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CIRCULAR MANAGEMENT OF MUNICIPAL BIO-WASTE IN THE CONTEXT OF KRAKOW'S SMART CITY STRATEGY

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Purpose: The purpose of article is to present the concept of municipal bio-waste circularity within the framework of Krakow's smart City strategy and to evaluate the energy potential of bio-waste based on conducted simulations.
Design/methodology/approach: A research process based on Desk Research analysis, utilizing existing data from the Marshal's Office of the Małopolska Region and the Krakow Development Strategy 2030. The assessment of smart city implementation in Krakow was conducted based on the Smart City Index. Furthermore, the article provides a review of the relevant literature.
Findings: The study shows that Krakow is successfully executing actions, fostering a city ecosystem aligned with sustainable development goals.
Research limitations/implications: The theoretical biogas production potential was estimated based on 2024 data regarding the volume of kitchen (code 20 01 08) and green (code 20 02 01) bio-waste collected in Krakow. The calculated energy potential of kitchen waste indicates a high return on investment, representing the missing link in Krakow's circular economy model.
Practical implications: The calculations have a practical application in the design of urban energy systems. Determining the energy potential of the kitchen and green waste enables the identification of specific zones, including residential complexes and public utility buildings, capable of achieving partial energy autonomy by integrating circular economy technologies.
Social implications: The study shows that smart city actions in the field of circular economy require social acceptance and resident participation to be successful. It should be clearly shown that waste is repurposed into clean energy, helping to decrease air pollution in Krakow while curbing the ever-increasing expects associated with waste management.
Originality/value: The novelty of this study consists in establishing a direct correlation between smart city strategies and the recovery of energy from kitchen waste as a core element of the circular economy. The novelty of this study lies in demonstrating a direct correlation between smart city strategies and energy recovery from kitchen waste as a key element of the circular economy. The analysis combines a case study typical of a management article with practical energy simulations demonstrating the potential of kitchen waste utilization.
Keywords: smart city, circular economy, municipal biogas plant.
Category of the paper: Research paper.

1. Introduction

The urban environment is shaped by physical elements that satisfy the needs of residents, such as residential and public buildings, shopping centers, roads and energy infrastructure. Development is achieved through the expansion of infrastructure, which leads to the consumption of natural resources and energy, and consequently to the emission of pollutants into the atmosphere and the generation of waste. It is estimated that cities consume around 75 per cent of the world's energy and generate as much as 70 per cent of global CO_2 emissions (Energy 101, 2022). For these reasons, measures are being taken to optimize energy consumption and reduce waste, with a view to ensuring the sustainable development of urban communities.

The world's largest cities and Polish cities alike must solve the same problems that make life difficult for their residents. These include a lack of housing, inefficient public transport, traffic congestion, healthcare, waste management and others. In order to address these issues in a comprehensive manner, the concept of a smart city was developed. It should be adapted to the geographical, economic and social conditions of each city. Transforming existing urban organisms to make them compatible with this concept takes time, financial resources and, most importantly, the participation of residents in the creation of programs and their involvement in their implementation. As economic and social conditions change, as do the demands of city inhabitants, it seems that the process can never be considered complete. The integration of circular economy within the smart city ecosystem enables advanced energy recovery models. By applying energy simulations to urban biodegradable waste streams, a smart city can optimize its local energy balance and reduce reliance on external power sources.

This article describes the origins of the concept of sustainable development, the circular economy model and the components of the smart city model. The main part of the publication consists of our own research on the implementation of the smart city| concept in Krakow and an indication of possible further actions in the area of municipal waste management.

The aim of article is to present the concept of municipal bio-waste circularity within the framework of Krakow's Smart City strategy and to evaluate the energy potential of bio-waste based on conducted simulations.

The present study aim to test the hypothesis that waste management activities in Krakow should be expanded to include the construction of a municipal biogas plant, which is an installation implementing the assumptions of the circular economy and smart city.

2.1. Research gap

Despite the extensive literature on smart city development and the circular economy, there is a noticeable lack of simultaneous assessment of the implementation efficiency of both concepts within a city. There is a lack of research in which the assessment of smart city initiatives is conducted based on the Smart City Index survey, used to evaluate such activities among the residents of Krakow. The majority of scholarly works evaluate smart city initiatives and the circular economy as separate entities. Previous studies smart city initiatives have relied on mathematical modeling tools to identify key activities across the six core dimensions of a smart city (Kauf et al., 2025). Existing literature, such as the work of Winkowska, has explored the smart environment dimension, with a particular emphasis on waste management practices in Kielce and Gdynia. Although several smart city rankings are described, the study identifies a gap in linking Smart City Index survey results with actual urban projects in a Polish city (Winkowska, 2021). Pech et al. performed a comparative analysis of two cities using smart city applications to drive circular economy transitions. The author's focus was limited to the analysis of isolated technical solutions implemented in cities (Pech et al., 2021). Regions in Context III. Principles of circular economics in regional management leading to increased efficiency of systems). Research concerning circular economy activities in the context of waste was conducted by Rolewicz-Kamińska and Wesołowska. The authors analyzed how waste morphology influenced the efficiency of waste collection (Rolewicz-Kalińska, Wesołowska, 2025). The publication by Czerwionka et al. presents the "Sztum Circular Economy" project. This publication shows that selective waste collection, green purchasing, and education are key drivers for circular economy implementation in smaller urban areas (Czerwionka et al., 2025). There is a notable absence of energy modeling that showcases the practical implementation of circular economy and smart city initiatives in urban environments.

None of the studies include simulations on producing energy from city-generated biodegradable waste. The findings indicate a clear need for integrated development of circular economy practices and smart city initiative.

