawrzenczyce, Kocmyrzow-Luborzyca, Mogilany, Niepolomice, Liszki, Skawina, Wielka Wies, Zabierzow
Variable rate for the collection of municipal waste from households per person	Michalowice, Swiatniki Gorne, Wieliczka, Zielonki
Frequency of collection of biodegradable waste from single-family homes depending on the season	Krakow, Biskupice, Czernichow, Igolomia-Wawrzenczyce, Kocmyrzow-Luborzyca, Mogilany, Michalowice, Swiątniki Gorne, Wielka Wies, Zabierzow
Frequency of biodegradable waste collection from multi-unit buildings depending on the season	Kocmyrzow-Luborzyca, Mogilany, Michalowice, Zabierzow
Limit of bio-waste bags collected per month or season	Czernichow, Kocmyrzow-Luborzyca, Niepolomice, Liszki, Wieliczka, Wielka Wies, Zielonki
No limit on the number of bio-waste bags collected per month or season	Krakow, Biskupice, Igołomia-Wawrzenczyce, Mogilany, Michalowice, Skawina, Swiatniki Gorne, Zabierzow

Source: own study based on [35].

All municipalities in the Krakow Metropolitan Area have regulations increasing the fee for municipal waste collection for unsorted waste. However, fees vary and are set individually in each municipality. There is also a noticeable difference in the per-capita fees for municipal waste collection from households, as shown in Figure 2. Most municipalities have a fixed fee, but a few have variable rates. These municipalities include Michalowice, Swiatniki Gorne, Wieliczka, and Zielonki. All municipalities in the Krakow Metropolitan Area have a reduced per-capita fee for composting biodegradable waste. Seven municipalities maintain a monthly or seasonal limit on the number of bags of bio-waste collected. However, most municipalities vary by the frequency of biodegradable waste collection from single-family homes depending on the season. This is due to the change in the volume of this waste fraction in the spring and summer compared to autumn and winter, particularly in single-family homes. The seasonality of multi-unit buildings is different. The frequency of collection of biodegradable waste from residents of such buildings varies in the following municipalities: Kocmyrzow-Luborzyca, Mogilany, Michalowice, and Zabierzow.

Municipal waste collection fees are charged for each person living in a household. The lowest rate is in the municipalities of Kocmyrzow-Luborzyca and Wielka Wies, at PLN 33 (Polish zlotys) each. The highest rate is in the municipality of Mogilany, at PLN 42. Some municipalities vary the fee depending on the number of residents (Świątniki Gorne and Wieliczka municipalities) and the type of building. A higher fee has been introduced for waste collection in multi-unit buildings (Michalowice and Zielonki municipalities). In both municipalities, the rate for multi-unit buildings is PLN 2 higher than for single-family buildings.

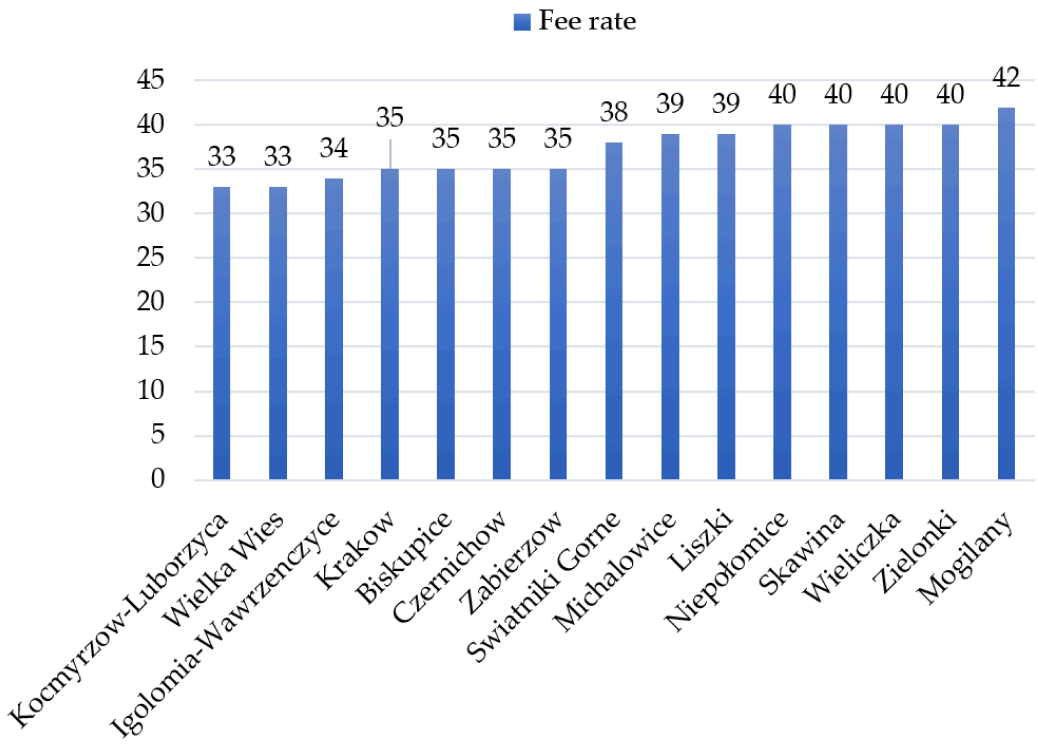


Figure 2. Fees per person in the Krakow Metropolitan Area in 2024 [35].

In Krakow, the waste collection fee is PLN 35 per person. The most important factor determining the fee in Krakow is the presence of a Thermal Waste Incineration Plant (Ekosincinerator) within its area. This facility eliminates the need for the city to pay external companies for the collection and disposal of combustible waste (RDF) to distant facilities, a costly expense in other municipalities. The incinerator produces electricity and heat, which is fed into the municipal grid. Revenues from this energy help balance the operating costs of the entire waste management system. Currently, the Ecosincinerator burns only municipal waste from Krakow. The city has also been intensively tightening the system for years. Thanks to inspections, the number of people registered in the system is high (nearly 770,000), which allows for the distribution of fixed costs among a larger number of payers [36].

2.2. Biodegradable Waste Collected from Households in the Krakow Metropolitan Area

Households generate two types of bio-waste: kitchen bio-waste (code 20 01 08) and green bio-waste (code 20 02 01). Kitchen bio-waste is organic waste generated at home from vegetable and fruit scraps, food scraps (excluding meat and bones), coffee and tea grounds, eggshells, pasta, groats, and rice. Green waste includes grass, leaves, flowers and their stems, thin branches, etc., originating from home gardens, city parks, lawns, and cemeteries. Both waste fractions (kitchen and green) are collected by their producers in brown bags or containers of the same color and are collected by companies that also collect mixed waste [36].

Table 2 presents the amount of kitchen and green waste collected in the Krakow Metropolitan Area in 2023 and 2024. The data show that in 2023, a total of nearly 75,000 Mg of green waste (code 20 02 01) and over 27,000 Mg of kitchen waste were collected. The largest amounts of both fractions of bio-waste were collected in Krakow (over 59,000 Mg of green waste, over 22,000 Mg of kitchen waste). Some municipalities did not report the amount of kitchen waste collected (Biskupice, Czernichow, Igolomia-Wawrzenczyce, Kocmyrzow-Luborzyca, Swiatniki Gorne, Wielka Wies). These are rural municipalities

where households dispose of bio-waste through composting. Discounts are offered per household or per person as an incentive. In the remaining municipalities, the total amount of kitchen waste collected amounted to approximately 4.9 thousand Mg and green waste to over 15.9 thousand Mg.

Table 2. Amount of Bio-Waste Collected in the Krakow Metropolitan Area in 2023 and 2024 [Mg].

Year	2023		2024	
Municipality	**Kitchen Waste**	**Green Waste**	**Kitchen Waste**	**Green Waste**
Krakow	22,140.79	59,040.72	23,347.73	63,335.67
Biskupice	0	811.08	0	1034.32
Czernichow	0	571.06	0	734.72
Igolomia-Wawrzenczyce	0	37.50	0	66.02
Kocmyrzow-Luborzyca	0	1568.82	0	1688.52
Liszki	1191.20	221.41	359.70	1401.00
Michalowice	249.62	555.43	36.44	930.03
Mogilany	1086.46	196.82	105.42	1320.36
Niepolomice	6.62	4259.85	8.32	4185.27
Skawina	147.64	1121.51	113.48	1299.81
Swiatniki Gorne	0	647.09	0	809.71
Wieliczka	293.22	1190.51	297.46	1442.56
Wielka Wies	0	1619.25	0	1813.07
Zabierzow	789.52	2705.59	583.38	3747.69
Zielonki	1184.84	739.56	641.24	1824.70
Sum	27,089.91	74,992.27	25,493.17	85,494.37

The next year analyzed was 2024. This year, the largest amount of green bio-waste was collected (code 20 02 01). The total amount was higher compared to the previous year, reaching almost 85,500 Mg. The largest amount of this waste fraction (over 63,300 Mg) was collected in Krakow [37]. In the remaining municipalities of the Krakow Metropolitan Area, a total of over 22,000 Mg of green waste was collected. The second type of bio-waste collected in 2024 was kitchen waste (code 20 01 08). A total of over 25,000 Mg was collected, which is almost 1500 Mg less than in 2023. The largest amount of this bio-waste fraction was collected in Krakow (over 23,300 Mg), which was over 1000 Mg more than in 2023. As in 2023, the amount of kitchen waste collected was not provided for six municipalities (Biskupice, Czernichow, Igolomia-Wawrzenczyce, Kocmyrzow-Luborzyca, Swiatniki Gorne, Wielka Wies). In the remaining municipalities, a total of over 2000 Mg was collected, which was almost 3000 Mg less than the amount collected 2023. This may be due to the greater number of households composting bio-waste.

Quantification of the Feedstock Gap

According to Statistics Poland (GUS) data and environmental analyses, the average generation of kitchen bio-waste in Poland ranges from 60 to 80 kg/person/year [38]. Based on available potential—assuming average 70 kg/person/year for the metropolis's approximately 1.14 million inhabitants—the potential volume is around 79,800 Mg/year. The feedstock gap amounts to 48,307 Mg/year, which means that in 2024, only ~40% of generated kitchen waste was collected. The current situation indicates low system efficiency. Increasing the volume of kitchen waste collected in cities requires a multi-faceted approach:

- Changes to waste collection methods: providing residents with ventilated kitchen bio-waste bins suitable for indoor use, which would facilitate home sorting and prevent waste decomposition and odor issues.
- Increasing the number of brown bio-waste containers in communal bin enclosures within housing estates.

- Collecting kitchen waste in brown bins rather than plastic bags in single-family homes; this measure would eliminate the risk of microplastic contamination.
- Moving away from voluntary municipal waste sorting (plastics and metal, paper, glass, biodegradable waste, and mixed waste). Waste sorting should be mandatory for every resident of the Krakow Metropolis municipalities, with heavy penalties imposed for non-compliance.
- Financial incentives for households that properly collect kitchen waste.

A negative outcome associated with home composting is the risk of losing high-quality substrate. In the Krakow Metropolitan Area, kitchen and green waste are collected separately in brown bags or bins and account for as much as 19% of all municipal waste. The number of households with their own compost bins varies depending on the nature of the specific municipality [39].

In rural agricultural municipalities such as Igolomia-Wawrzenczyce, Kocmyrzow-Luborzyca, and Czernichow, residents do not segregate kitchen waste. Instead, they compost it in home composting bins. This may be because houses are situated on large plots with space for a compost bin, and the resulting compost is used to fertilize crops. Fee reductions for composting serve as an additional incentive. In other rural municipalities where agriculture is not the primary activity, single-family housing predominates, and kitchen and green waste are either composted or collected in brown bags. Between 30% and 50% of property owners submit a declaration stating that they have a home compost bin [38]. Multi-family housing predominates in Krakow itself, and only a small percentage of households own compost bins. Krakow Community Compost Bins are being established in the city for residents of tenement houses and apartment blocks [40]. Over time, this civic initiative could lead to a reduction in the amount of collected kitchen waste that could serve as feedstock for a biomethane plant.

Approximately 334,000 people reside in the municipalities of the Krakow Metropolis. Assuming that 30–50% of kitchen waste ends up in compost bins [38], between 6000 and 10,000 tonnes of kitchen waste can be composted. If the entire waste stream were directed to composting facilities, there would be a shortfall of over 20,000 tonnes of kitchen waste. In terms of biomethane production, this would represent a loss of over 1.2 million cubic meters and approximately 12,000 MWh of energy.

The current situation indicates low system efficiency. Collection could be optimized if logistics in multi-family housing were improved. We anticipate increased participation through the introduction of better education and incentive schemes. Conversely, a negative scenario regarding home composting entails the risk of losing high-quality feedstock.

2.3. The Use of Bio-Waste for Energy Purposes

Processing biodegradable municipal waste through anaerobic fermentation in biogas plants is one of the most effective ways to achieve the goals of a circular economy. Choosing this method offers energy, environmental, and economic benefits.

The byproduct of the anaerobic digestion of biowaste is biogas, consisting primarily of methane, carbon dioxide, and hydrogen sulfide. It is classified as a renewable energy source. Depending on the raw material, biogas typically contains 50–75% methane, 25–40% carbon dioxide, and trace amounts of hydrogen sulfide, hydrogen, or ammonia [41,42].

Biogas contains methane, which is an energy component. Depending on its content, its calorific value ranges from 19 to 23 MJ/m^3. When burned in cogeneration systems, one cubic meter of biogas can produce an average of about 2.2 kWh of electricity and nearly 8 MJ of heat [43].

The biogas production process involves four stages. The first stage is hydrolysis, which is the breakdown of complex organic compounds such as proteins, carbohydrates,

and fats into simple organic compounds (fatty acids, amino acids, or sugars). The second stage is acidification, which occurs with the participation of acid-forming bacteria and leads to the production of fatty acids, carbon dioxide, and hydrogen from the products formed in the first stage. Small amounts of alcohol and lactic acid are produced, which are then converted into acetic acid, hydrogen, and carbon dioxide in the next stage, with the participation of acetic acid bacteria. The final product of fermentation is biogas [44].