2. Literature review

2.2. The concept of sustainable development in cities

The natural environment of modern humans is cities, where more than half of the world's population lives. According to UN data, more than half of the world's population (55%) currently lives in urban areas, and by 2050 this figure is expected to rise to as much as 68% (Desa, 2014). Urban agglomerations have specific living conditions resulting from high population density and housing needs, as well as the need to commute from home to work and school, to go shopping, visit the doctor, run errands or enjoy entertainment. A large percentage of residents use private transport, which means they have to spend a lot of time in traffic jams (Mierzejewska, 2015). This phenomenon occurs in agglomerations with millions of inhabitants and in cities with up to 100,000 inhabitants, which is also observed in Poland. These problems have given rise to the idea of sustainable cities, which aim to comprehensively address the institutional, environmental, social and economic challenges resulting from rapid urbanization, population density, and inefficient resource management. issues. The main goal is to create urban spaces that are friendly to people and the environment, meeting the needs of current residents without limiting the opportunities of future generations (Rzeńca, 2016). In the world's most popular development strategy, Agenda 2030, there are 17 Sustainable Development Goals and 169 related actions to be achieved by all parties. They take into account economic, social and environmental aspects. Agenda 2030 was adopted in 2015 by 193 UN member states, unanimously, through the resolution "Transforming our world: the 2030 Agenda for Sustainable Development". These goals relate to eradicating poverty and hunger, ensuring a good quality of life, health, education, economic development, clean energy and innovation, as well as environmental and climate protection. For urban development, Goal 11 – Sustainable cities and communities – is the most important (Cele zrónoważonego rozwoju). The aim is to create inclusive, safe, resilient and environmentally friendly spaces. Implementation is based on integrating ecological, social and economic aspects. Key management concepts that implement these objectives in cities include smart city and circular city based on the circular economy.

2.3. Circular economy in cities

The circular economy in sustainable cities is a resource management model that aims to eliminate waste and pollution and keep products and materials in use through repair and reuse. It replaces the linear economy model (take – make – use – dispose), which consumes large amounts of raw materials and pollutes the environment (Dincă et al., 2022). The circular economy is seen as a driver for sustainable development worldwide. In comparison to sustainable development, it is a newer approach that focuses primarily on minimizing inputs, strengthening and protecting natural resources, as well as managing limited resources efficiently and reducing overall risk (Lakatos et al., 2021). The circular economy is "a model of production and consumption that involves sharing, consuming, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible" (Kirchherr et al., 2017; Gospodarka o obiegu zamkniętym, 2023). This approach extends the life cycle of products, which in practice means less waste will be generated. The concept of circular economy is based on minimising the environmental impact of manufactured products through the selection of components and design that enable their reuse (Imperatives Strategic, 1987). The concept of cradle-to-cradle is related to the circular economy. It is a way of designing and manufacturing objects in accordance with the concept of sustainable development. After they have been used, they can be reintroduced into circulation (Bakker et al., 2011). In the circular model, there is no waste, only raw materials that become resources. This economic model makes resource management more efficient and reduces the risk of depletion. Well-managed waste becomes a raw material that re-enters the product life cycle.

In the first place, the principles of the circular economy should be based on a hierarchy of resource management based on the 3xR principle, i.e. reduce, reuse, recycle (Kirchherr et al., 2017; Wysokińska, 2018). The circular economy is seen as a sustainable economic system in which economic growth is independent of the consumption of resources such as fossil fuels, minerals, metals and biomass (MacArthur, 2013; Ghisellini et al., 2016). It focuses on sustainable development in areas such as industrial ecology, waste management, renewable energy, recycling and smart cities. By reusing and recycling municipal waste, the global demand for raw materials used in the production of materials and energy resources is reduced. This results in a reduction in greenhouse gas emissions into the atmosphere (Aceleanu et al., 2019). Over the years, technological advances have led to the development of waste-to-energy (W2E) technologies, which have become more affordable and efficient. In addition, waste can be used to manufacture various products which, when properly designed, can be used for a long time. Therefore, municipal waste in the circular economy is treated as a resource rather than waste (Musti, 2020). In addition to guidelines and waste management schemes, the European Union also promotes the circular economy among the general public through education. The aim is to raise awareness among citizens and businesses in order to reduce waste generation and greenhouse gas emissions. These areas of education include: selective waste collection, energy saving and waste reduction in households and businesses (Kowalska et al., 2020). According to European Union guidelines, the value of products, materials and resources should be maintained for as long as possible and waste generation should be minimized. This is the basis for the development of smart cities (Closing the Loop, 2015).

2.4. Smart city concept

A modern city consists of many elements, making it an open, complex socio-economic system, and its development depends on the connections between its individual elements (Sikora-Fernandez, 2013). There is no clear definition of a smart city in the literature. Komnimos attempted to define a smart city. According to it, a smart city is defined as an area with a high capacity for learning and innovation, creativity, research and development institutions, higher education, digital infrastructure and communication technologies, and well-developed governance (Komnimos, 2002, p. 1). According to Bakici et al., a smart city should connect people and information, using new technologies to create a sustainable, more ecological, competitive and economically innovative organism in order to improve the quality of life there (Bakıcı et al., 2012). Barrionuevo et al. defined a smart city as the use of all available information, technologies and resources in an intelligent and coordinated manner by integrating them (Barrionuevo et al., 2012). According to Nan and Pardo, the information collected helps identify problems and demonstrate how they can be solved. This facilitates rapid action in the event of natural disasters, the need for optimal resource utilization decisions, and cooperation between various city authorities (Nam, Pardo, 2012). Zygiaris defined the roles of smart cities as cities:

- green – referring to urban infrastructure, environmental protection and reduction of CO_2 emissions,
- connected – related to the broadband economy revolution,
- intelligent – stating the ability to generate added value information in real time from sensors and actuators (Zygiaris, 2013).

According to Żukowska and Chmiel, the concept of a smart city refers to an ultra-modern city that meets the needs of businesses, institutions and all citizens. The concept is characterized by a holistic approach to urban development and the use of solutions based on communication technologies ICT – Information and Communication Technologies (Żukowska, Chmiel, 2022). A smart city focuses on implementing sustainable development principles in the social, economic and environmental spheres, without compromising the interests of future generations (Żukowska, Chmiel, 2022a). Characterized by modern administration or offices that provide new public services based on user-friendly information and communication services in local government (Gonzales, Rossi, 2011; Ferro et al., 2013).