Biogas, as a valuable energy resource, can be used for:

- producing electricity through combustion in gas engines or turbines,
- producing heat and electricity in CHP (Combined Heat and Power) cogeneration units,
- supplementing the natural gas grid,
- as a fuel for transport engines.

Furthermore, it can be used as a feedstock for technological processes (for example, in the production of methanol or ammonia) [45].

Data from municipalities in the Krakow Metropolitan Area regarding the amount of collected green waste (code 20 02 01) and kitchen waste (code 20 01 08) were used to calculate the potential for biomethane production. This study estimated the potential for biogas and biomethane production from organic waste generated in households using a simulation model. Table 3 summarizes the data used for simulation calculations [44].

Table 3. Date from the simulation calculations.

Parameter	Symbol	Unit	Green Waste	Kitchen Waste
Dry matter (d.m.)	% *d.m.*	[%]	12–28	15–20
Dry organic matter (d.o.m.)	% *d.o.m.*	[%]	85–90	85–95
Biogas yield	U_{biogas}	m^3/Mg d.o.m.	450–550	500–700
Methane content in biogas	$Z_{methane}$	[%]	50–55	55–62
Energy potential of biomethane	E	KWh/m^3 CH_4	9.97	9.97
Methane loss intake gas	s	%	1–2	1–2

Source: Our own study based on [44,45].

Calculation of the volume of biogas produced *V biogas* in the reactor:

$$V\ biogas = M * \%\ d.m. * \%\ d.o.m. * U\ biogas\ [m3], \quad (1)$$

where

- *M*—mass of substrate in Mg,
- *U biogas*—biogas yield from 1 Mg % *d.m.*—percentage of dry matter in the substrate,
- % *d.o.m.*—percentage of dry organic matter in dry matter,
- % *d.m.*—percentage dry matter

Our calculation of biomethane volume *V methane* used the formula:

$$V\ methane = V\ biogas * Z\ methane * (1 - s)\ \ [m3], \quad (2)$$

where

- *V biogas*—volume of biogas produced in the reactor,
- *Z methane*—methane content in biogas,
- s—the loss of methane during the process of upgrading biogas to biomethane.

2.3.1. One of a Time Sensitivity Analysis

A sensitivity analysis has been made to illustrate the influence of different factors on the actual results of biomethane production from green waste and kitchen waste. The

analysis has been based on data presented in Table 3. The obtained results are presented in two distinct tornado charts (Figure 3).

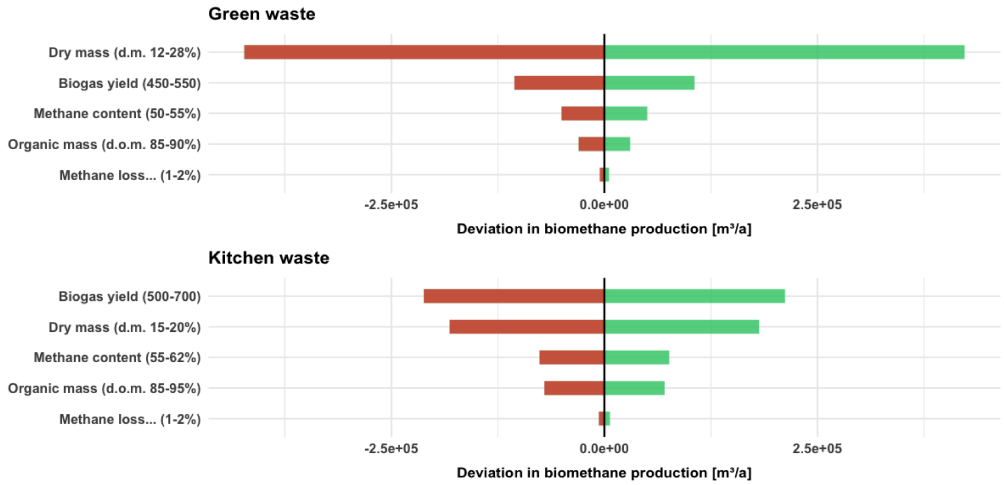


Figure 3. Tornado chart of factors affecting yearly methane production volume.

A comparative sensitivity analysis reveals distinct parameter hierarchies governing biomethane production across the two feedstocks. For green waste, dry mass content represents the singular dominant parameter, exerting an effect that substantially eclipses all remaining factors. In contrast, the methane yield from kitchen waste is driven by two co-dominant parameters: biogas yield and dry mass content. Furthermore, the secondary variables—methane content and organic fraction—demonstrate a markedly more balanced influence in the kitchen waste system than in the green waste model.

Notable discrepancies also emerge regarding the absolute magnitude of these primary drivers. The variance induced by dry mass in green waste processing significantly exceeds the combined impact of the top parameters for kitchen waste. Consequently, this pronounced sensitivity to dry mass introduces heightened operational risk regarding the real-world efficiency of green waste valorization. Because kitchen waste exhibits a more distributed sensitivity profile, it presents greater operational resilience. These findings underscore that green waste management requires stricter supply chain controls and pretreatment protocols to maintain optimum dry mass thresholds and guarantee target biomethane yields.

2.3.2. Calculations of Biogas and Biomethane Production from Green and Kitchen Waste for Variants 1 and 2

The simulation was carried out in two variants using the data presented in Table 2 for calculations regarding the amounts of green and kitchen bio-waste, assuming their full use. Water scrubbing was chosen as the biogas upgrading technology. This is a common method in which CO_2 is dissolved in water under pressure. In typical waste gas recirculation plants, methane losses are typically s = 1 − 2% [46]:

- Variant 1 (pessimistic) assumed minimum *d.m.* and *d.o.m.* content for biodegradable waste collected in Krakow. A minimum biomethane content in biogas [%] and a maximum methane loss during the upgrading process were also assumed [s = 2%]
- Variant 2 (optimistic) assumed maximum *d.m.* and *d.o.m.* for biodegradable waste collected in all municipalities of the Krakow Metropolitan Area. A maximum biomethane content in biogas [%] and a minimum methane loss during the upgrading process were also assumed [s = 1%].

Averaged data on the dry matter (*d.m.*) and dry organic matter (*d.o.m.*) as well as biogas yield and biomethane content in the waste, presented in Table 3, were used to calculate the

amount of biomethane produced. For green waste, the biogas yield was assumed to be 450 and 550 $Nm^3/1$ Mg, and for kitchen waste, the biogas yield was assumed to be 500 and 700 $Nm^3/1$ Mg. Table 4 is presented simulations of the results obtained for variant 1.

Table 4. Simulation results for Variant 1.

Parameter	Symbol	Unit	Green Waste	Kitchen Waste	Sum
		Data			
Mass of waste	M	Mg	59,040.72	22,140.79	81,181.51
Content d.m.	% *d.m.*	%	12	15	-
Content d.o.m.	% *d.o.m.*	%	85	85	-
Biogas yield	U_{biogas}	$m^3/1$ Mg	450	500	-
Methane content	$Z_{methane}$	%	50	55	-
Methane loss intake gas	s	%	2	2	-
		Results			
Biogas volume	V_{biogas}	m^3	2,709,969.05	1,327,884.83	4,121,444.41
Methane volume	$V_{methane}$	m^3	1,327,884.83	760,785.22	2,088,670.05
Energy	E	MWh	13,239.01	7585.03	20,824.04

Source: Our own study.

- Variant 1—Green and kitchen waste collected in Krakow in 2024.

Table 5 is presented simulations of the results obtained for variant 2.

Table 5. Simulation results for Variant 2.

Parameter	Symbol	Unit	Green Waste	Kitchen Waste	Sum
		Data			
Mass of waste	M	Mg	85,494.37	25,493.17	110,987.54
Content d.m.	% *d.m.*	%	28	20	-
Content d.o.m.	% *d.o.m.*	%	95	95	-
Biogas yield	U_{biogas}	$m^3/1$ Mg	550	700	-
Methane content	$Z_{methane}$	%	55	62	-
Methane loss intake gas	s	%	1	1	-
		Results			
Biogas volume	V_{biogas}	m^3	12,507,826.33	3,390,591.61	15,898,417.94
Methane volume	$V_{methane}$	m^3	6,810,511.44	2,081,145.13	8,891,656.57
Energy	E	MWh	67,900.80	20,749.02	88,649.82

- Variant 2—Green and kitchen waste collected in the Krakow Metropolitan Area in 2024.

2.3.3. Calculations of Biogas and Biomethane Production from Kitchen Waste for Variants 3 and 4

Next, a simulation of biogas, biomethane, and energy production was performed for Variant 3 and Variant 4, using only kitchen waste for calculations, as it is available year-round and collected in similar quantities each month. Therefore, it can be stored for a short period and used as a substrate in the biogas plant on an ongoing basis. Green waste is collected in large quantities only from April to November. Green waste also includes small tree branches, which should be removed as they are unsuitable for methane fermentation. Therefore, the actual mass of this waste may be several percent lower than the one assumed for the calculations. To ensure a constant supply of green waste for the biomethane plant, it would be necessary to prepare silage from it, which would generate additional costs [47]. Furthermore, grass blades cannot exceed 4 cm in length, as they could damage the mixers

in the fermenters. It seems that collected green waste should continue to be transformed into compost at the Barycz Composting Plant.

The calculations for Variant 3 and Variant 4 assumed average values for biogas yield (600 m^3/Mg) and methane content (60%), as well as the average dry matter content in kitchen waste (20%) and the average dry organic matter (90%). This allowed us to produce 1,235,727.08 m^3 of biomethane in Variant 3 and 1,422,830.92 m^3 of biomethane in Variant 4. The simulation results for Variants 3 and 4 are presented in Tables 6 and 7.

Table 6. Simulation results for Variant 3.

Parameter	Symbol	Unit	Value
Data			
Mass of waste	M	Mg	22,140.79
Content d.m.	% *d.m.*	%	18
Content d.o.m.	% *d.o.m.*	%	90
Biogas efficiency	U_{biogas}	m^3/1 Mg	600
Methane content	$Z_{methane}$	%	58
Methane loss intake gas	s	%	1
Results			
Biogas volume	V_{biogas}	m^3	2,152,084.79
Methane volume	$V_{methane}$	m^3	1,235,727.08
Energy	E	MWh	12,320.19

Source: Our own study.

Table 7. Simulation results for Variant 4.

Parameter	Symbol	Unit	Value
Data			
Mass of waste	M	Mg	25,493.17
Content d.m.	% *d.m.*	%	18
Content d.o.m.	% *d.o.m.*	%	90
Biogas efficiency	U_{biogas}	m^3/1 Mg	600
Methane content.	$Z_{methane}$	%	58
Methane loss intake gas	s	%	1
Results			
Biogas volume	V_{biogas}	m^3	2,477,936.12
Methane volume	$V_{methane}$	m^3	1,422,830.92
Energy	E	MWh	14,185.62

- Variant 3—Kitchen bio-waste collected in Krakow in 2024 in the amount of 22,140.79 Mg.
- Variant 4—Kitchen bio-waste collected in the Krakow Metropolitan Area in 2024 in the amount of 25,493.17 Mg.

The difference in the amounts of biomethane that can be produced in Variant 3 (m^3) and Variant 4 (1,422,830.92 m^3) is 187,103.83 m^3 (15%) in favor of Variant 4. It seems that this difference is too small to increase the waste collection area from 327 km^2 to 666 km^2.

The difference in the amount of biomethane produced between Variants 3 and 4 is 215,061.88 m^3, in favor of Variant 4. The difference is too small to make increasing the waste collection area profitable. Optimistic assumptions led to significantly higher energy yields than pessimistic variants. Green waste (included in Variants 1 and 2) is a more challenging raw material due to its seasonality and the need for costly ensiling, therefore Variants 3 and 4, based on kitchen waste, are indicated as more stable for continuous operation of the biomethane plant.

2.3.4. Validation of Results

In Variant 3 and Variant 4, the methane yields are ~55 m^3/Mg of fresh mass. Both results fall within the upper range of yields achievable under real-world conditions for the organic fraction of municipal solid waste (OFMSW). The aforementioned reference plant in Simmering achieves a methane yield of 45 m^3/Mg of fresh mass. Consequently, the yields for Variant 3 and Variant 4 are 22% higher than the value reported for the Simmering plant. This difference can be attributed to the fact that biomethane production at Simmering takes place under actual operating conditions, whereas the analysis above assumes optimal conditions and uses average values for dry matter (d.m.), dry organic matter (d.o.m.), and biogas methane content. The higher efficiency of the model (by 30%) results from the assumption of optimal process conditions—such as tightly controlled parameters and stable substrates—which constitutes a key limitation of the model, as these ideal states rarely reflect actual operating environments. Comparing these yields with literature values confirms that the results for Variants 3 and 4 fall within the range of biomethane potential (BMP) for OFMSW—a value known to vary significantly in scientific literature depending on waste composition and process conditions. This is corroborated by studies conducted by Pangallo et al., who report that methane yields from OFMSW in high-efficiency plants can reach levels of 60–65 m^3/Mg of fresh mass [48].

Other studies on the kitchen waste fraction often indicate a potential yield exceeding 60 m^3/Mg in high-efficiency systems [49]. Cesaro et al. indicate that typical biogas yields in full-scale plants range from 100 to 150 m^3 per Mg of fresh mass. With a methane concentration of 55–65%—typical for such facilities—the methane yield falls within the range of 55–97 m^3 per Mg of fresh mass [50].