These definitions show that advanced information and communication technologies (ICT) have a dominant role in the development of modern cities. Lazaroiu and Roscia indicate that the term smart city should refer to a city where available and new resources and possible investments are optimized. These goals can be achieved with the support of advanced information and communication technologies, particularly in areas such as energy, technological infrastructure, public safety, waste management and transport (Lazaroiu, Roscia, 2012). Modern cities require large amounts of energy and water to function, which must satisfy the needs of increasingly populated cities. Residents play a key role in the smart city ecosystem, as their activities influence the processes taking place in the city related to the flow of energy and matter. The primary sources of energy are fossil fuels and renewable energy, while matter comes in the form of waste generated from the production and consumption of products (Ba, 2017). The smart city concept seems to be the best for managing cities, as in addition to saving energy and water, it solves the problem of waste management and air protection (Musti, 2020; Aceleanu et al., 2019). The problems with establishing a single definition stem from the different perceptions of the smart city concept in different countries. In the European Union and its strategic documents, the emphasis is on clean energy, energy savings and reducing CO2 emissions into the atmosphere. In the US, smart cities are perceived as those that have human and social capital, transport and communication technologies, their development is in line with sustainable development, and the authorities ensure a better quality of life. In Australia, the concept of a smart city focuses on creative industries and digital media (Sikora-Fernandez, 2013). Despite the lack of a clear definition of a smart city, six main areas can be identified that make up the idea of 'smart'. The elements of a smart city include: smart mobility, smart economy, smart people, smart living, smart governance and smart environment (Glinka, 2017;

Khatoun, Zeadally, 2016). The intelligence of cities is measured using six components, comprising 28 factors presented in Table 1.

Table 1.
Six smart components and factors for measuring urban intelligence

Component	Factors for measuring urban intelligence
Smart economy	Spirit of innovation, entrepreneurship, economic image and trademarks, productivity, labor market flexibility, international cooperation
Smart people	Level of qualifications, lifelong learning, ethnic pluralism, creativity
Smart governance	Participation in public life, public and social services, transparency of governance
Smart mobility	Local, national and international accessibility, IT infrastructure accessibility, sustainability of the transport system
Smart environment	Environmental conditions, air quality, environmental awareness, sustainable resource management
Smart living	Cultural facilities, health conditions, safe communities, housing conditions, educational facilities, tourist appeal, economic prosperity

Source: (Baraniewicz-Kotasińska, 2017).

In order to make a city more resident-friendly, measures must be introduced to protect the environment and use natural resources more efficiently. A smart city that cares about the environment should implement measures in line with the circular economy, which increases its economic, social and environmental value (Dincă et al., 2022). From an ecological perspective, a concept has been developed that describes this area of smart city functioning in greater detail. One such concept is the green city, according to which a city takes politically and socially responsible actions to achieve high environmental quality, which contributes to human well-being (Pace et al., 2016). Another concept is the eco-city, according to which expenditure (resources) and production (waste) are minimised. Residents agree to the construction of an eco-city and commit to living in harmony with the biosphere (Rudloff, 2018).

Polish cities are implementing elements of the smart city concept into their urban management processes. This is indicated by the global Smart City Index ranking, which focuses on the economic and technological aspects of smart cities and on the human dimension of smart cities, i.e. quality of life, environment and integration. In 2025, the two largest Polish cities, Warsaw and Krakow, were included in the ranking.

This holistic approach will allow us to assess whether Krakow is actually becoming a smart city or whether it is just individual innovations.

3. Methods and research

This article presents a detailed analysis of the case of Krakow. This choice is dictated not only by the city's high ranking but, above all, by the continuation of previous research on this metropolis, which allows for a more in-depth, retrospective assessment of the changes implemented (figure 1).

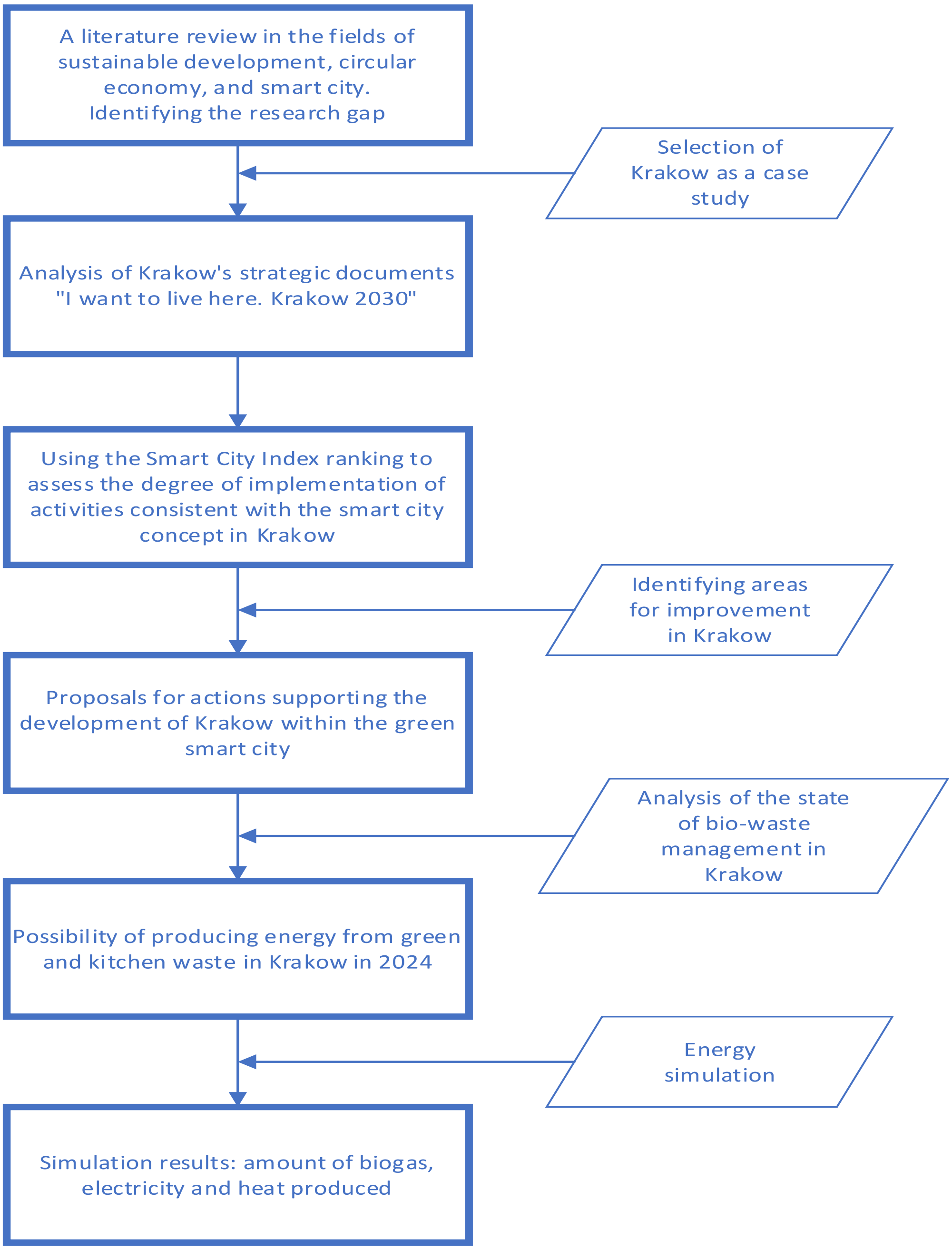

Figure 1. Methodologies of the research.