2.3.5. Valorization of Digestate in an Urban Biomethane Plant Model

Digestate is the end product of the methane fermentation process that remains in the reactor after biogas has been extracted. It accounts for approximately 85–90% of the feedstock mass supplied to the facility. In the context of the circular economy, digestate should not be treated as waste, but rather as a valuable organic fertilizer. In terms of fertilizing value, it is rich in plant nutrients such as nitrogen, phosphorus, and potassium (NPK). Thanks to the fermentation process, the nitrogen it contains is more readily available to plants than in traditional natural fertilizers [45].

A significant challenge in urban biogas plants is the presence of physical contaminants, such as microplastics originating from waste bags or labels. The presence of plastics in the digestate significantly reduces its market value and may preclude its safe use in agriculture [51]. The process of upgrading digestate involves its mechanical separation into solid and liquid fractions, which allows the fertilizer to be better tailored to soil needs and facilitates its transport. In advanced installations, it is also possible to recover compounds such as struvite (magnesium ammonium phosphate) from the liquid phase [52].

The resulting digestate must meet stringent quality and safety requirements. Under Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products, products bearing the CE mark may circulate freely or be placed on the market within the Single Market without additional authorizations. The regulations mandate strict control of heavy metal and pathogen content (including **Salmonella** and **E. coli**), necessitating the pasteurization of the feedstock [53]. In Poland, the inspection of digestate is carried out by the Polish Centre for Testing and Certification S.A. and the Institute of Technical Supervision Sp. z o.o. (Polskie Centrum Badań i Certyfikacji S.A. oraz Instytut Nadzoru Technicznego Sp z o.o.) [54].

2.4. The Methodology for Biomethane Potential Assessment

The dynamics of the potential are illustrated by the number of apartments and single-family houses of typical size (area) in Krakow whose demand for thermal energy for heating and ventilation can be fully satisfied by available amount of biomethane. The analysis is based on two variants of the available biomethane supply E_{bm} generated from kitchen waste collected in 2024. The first one—Variant 3 (1,235,727.08 m^3)—results from the application of kitchen waste collected in Krakow only, and the second one—Variant 4 (1,422,830.92 m^3)—results from the application of collected kitchen waste in both Krakow and adjacent municipalities.

The choice of such a topic results from the primal importance of the thermal energy supply for the residential sector in Poland, which has a long heating season. For example, the last heating season in Krakow lasted for 244 days [55]. In other words, it covered two thirds of the whole year. Moreover, the majority of the residential sector in Krakow [56] (Table 8) and the other largest Polish cities is old. Hence, it generates considerable demand for thermal energy due to its poor energy efficiency [57].

Table 8. Estimated age structure of residential buildings in Krakow (based on) [58].

Year of Completing	<1945	1946–1970	1971–1995	1996–2004	2005–2009	2010–2018	2019–2024	Overal
Share [%]	10.1	42.1	4.9	12.4	7.3	18.1	10.0	100.0

The higher demand for thermal energy results in a need for energy production. The majority of the thermal energy demand in Poland is met by the application of environmentally dirty fossils like coal, lignite, crude oil, and natural gas. This results in the possibility of generating considerable pollution of the environment with greenhouse gases and dust particles. Therefore, systemic initiatives are taken to reduce the consumption of fossil fuels in thermal energy generation. For example, legal terms have been introduced in the EU with the goal of a deep reduction of the demand for thermal energy in buildings in the short term and the final intent of achieving climatic neutrality in the whole building sector in the future, as is stated in the EPBD directive [59].

There are several official indicators for the energy efficiency of buildings or their separate parts, e.g., demand for primary non-renewable energy (*EP*), final demand for energy (*EK*), and annual usable energy for heating, ventilation, cooling, and domestic hot water preparation (*EU*). However, *EP* and *EK* depend on technical details related to the specifics of the actual technical means and fuel applied to a given building. Hence, they are rather well suited for interval characterization of the overall energy efficiency of residential stock (Table 9). Note that these two indicators are strictly related to each other as the demand for primary non-renewable energy results from an algebraic transformation of the final demand for energy thanks to the application of a proportion coefficient related to a dimensionless ratio of non-renewable energy input w [60] related to the applied energy sources. Furthermore, the data in Table 4 indicate that older residential buildings fail to satisfy the baseline universal energy efficiency threshold of EP = 140 kWh/(m^2 a).

Table 9. Estimated EP typical intervals for residential houses [61].

Year of Construction	<1918	1918–1944	1945–1970	1971–1978	1979–1988	1989–2002
EP [kWh/(m^2 a)]	>350	300–350	250–300	210–250	160–210	140–180
EK [kWh/(m^2 a)]	>300	260–300	220–260	190–220	140–190	125–160

The EU indicator does not fit our needs, either. This is due to its compound nature, which includes not only the annual demand for heating and ventilation (EU_h) but also the

annual demand for domestic hot water preparation (EU_w), which is dependent on actual number of inhabitants and cooling (EU_c) and which we did not consider.

$$EU = EU_h + EU_w + EU_c \quad [\text{kWh}/(\text{m2 a})]. \tag{3}$$

Therefore, EU_h has been finally applied in the analysis of local biomethane utilization. Note that all indicators refer to a unit of usable building area and a year. The actual demand for thermal energy for an apartment or building with a given EU_h and overall usable area of A would yield:

$$E_h = EU_h\, A \quad [\text{kWh}/(\text{m2 a})]. \tag{4}$$

To make our analysis more realistic, the expected improvement of residential stock in energy effectiveness due to the moving of the implementation date of the EPBD directive is considered. The actual implementation of EPBD directive is left to the EU member states. The assumed general agenda for the implementation in Poland is presented in Table 10, where $EU_{h\,exp}$ denotes expert assessment-based projected average annual demand for energy for heating and ventilation. The agenda is then applied in the analysis of biomethane utilization potential for heating residential stock in Krakow. The actual calculations are based on three cases that account for changes in the expected development of this very ambitious implementation process:

1. The optimistic case with the quicker implementation of the improvements $EU_{h\,opt}$.
2. Average (expected) case ($EU_{h\,avg}$).
3. Pessimistic case with the delayed improvements ($EU_{h\,pes}$).

Table 10. Framework of EPBD implementation in Poland.

Year of Construction	EU_h for Dominant Stock Fraction	$EU_{h\,exp}$	Key Factors
	[kWh/(m^2 a)]	[kWh/(m^2 a)]	
2024	150–250	~150	Start of mass thermal renovation of old buildings
2030	70–100	70–80	Zero Energy Building [62,63] standard universality
2040	40–70	60–70	Deep mass thermal modernization effect
2050	<40	<40	Climate neutrality of most of the stock [64]

The assumed expert assessment-based values for annual demand for energy for heating and ventilation are presented in Table 11.

Table 11. Assumed levels of annual demand EU_h.

Year	$E_{h\,opt}$	$E_{h\,avg}$	$E_{h\,pes}$
	[kWh/(m^2 a)]		
2024	150	175	250
2030	70	80	100
2040	60	65	80
2050	30	35	40

The application of considered cases results in the following thermal energy demand for a single apartment or a single-family house of usable area A:

$$E_{h\,opt} = EU_{h\,opt}\, A,\; E_{h\,avg} = EU_{h\,avg}\, A,\; E_{h\,pes} = EU_{h\,pes}\, A\, [\frac{\text{kWh}}{\text{a}}] \tag{5}$$

where A denotes the area of an apartment or a single-family house in sq.m.

Optimistic (N_{opt}), average (N_{avg}), and pessimistic (N_{pes}) numbers of biomethane-supplied apartments or single-family houses in a given area are given by the formula:

$$N_{opt} = E_{bm}/E_{h\ opt}, \quad N_{avg} = E_{bm}/E_{h\ avg}, \quad N_{pes} = E_{bm}/E_{h\ pes} \tag{6}$$

The non-integer results of calculations according to Equation (6) are rounded down to the integer number.

The average apartment area of 57.8 m^2, registered by official census data for Krakow [65], is basically utilized in this regard. However, census data for 2024 [66] reveal a larger average size of newly commissioned apartments, yielding 62.5 m^2 instead. This is why a linear year by year change in average apartment area is also included in calculations with this target average apartment area in 2050. The energy demand for a single-family house with a reasonable area of 141.8 m^2 is addressed for the estimation of the number of single-family houses heated by biomethane, too [67].

While Szyba and Mikulik (2023) [47] presented a preliminary feasibility analysis of biogas production in Krakow, the present study builds upon that foundation by incorporating current data on waste collected in Krakow and the municipalities of the Krakow Metropolis in 2024, simulating long-term energy potential—particularly regarding biomethane injection into the natural gas grid—and integrating the types of thermal modernization required by the EU's EPBD directive.

3. Results and Discussion

The results of the calculations are presented in the following tables and figures. The results for apartments with constant usable area equal to 57.8 m^2 are presented in Table 12 and Figure 4. Table 13 and Figure 5 present the results obtained for a yearly increase in the average usable apartment area. The results for a single-family house with the assumed constant usable area are presented in Table 14 and Figure 6.

Table 12. Estimated number of biomethane-supplied apartments for constant average usable area.

Year	$E_{h\ opt}$	$E_{h\ avg}$	$E_{h\ pes}$	Variant 3			Variant 4		
	[kWh/a]			N_{opt}	N_{avg}	N_{pes}	N_{opt}	N_{avg}	N_{pes}
2024	8670	10,115	14,450	1421	1218	853	1636	1402	982
2030	4046	4624	5780	3045	2665	2132	3506	3068	2454
2040	3468	3757	4624	3553	3279	2665	4090	3776	3068
2050	1734	2023	2312	7105	6090	5329	8181	7012	6136

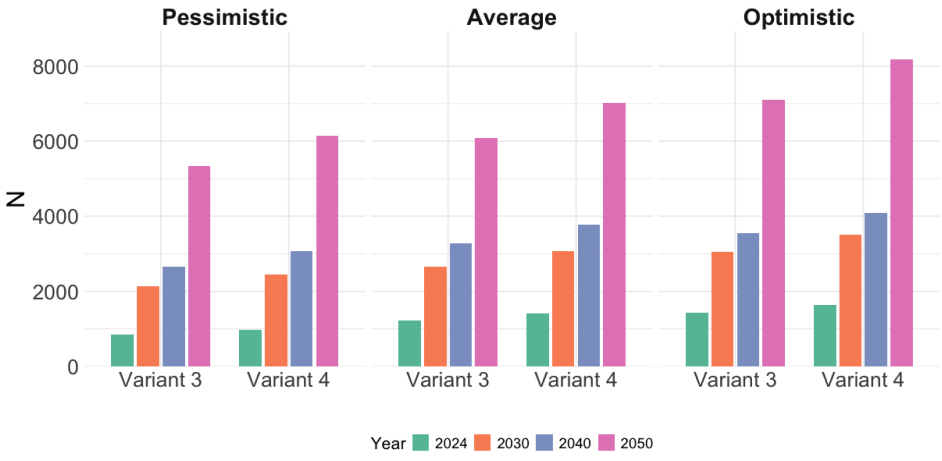


Figure 4. Estimated number of biomethane-supplied apartments of constant usable area of 57.8 m^2.

Table 13. Estimated number of biomethane-supplied apartments for changing average usable area.

Year	A	$E_{h\ opt}$	$E_{h\ avg}$	$E_{h\ pes}$	Variant 3			Variant 4		
	[m^2]		[kWh]		N_{opt}	N_{avg}	N_{pes}	N_{opt}	N_{avg}	N_{pes}
2024	57.8	8670	10,115	14,450	1421	1218	853	1636	1402	982
2030	58.9	4123	4712	5890	2988	2615	2092	3441	3011	2408
2040	60.7	3642	3946	4856	3383	3122	2537	3895	3595	2921
2050	62.5	1875	2188	2500	6571	5631	4928	7566	6483	5674

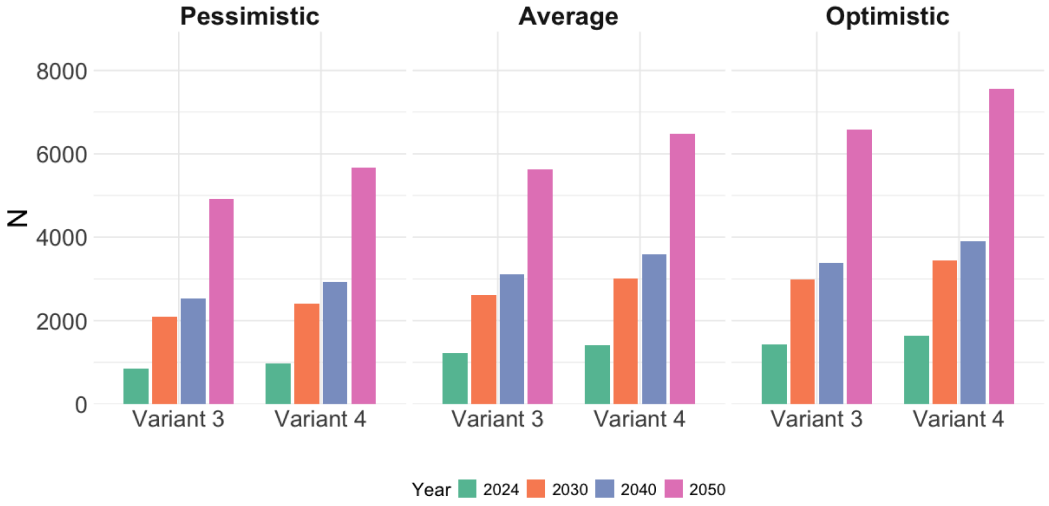


Figure 5. Estimated number of biomethane-supplied apartments for changing average usable area.

Table 14. Estimated number of biomethane-supplied single-family houses with a usable area of 141.8 m^2.