3.1. Objects analysis

Krakow is an example of a city modernized according to the smart city and circular economy model. Located in the Vistula River Valley and surrounded by hills, it lies at the intersection of the A4 motorway and the S7 expressway. Due to its numerous historical monuments, it is a center of domestic and international tourism. Residents from across the Małopolska Voivodeship and neighboring voivodeships come to Krakow to work, study, and shop. It is a dynamically developing city, as evidenced by the increase in its population from 761,000 in 2015 to over 806,000 in 2024 (Bank Danych Lokalnych, 2025). Krakow was chosen as a case study due to previous research interests in the city and favorable conditions for conducting systematic research. Based on the city's development strategy, the degree of implementation of smart city and circular economy initiatives was assessed, and the potential for biogas production from biodegradable waste was calculated based on datBaraniewicz-Kotasińskaa provided by the Marshal's Office of the Małopolska Voivodeship. Striving to become a modern urban center combining a high standard of living with cutting-edge technology and a resident-friendly environment, Krakow is committed to implementing the principles of a smart city and a circular economy.

3.2. Krakow's activities within the smart city framework

In 2018, the Krakow City Council adopted the city development strategy titled 'This is where I want to live. Krakow 2030,' developed in accordance with the smart city model. Its goals are achieved through strategic programs and non-program tasks, including independent projects across various management fields (Kraków przyszłości, 2024).

Among the most important projects implemented in line with smart city components are:

- *Smart economy* – Virtual assistant, which is a free mobile application. Using text and voice commands, users can obtain information regarding business services as well as other procedures carries out by organization units. This tool allows for the handling of official matters at various times of the day and from any location. It provides particular support for busy people and with disabilities.
- *Smart mobility* – It is implemented through a modern, eco-friendly fleet consisting of trams, electric buses, and vehicles powered by compressed natural gas (CNG) that meet Euro 6 emission standards. Smart traffic management systems are in operation. An integrated and secure transport system creates a high-speed network through a traffic control system that grants priority to public transport at intersections. The Agglomeration Fast Rail links central Krakow with the international airport and a number of neighboring communes. Discounts for individuals registered or paying taxes in Krakow who hold a Krakow City Card serve as an incentive to encourage the use of public transportation (Uchwała nr XCIV.2449/18 Rady Miasta Krakowa, 2018).
- *Smart environment* - Refers to waste to energy plants and the management systems for water supply and sewage networks. Biogas plants at two of Krakow's wastewater treatment facilities produce electricity and heat in a cogeneration process. The development of urban green areas and parks provides the city with 'green lungs' and creates a haven for wild birds, hedgehogs, and rodents. Pocket parks and green transit stops are being developed to cater to residents seeking a connection with nature a place to unwind. As part of Krakow's ongoing battle against smog, air quality monitoring devices and information displays providing real-time pollution data have been set up in numerous high-traffic locations. Measures are being implemented to decrease urban energy consumption. The transition to energy-efficient LED street lighting was finalized in 2016. The smart lighting control system cut energy consumption by 63%, significantly

lowering the city's electricity bills. Reducing CO_2 emissions into the atmosphere is an additional benefit (Uchwała nr XCIV.2449/18 Rady Miasta Krakowa, 2018).

- *Smart governance* – This field focuses on the monitoring of restricted traffic zones using specialized camera systems. The cameras verify vehicles entering restricted areas. It helps city guards monitor and enforce prohibited entry zones. This all aids in protecting the environment, adapting to climate change, and ensuring the safety of the local community (Uchwała nr XCIV.2449/18 Rady Miasta Krakowa, 2018).

The efficiency of municipal initiatives is enhanced by consecutive rounds of the citizen budget, where residents leverage their knowledge of local issues and needs through high levels of engagement. Mobile applications that enable the reporting of local issues, such as road damage or water utility failures, are also gaining popularity.

3.3. Evaluation of Krakow's activities within the smart city framework

Krakow and Warsaw stand as the sole Polish cities featured in the prestigious Smart City Index ranking, established by the Switzerland-based International Institute for Management Development (IIMD). It encompasses key sectors, including mobility, health, safety, data management, and sustainability. The index assesses how cities utilize technology and innovation to enhance the quality of life for their inhabitants and manage key infrastructure, including transport, energy, safety, and sustainability. The ranking is based in the subjective opinions of city residents regarding how their cities function. Responders choose 5 out 15 priority areas of city functioning. The assessment utilizes the Human Development Index (HDI), which evaluates factors such as health and longevity, education, and standard of living (Smart City Index, 2025).

In the first edition of the index, published in 2019, Krakow ranked 69th out of 102 cities evaluated. The priority areas of city functioning for residents were air pollution (75%), traffic congestion (60.8%) and affordable housing (50.8%). For those surveyed, areas such as citizen engagement, social mobility/inclusiveness, and corruption /transparency (picture 3). In 2025, Krakow ranked 70th out of 146 cities evaluated. In this edition, the majority of respondents stated that the priority areas in cities, are affordable housing (61.5%), air pollution (57.8), and road congestion (47.9%). Following these were security, fulfilling employment, health service, green spaces, and broad-based urban services (Smart City Index, 2024, 2025).

Comparing the importance of priorities in the three key areas addressing basic human needs across both edition, it can be concluded that efforts to improve air quality have yielded results, but for 57.8% of residents, the improvements is insufficient. Comparing the importance of priorities in three key areas responding to basic human needs from both editions, it can be concluded that efforts to improve air quality have brought results, but for 57.8% of residents the improvement is insufficient. The reduced severity of traffic congestion is a results of the construction of new tram lines and expressways, such as the Łagiewnicka Route, yet nearly half of the residents remain dissatisfied with the situation. The problem of affordable housing availability has not been resolved; instead, it is escalating. The sense of security has decreased followed by issues with water, waste, and education.