Year	$E_{h\ opt}$	$E_{h\ avg}$	$E_{h\ pes}$	W3			W4		
		[kWh]		N_{opt}	N_{avg}	N_{pes}	N_{opt}	N_{avg}	N_{pes}
2024	21,270	24,815	35,450	579	497	348	667	572	400
2030	9926	11,344	14,180	1241	1086	869	1429	1250	1000
2040	8508	9217	11,344	1448	1337	1086	1667	1539	1250
2050	4254	4963	5672	2896	2483	2172	3335	2858	2501

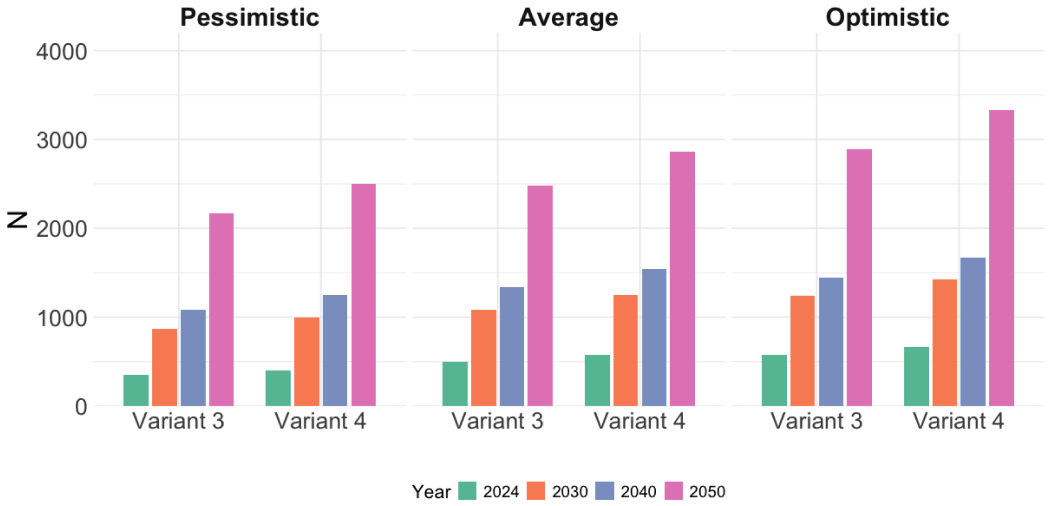


Figure 6. Estimated number of biomethane-supplied single-family houses of usable area equal to 141.8 m^2.

The presented simulation analysis provides insightful results. Tables 12 and 13 and Figures 4 and 5 confirm that both variants of biomethane availability initially cover the thermal energy demands of well above a thousand average apartments in Krakow and several hundred single-family houses. The excess of biomethane for Variant 4 results in almost 25% more covered apartments than Variant 3. The assumed considerable reduction agenda of average demand for thermal energy results (Table 11) in a continuous rise of the number of covered apartments and single-family houses by several thousand. The most rapid changes in the number of apartments appear between 2024 and 2030 and between 2040–2050. The scale of changes is moderately affected by the assumed apartment area rise (Table 13). Table 14 and Figure 6 show that the number of single-family houses behaves similarly. The tables also show that any deviation from the expected course of the agenda, assumed by means of average demand for thermal energy, may result in considerable change in the estimated number of apartments and single-family houses covered by biomethane supply. The difference in the number of covered apartments may reach hundreds or thousands depending on actual agenda stage, but the difference in the number of covered single-family houses may reach several hundreds. The results obtained are generally in line with the actual real experiences of pioneers in the generation of biomethane for space heating in residential buildings, such as in Austria [68] where the demand for space heating of almost 1000 Vienna apartments is covered by gas from bio-waste [56].

According to market data, the average cost of a biogas to biomethane upgrading line is estimated at 900 thousand EUR for a plant with an electrical capacity of 1 MW and 1.4 million EUR for an alternative biogas plant with an electrical capacity of 1.75 MW [69]. The cost of a biogas purification installation is difficult to estimate, as it depends on the cost of the chosen technology, variations in material costs, and the location. The financial aspects of biomethane production are influenced by capital expenditures (CAPEX) and operating expenditures (OPEX), which vary according to the facility's size and the types of feedstocks used. Capital expenditures (CAPEX) refer to funds allocated by a company for the acquisition and upgrading of physical assets, such as buildings, equipment, machinery, and vehicles. Operating expenditures (OPEX) comprise the ongoing costs incurred by a biomethane plant in the production process, including maintenance and repair of equipment and production facilities; costs related to electricity, heat, and other inputs; labor costs; feedstock pretreatment; and so forth [70].

Constructing a biomethane plant within the city should be economically viable. An economic analysis of a facility with an output of 1.3–1.6 million m^3 of biomethane per year indicates challenges in achieving full profitability under current market conditions. The investment costs (LCOB) for a biomethane plant producing approximately 4.5 million m^3 of biogas per year are as follows [70]:

Biogas purification plant—cost 1.6 million EUR *
Biomethane injection station for the distribution network—411.9 thousand EUR*
Gas pipeline construction (1000 linear meters)—137.2 thousand EUR*
Total—2.15 million EUR *

* Assumed: 1 EUR = 4.33 PLN (average exchange rate as of 21 July 2026).

The cost of installing a biogas purification system to produce biomethane is difficult to estimate because it depends on the cost of the selected technology, the cost of the materials used, and local conditions [70]. However, to better understand the real financial burden, it is worth analyzing the standardized operating costs (OPEX), capital expenditure (CAPEX), and the LCOB indicator for facilities of varying production scales (Table 15).

Table 15. Summary of CAPEX, OPEX, and LCOB indicators for biogas purification installations with different efficiency [71,72].

Installation Efficiency [m^3/Year]	OPEX [EUR/MWh]	CAPEX [EUR/MWh]	CAPEX [EUR] (Lump Sum)	LCOB [EUR/MWh] (15-Year Period of Operation)
~1,800,000	~87	~125	~2,229,750	~102.20
~4,500,000	~81	~104	~4,665,960	~93.65
~9,000,000	~79	~97	~8,703,810	~90.80

As the plant's efficiency increases (from ~1.8 million to ~9.0 million m^3/year), both unit operating costs (OPEX) and capital expenditure (CAPEX) decrease noticeably. Unit OPEX decreases from EUR 87/MWh to EUR 79/MWh, while unit CAPEX decreases more dynamically—from EUR 125/MWh to EUR 97/MWh. Over the 15-year period of a biomethane plant's operation, the LCOB decreases with increasing plant efficiency (from EUR 102/MWh for the smallest plant to EUR 90.80/MWh for the largest), making these plants more economically viable.

The profitability of constructing a biomethane plant also depends on the type of financial support. In Poland, the proposed level of support in the form of a fixed purchase price depends on the type of biogas used. For biomethane plants producing biomethane from agricultural biogas, the price is set at approximately 126 EUR/MWh, while biomethane produced from other types of biogases, it is around 125 EUR/MWh [73].

The data presented in the article regarding the quantity of kitchen waste collected in Krakow do not reflect the full potential for biomethane production. Only a portion of kitchen waste is properly sorted and suitable as feedstock for a biomethane plant; over 30% of kitchen waste ends up in the mixed waste stream [74]. According to the literature, the average person generates 60–80 kg of kitchen waste per year [38,75]. Currently, this figure exceeds 20 kg per person. The potential for biomethane production is therefore much higher. If the collection of biodegradable waste were carried out properly, it would be possible to produce up to 5 million m^3 of methane per year (i.e., 574 m^3/h).

High capital costs, which determine the profitability of investments in biomethane plants, are just one of several factors influencing the efficiency of such facilities. An equally significant challenge is optimizing plant operations given the disparity between a stable production profile and the seasonal fluctuation of gas demand. Biomethane production is a stable, continuous process, whereas the demand for gas for residential heating is subject to seasonal variation. It is not feasible to curtail biomethane production during the spring and summer months, as doing so would halt the methanogenesis process in the reactor and restarting it would entail substantial costs. Generating large volumes of biomethane can present a challenge typical of isolated renewable energy installations. However, this issue is resolved once the produced biomethane is fed into the gas grid, which incorporates storage facilities that supply consumers using the gas for applications such as heating water in buildings or fueling motor vehicles.

Additionally, a considerable continuous rising trend in the number of covered apartments is expected in the following years. The number of covered apartments and single-family houses is expected to exceed the initial number of covered apartments and houses in 2050 by four to five times (about 5000–7100 apartments and 2500 single-family houses for Variant 3, as well as 5700–8200 apartments and 2900 single-family houses for Variant 4).

All in all, the results obtained confirm the practical potential of kitchen waste-based biomethane for heating residential houses in Krakow. This is mainly due to the relatively stable source of raw material that allows for the continuous availability of biomethane and its compatibility with popular natural gas-fueled appliances. This fact provides several unique opportunities. The first one is rather obvious and pertains to energy safety

regarding single-family houses and all dwelling houses in sparsely urbanized peripheral Krakow districts without direct access to the municipal heating system, in particular. The second opportunity deals with the application of biomethane for emergency heating off the actual heating season. The third opportunity deals with the comfort of heating operation management as in the case of using automated natural gas heating systems. The fourth opportunity results from specific feedback between the development of the energy transformation process and the renewable character of biomethane from kitchen waste. On the one hand, a continuous decrease in unit demand for thermal energy owing to essential improvements in building technology and energy management would automatically favor enlarging the scale of biomethane utilization. On the other hand, though, biomethane from kitchen waste is legally treated as a specific kind of renewable biogas energy source. This fact results in a more advantageous factor w (the actual value of 0.5) compared with natural gas (1.1, at least) according to ordinance [49]. Thus, the wider application of biomethane in compatible thermal appliances instead of or even after mixing with natural gas would greatly assist in a massive and rapid reduction of the demand for primary non-renewable energy. *EP* is already subject to considerable reductions thanks to parallel independent reduction in the demand for final energy *EK*.

Producing biomethane from biodegradable waste prevents its uncontrolled decomposition, a process that releases methane—which has a CO_2 equivalent of 25—into the atmosphere. According to KOBiZE, the CO_2 emission factor for natural gas is 56.15 kg/GJ, while for biomethane it is 54.6 kg/GJ [56].

Although the direct combustion emission rates for both fuels are similar, from a climate protection perspective, biomethane is a carbon-neutral fuel. The carbon dioxide produced by burning biomethane originates from biomass, meaning it circulates within a closed, short-term carbon cycle and does not increase the total pool of greenhouse gases in the atmosphere—unlike natural gas. This distinction classifies biogas as a green, renewable energy source.

4. Conclusions

The primary aim of this study was to evaluate the energy potential of biodegradable municipal waste within the Krakow Metropolitan Area (KMA) and to determine its feasibility as a sustainable heat source for the residential sector by 2050. This investigation was driven by the urgent need to transition from a linear "waste disposal" model to a circular "resource recovery" paradigm, as dictated by the European Green Deal. Our research specifically sought to address the significant technological gap in Poland—where municipal bio-waste is currently diverted primarily to traditional composting—by modeling the transition to dedicated biomethane production facilities. By analyzing the waste streams of over 1.1 million inhabitants across 15 municipalities, we aimed to provide a strategic roadmap for enhancing regional energy security and achieving climate neutrality through the utilization of locally generated organic raw materials.

The methodology was built upon several critical assumptions designed to mirror real-world operational challenges and evolving energy standards. We differentiated between kitchen waste (code 20 01 08) and green waste (code 20 02 01), assuming that kitchen waste is the superior feedstock due to its stable, year-round availability and higher methane yield. Our simulation model employed four distinct variants, ranging from a pessimistic urban-only scenario to an optimistic metropolitan-wide integration, utilizing empirical data from 2023–2024. Furthermore, a foundational assumption of this research was the synergy with the EPBD directive; we integrated projections for deep thermal modernization of the residential stock, assuming that building energy demand will decrease significantly from current levels (~150–250 kWh/m^{2}a) to zero-emission standards (<40 kWh/m^{2}a) by

2050. These assumptions allowed us to project the long-term reach of a fixed volume of biomethane across a modernizing building landscape.

The obtained results reveal a substantial and underutilized energy reservoir within the KMA, with potential annual biomethane production from kitchen waste ranging from approximately 1.23 million m^3 to over 1.42 million m^3. A key finding is the remarkable "multiplication effect" of energy efficiency: while the biomethane produced from kitchen waste today can satisfy the heating demands of roughly 1000 to 1600 average apartments, the same volume of waste will be capable of heating between 5000 and 8200 households by 2050 due to reduced building energy consumption. This represents a four- to five-fold increase in resource efficiency over the next quarter-century. Additionally, the data confirms that metropolitan integration provides a 25% increase in energy yields compared to a purely urban approach, underscoring the importance of regional cooperation in maximizing the scale of renewable energy investments.

Despite these promising findings, the study highlights several critical limitations that must be addressed by policymakers. Technologically, Poland's municipal sector remains outdated, lacking the specialized fermentation plants necessary to purify biogas into grid-quality biomethane. From an operational standpoint, green waste presents significant hurdles due to its extreme seasonality and the technical requirement for costly ensiling or precise mechanical preparation to avoid damaging fermentation equipment. Furthermore, we observed a logistical limitation regarding the expansion of the collection area; for kitchen waste, doubling the geographical area to include the entire metropolis yielded only a 15% increase in feedstock volume, which may be offset by increased transportation costs. Finally, the rising popularity of home composting, though environmentally beneficial, poses a risk to industrial-scale energy production by reducing the total volume of high-quality kitchen waste entering the municipal system.

Future research should build upon this framework by conducting detailed Life Cycle Assessments (LCA) to precisely quantify the carbon footprint reductions achieved by replacing natural gas with "green" biomethane in specific urban contexts. Economic modeling is also required to establish investment thresholds for municipal biomethane plants, particularly regarding the costs of purification and grid injection versus local cogeneration. Additionally, there is a fertile area for inquiry into social and financial policy instruments aimed at optimizing household waste segregation and managing the balance between home composting and municipal energy recovery. Finally, future simulations could incorporate more granular data on specific building technologies to assess how different thermal renovation strategies interact with the seasonal availability of bio-waste, ensuring a robust and resilient local energy system for the future.

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