Analyzing the data shown in Figure 2, it can be hypothesized that current efforts should focus on implementing the "Green Smart city" concept, namely environmental production.

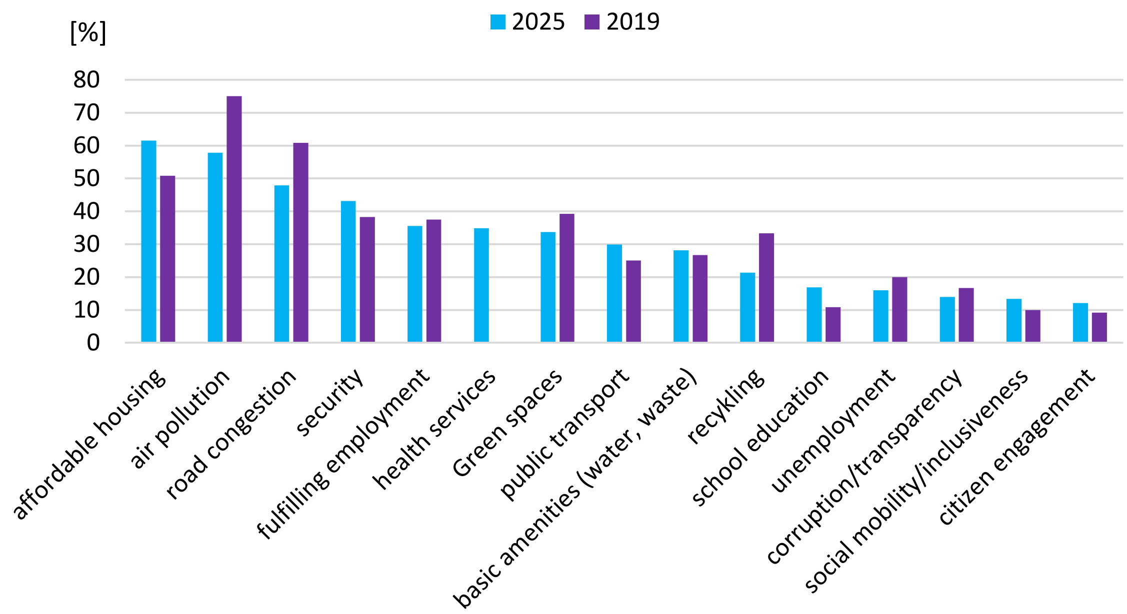

Figure 2. Priority areas selected by Krakow residents in the 2019 and 2025 Smart City Index.
Source: (Smart City Index, 2019, 2025).

3.4. Recommendations for further measures in the field of Green Smart City development

The realization of the green smart city vision necessitates the construction of affordable housing, the reduction of Green House Gases (GHG) and particulate matter emissions, the mitigation of traffic congestion, the expansion of public transit, and enhanced waste management systems.

Krakow has experience in implementing large-scale infrastructure projects in waste management and environmental protection. These include a thermal waste treatment plant and two modern wastewater treatment plants equipped with facilities for biogas production and co-generation combustion. The thermal waste treatment plant processes more than 200,000 megagramms (Mg) of waste per year, producing electrical energy and thermal power. In 2024, it generated over 69,000 MWh of electricity and more than 1.3 million GJ of heat per year. The biogas installation at the "Płaszów" sewage treatment plant generates about 12,000 MWh of electrical energy and more than 43,000 GJ of heat per year (Oczyszczalnia ścieków Płaszów…, 2024). The biogas plant at the "Kujawy" wastewater treatment facility has an annual production of approximately 12,000 MWh of electricity and over 38,000 GJ of thermal energy (Energia ze źródeł odnawialnych…, 2023). These facilities solve the problem of managing mixed waste and sewage sludge. The challenge of managing separately collected biodegradable waste (bio-waste) remains to be addressed, specifically green waste (code 20 02 01) and kitchen waste (code 20 02 08). The introduction of separate municipal waste collection in 2013, in accordance with the Waste Act (Ustawa o odpadach, 2012), has led to a steady increase in the volume of segregated bio-waste collected by Krakow residents, as shown in Figure 3.

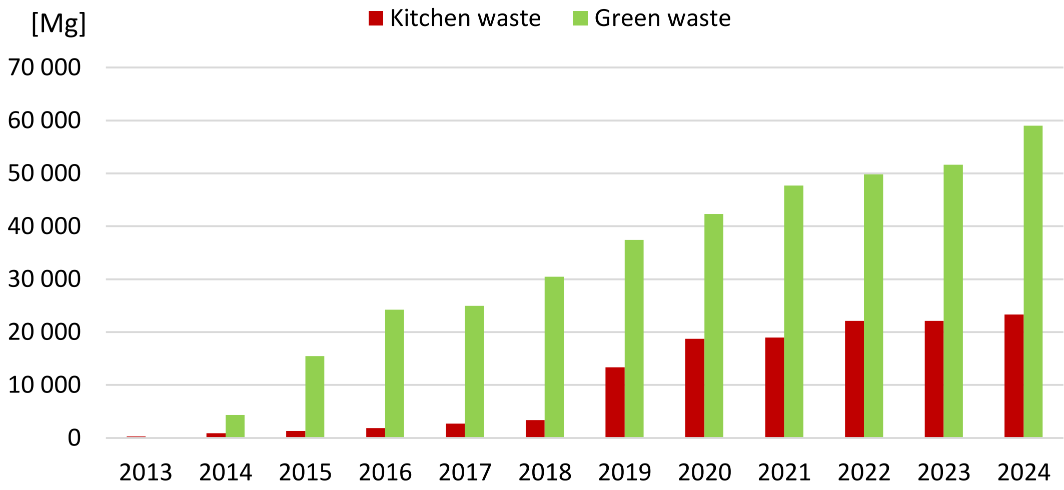

Figure 3. The amount of green waste and kitchen waste collected from residents of the Municipality of Krakow in 2013-2024.

Source: Based own: (Analiza stanu gospodarki odpadami…, 2013-2024).

Biodegradable waste under code 20 02 01 includes grass, leaves, and shredded branches. These originate from private gardens and municipal green areas (parks, cemeteries, and roadsides). In 2024, over 63,000 Mg of green waste were collected and pecked up. Almost all green waste, collected under the selective waste collection program and received at the municipal selective waste collection point, was recycled through composting at the "Barycz" green waste composting plant, owned by the Municipality of Krakow. The cost expenditure for waste treatment at this composting facility amounted to over 20 million PLN in 2024. Only about 100 megagrams (Mg) of green waste were treated in another installation (Analiza stanu gospodarki odpadami…, 2024).

Biodegradable kitchen waste (code 20 01 08) from households and companies is collected in brown bags or bins. In 2024, over 23,000 Mg of biodegradable kitchen waste was collected from the residents of Krakow. All collected waste was entirely treated at municipal processing plants. More than 20,000 Mg of waste was treated in processing plants situated outside the city of Krakow. Long-distance ccollection and transport of green and kitchen waste generate significant costs, which in 2024 amounted to over 14.6 million PLN (Analiza stanu gospodarki odpadami…, 2024).

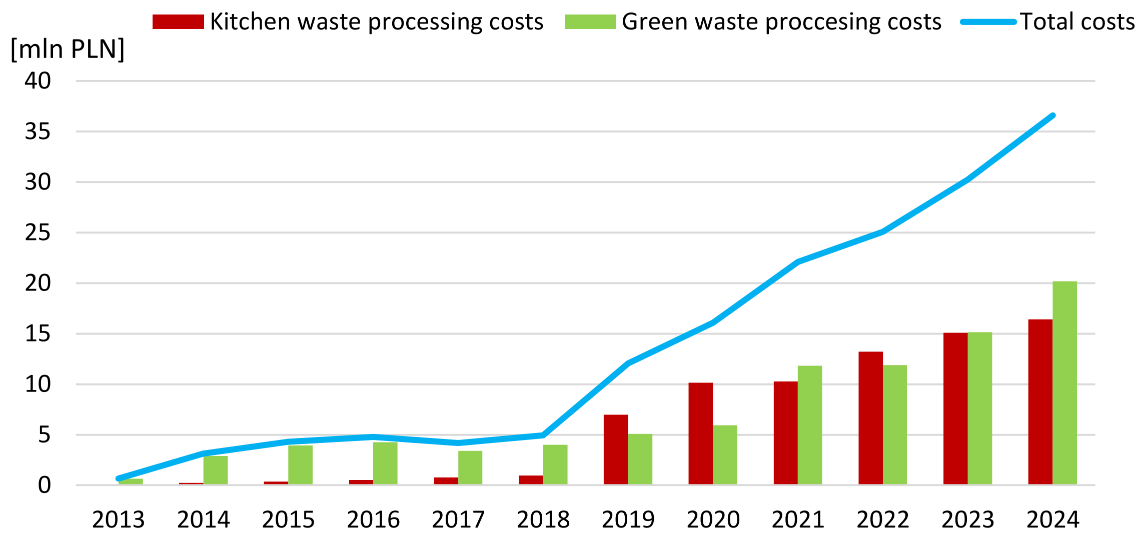

Figure 4. Costs of processing green and kitchen waste collected in households of the Municipality of Krakow in 2013-2024.

Source: Based own (Analiza stanu gospodarki odpadami…, 2013-2024).

The data presented in Figure 4 shows that the costs of processing waste collected in Krakow have exhibited a strong upward trend since 2013. In 2024, the total costs of their processing amounted to over 36.5 million PLN, which accounted for more than 13% of the total costs municipal waste collection, transport, recovery, and disposal in Krakow (Analiza stanu gospodarki odpadami…, 2024). Reducing these costs, or even generating a profit from waste management, could be achieved by utilizing the waste for green energy production in municipal biogas plants.

3.5. The possibilities of generating energy from biodegradable waste collected in Krakow

Data provided by the Marshal's Office of the Małopolska Region shows that the amount of bio-waste collected from both fractions is increasing year by year, it show Table 2. In 2021, approximately 50,000 Mg of green waste and about 19,000 Mg of kitchen waste were collected. In 2022, the volume of green and kitchen waste collected rose by about 2000 Mg. A significant increase in the volume of green waste collected occurred in 2023. At that time, over 59,000 Mg of green waste was collected, while the mass of collected kitchen waste was slightly higher than the previous year. In 2024, the highest volume of bio-waste among the analyzed years was collected, amounting to over 63,000 Mg of green waste and more than 23,000 Mg of kitchen waste. The data shown in the Figure 3.

Table 2.
Volume of green waste (code 20 02 01) and kitchen waste (code 20 01 08) collected in Krakow, 2021-2024

Year	Waste code	
	20 02 01	20 01 08
2021	49826.00	19003.03
2022	51659.07	22116.72
2023	59040.72	22140.79
2024	63335.65	23347.73

Based on data from Marshal's Office of the Małopolska Region regarding the volume of waste collected within the Municipality of Krakow in 2024, calculations were initiated to determine the potential production of biogas, biomethane, electricity and heat. For this purpose, a simulation was conducted showing, the potential for biogas production from kitchen bio-waste (code 20 01 08) and green waste (code 20 02 01) generated by the residents of Krakow. The calculations were performed for the total mass of waste in order to obtain information on the maximum possible energy production and to determine whether this would be a profitable investment for Krakow.

The data collected on biodegradable waste in Krakow for 2024 did not include information regarding the dry matter content of the feedstock for the biogas plant; therefore, biogas yields per 1 Mg of fresh matter were adopted for the calculations. For waste code 20 02 01, the biogas yield V_{bg} was assumed to be 150-200 Nm^3, and for waste code 20 01 08, the assumed biogas yield V_{bg} was 200-500 Nm^3. The specified biogas yield were adopted from the literature (Biogaz. Produkcja i wykorzystanie, 2021). The biomethane C_{bm} content in cubic meters (show in Table 3) was calculated based on the following formula (1).

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

Assuming the calorific value of biomethane W = 9.3 kWh/Nm^3, the total energy E_t, generated from 1 Mg of waste was calculated using formula (2).

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

The electric energy E_e and thermal energy E_h obtained from 1 Mg of bio-waste were calculated according to formulas (3) and (4).

$$E_e = E_t \cdot \frac{\eta_e}{100} \tag{3}$$

$$E_h = E_t \cdot \frac{\eta_t}{100} \tag{4}$$

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

The electric power of the generator P_e was calculated from formula (5).

$$P_e = \frac{E_e}{T_w} \tag{5}$$

The values used to calculate the potential for producing biogas, biomethane, electricity and heat in 2024 are presented in Table 3.

Table 3.
Values used to calculate energy production in a municipal biogas plant

Item	Unit	Waste code	
		20 02 01	**20 01 08**
Biogas yield	Nm^3	150-200	200-500
Biomethane content in biogas	%	55	60
Calorific value of biomethane	kWh/Nm^3	9.3	9.3
Electrical energy yield	%	35	35
Thermal energy yield	%	55	55
Generator operating time	hour/year	8000	8000

Source: Biogaz. Produkcja, wykorzystanie, 2005.

4. Results

To calculate the annual biogas, biomethane, electricity, and heat yields for the municipal biogas plant, the values from Table 3 were used, along with data on the amount of waste collected for 2024 (Table 2). The simulation began by calculating the amount of biogas and biomethane produced, which are the energy carriers in the biogas plant. Next, the total amount of electricity and heat produced was calculated, as well as the amount of heat used for the biogas plant and for sale to consumers. The obtained results are for the minimum and maximum biogas yields from green waste (code 20 02 01) and kitchen waste (code 20 01 08). The simulation results are presented in Table 4 and Figures 6 and 7.

Table 4.
Amount of biogas, biomethane, electricity, and heat produced from bio-waste collected from Krakow residents in 2024

Item	Unit	Yield	Waste code	
			20 02 01	**20 01 08**
Amount of waste	Mg/year	-	63 335.65	23 347.73
Total biogas yield	m^3/year	Min	9 500 347.5	4 669 546.0
		Max	**12 667 130.0**	**11 673 865.0**
Total biomethane yield	m^3/year	Min	5 225 191.1	2 801 727.6
		Max	**6 966 921.5**	**7 004 319.0**
Total electricity generation	MWh	Min	17 008.0	9 119.6
		Max	**22 677.3**	**22 799.1**
Total thermal energy generation	MWh	Min	26 726.9	14 330.8
		Max	**35 635.8**	**35 827.1**
Internal heat consumption	MWh	Min	8018.1	4299.3
		Max	**10690.7**	**10748.1**
Exportable heat	MWh	Min	18 708.8	10 031.6
		Max	**24 945.1**	**25 079.0**
Biogas plant electric power	MW	Min	2.1	1.1
		Max	**2.8**	**2.8**

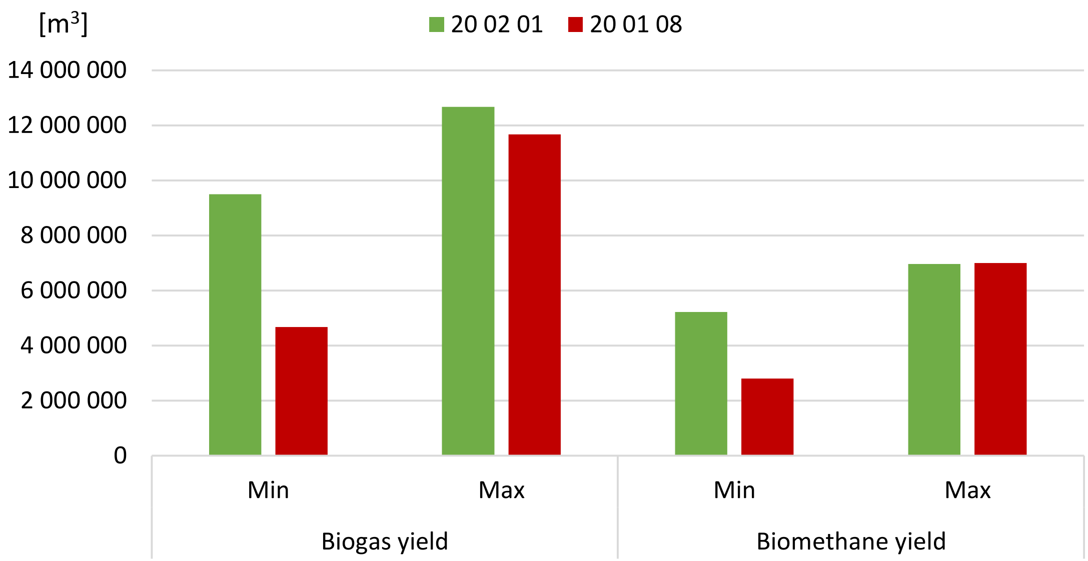

Figure 5. Minimum and maximum amounts of biogas and biomethane that can be obtained in 2024 from biodegradable municipal waste.

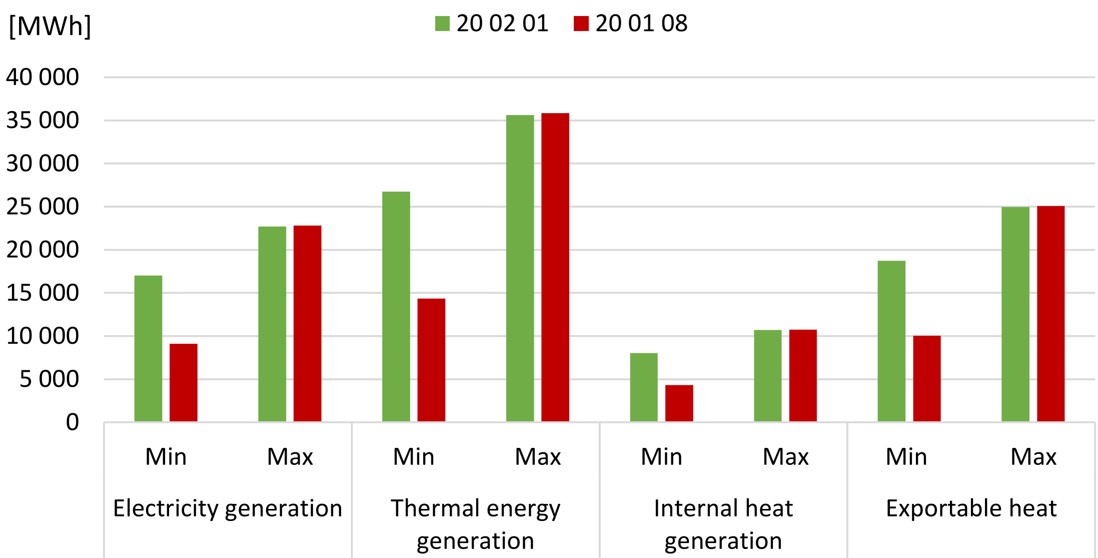

Figure 6. Minimum and maximum amounts of electricity and heat that can be produced in 2024 from biodegradable municipal waste.

From approximately 14 million m^3 to over 24 million m^3 of biogas V_{bg} can be produced annually from the given biodegradable waste. It contains between 55 and 60% methane V_{bm}, which is burned in cogeneration units in a biogas plant. This results in the generation of electrical energy E_e and thermal energy E_h. This allows for the production of electricity E_e which will be sold consumenrs in amounts from over 26,000 to over 45,000 MWh and thermal energy E_h in amounts from approximately 41,000 to over 71,000 MWh. Of the produced thermal energy E_h, 30% must be allocated to maintaining the fermentation process in the fermentation chambers. The remaining heat E_h can be sold or transferred to the Krakow district heating network.

5. Discussion

The biogas quantities presented in the table could be achieved by utilizing 100% of the biodegradable waste collected in 2024, provided it is supplied regularly to the fermentation chambers. Meanwhile, green waste (20 February 2020) is collected from households only between April and October. Preparing grass silage could ensure some regularity of deliveries (Szyba, Mikulik 2023). 1 Mg of such silage can yield 170 to 200 Nm^3 of biogas (Biogaz, Produkcja, Wykorzystanie, 2023). Preparing silage incurs additional costs. These costs seem unnecessary, as the disposal of this waste fraction is carried out in a composting plant. One ton of grass silage yield between 170 and 200 Nm^3 of biogas (Biogaz, Produkcja, Wykorzystanie, 2005).

The collection of kitchen waste (code 20 01 08) is continuous, with only minor seasonal fluctuations. The variations in feed quantities and the differing rations of carbohydrates, proteins, and fats do not pose an obstacle to maintaining the fermentation processes. The viability of this approach is demonstrated by performance of municipal biogas facilities in Sweden, Denmark and Austria (Olsson, Fallde, 2015; Raven, Gregersen, 2007; Nowak et al., 2015). The primary issue regarding the collection of this waste lies in the frequency of removal from the points of origin. In the summer, extended lead times lead to waste decomposition, resulting in unstable anaerobic digestion inside the digesters. Pre-decomposed kitchen waste generates an excessive amount of volatile fatty acids. Their accumulation leads to a rapid drop in pH within the biogas plant, which kills methanogenic bacteria and halts energy production (Zhang et al., 2007). Increasing the waste collection frequency will raise costs and reduce profitability. A potential solution could be collection of waste in households using hermetically sealable paper bags, a practice already established in Sweden. Studies conducted by Bernstad and la Cour Jansen confirm that paper packaging not only facilitates waste separation but, above all, prevents the premature rotting bio-waste. This results in a more stable fermentation process and higher methane production compared to waste collected in plastic bags (Bernstad, la Cour Jansen, 2012). Due to the year-round availability of kitchen waste in consistent volumes, and the steadily increasing amount of this fraction collected in Krakow, the construction of municipal biogas plant utilizing exclusively kitchen bio-waste should be considered. Preparing grass silage to ensure a consistent year-round supply would incur additional costs and labor. Green waste would continue to be processed at that the "Barycz" composting plants as it has been to date.

The development of a municipal biogas plant does not entail substantial adverse effects on the local population or the surrounding environment. In the long-term perspective, the operation of a municipal biogas plant will contribute to the improvement of local air quality by partially displacing the combustion of fossil fuels as an energy source. This will result in a reduction of CO_2 emissions into the atmosphere (Al-Wahaibi et al., 2020).

Failure to build municipal biogas plants will hinder the implementation of Poland's Energy Policy until 2040 in the field of renewable energy development and the achievement of the target set out in Directive 2009/28/EC of the European Parliament on the promotion of the use of energy from renewable sources (Polish Energy Policy until 2040).

To achieve the aforementioned Sustainable Development Goals and the goals of EU and Polish policies, society must engage in their implementation. This begins with the basics: proper segregation of bio-waste and the creation of a system that will enable its collection and disposal at a biogas plant.

6. Conclusions

In Krakow, a waste collection system is in place for the following fractions: plastic and metals, paper, glass, biodegradable waste and mixed waste of the latter; of the latter, more than 48% was collected in 2024. Mixed waste can contain approximately 32.7% of green and kitchen waste (Pawnuk et al., 2022). In 2024 green waste accounted for 14.7% and kitchen waste for 5.4% of the total amount of all waste fractions collected. Currently, their disposal poses a significant burden on the city’s waste management system. Biodegradable waste can be processed and converted into electricity and heat in municipal biogas plants, and the revenue from energy sales can bolster the city’s budget.

Green waste is collected from March until the end of November, and the volume gathered depends on the intensity of the growing season. This waste fraction in successfully treated at the “Barycz” composting facility, resulting in the production of organic compost. Kitchen waste is collected from households throughout the entire year, with quantities remaining relatively stable regardless of the season. The study presents a simulation demonstrating the potential for biogas production from biodegradable municipal waste collected in Krakow during 2024. Due to the year-round availability of food waste, the collected amount would allow for the production of approximately 4.6 to 11.6 million m^3 of biogas with a methane content of 60%. The significant discrepancy in the results is due to the variable composition of food waste; only a detailed analysis would allow for the determination of the approximately composition of these wastes. The biogas produced through cogeneration would yield both electricity and heat, as well as digestate, which serves as an excellent organic fertilizer for the green areas in Krakow.

The building of a municipal biogas plant would allow for a reduction in food waste disposal costs, which in 2024 amounted to nearly 16.4 million PLN in Krakow. High disposal costs are driven, among other factors, by the transport of these wastes to facilities located up to 300 km from Krakow, which currently lacks its own treatment plant for this specific waste fraction.

Building a municipal biogas plant in Krakow is possible. This will reduce the costs of disposing of kitchen bio-waste (code 20 01 08) and increase the share of renewable energy sources in Krakow's energy mix. Together with two biogas plants at the sewage treatment plant and the Waste to Energy, the share of renewable energy sources in Krakow's energy mix will be strengthened. The municipal biogas plant aligns with the circular economy concept supported by the European Commission and implements the UN Sustainable Development Goals: Goal 7 – Affordable and Clean Energy; Goal 11 – Sustainable Cities and Communities. This research confirms the hypothesis posed in the introduction of this article (Cele zrównoważonego rozwoju).

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