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NEW APPROACH FOR CALCULATION OF RECYCLING RATES OF MUNICIPAL WASTE IN THE CIRCULAR ECONOMY (CE)

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Abstract
In December 2020, new waste recycling targets were adopted for the functioning of municipal waste management systems, which are the result of the transformation of the Polish waste management system from a linear model into circular economy. Municipal waste management systems are very diverse, undergoing a constant evolution since 2013, i.e. since municipalities took over the management of the system, related to the collection, processing and disposal of waste, they must be effective, i.e. achieve the objectives of environmental policy. The assumptions of the European Union (EU) environmental policy, in particular new waste recycling rates set until 2035, determine the direction of development of waste management and at the same time the implementation of circular economy. The aim of the paper is to analyse the methods of calculating new recycling rates permitted by European law and to try to implement the methodology into national regulations. In addition, based on the available statistical data on the Polish municipal waste management system, the analysis was supplemented by simulation of solution enabling the achievement of high recycling levels in 2035.

Keywords: **Municipal waste; Recovery; Recycling; Circular economy.**

1. INTRODUCTION

Municipal waste management built in Poland since 2013, i.e. since municipalities took over the management of the system, including the adopted systemic solutions, is making progress, which is measured by the increasingly higher levels of preparation for reuse and recycling achieved. Initially, municipal waste management was focused on achieving social benefits: reducing the share of waste deposited in landfills, organizing selective waste collection "at the source", as well as recycling and recovery of secondary raw materials [1].

Planning is a crucial component of short- and long-term municipal waste management. Establishing the relationship between factors determining the amount of waste generated by municipalities and forecasting waste management needs to play a fundamental role in the development of effective planning strategies and implementation of sustainable development [2].

The municipal waste management system should be built based on the principles of sustainable development and the methods adopted to solve the problems must be adapted to the specificity of the society, taking into account the local, regional and national experience and conditions. In Poland there has been a discussion for many years on the introduction of such a model of municipal waste management that would propose optimal solutions for the collection, segregation, management and disposal of municipal waste with respect for natural resources. Undoubtedly, such a model must be built according to the principle of three reduction, rationalization, recycling [3].

The goals set for 2020, i.e. the obligation to achieve a minimum level of 50% preparation for re-use and recycling of at least 4 fractions of municipal waste, i.e. paper, metals, plastic and glass [4], should be seen as a stage on the way to achieving the ambitious perspective goals set by 2035, obliging to achieve 65% level of preparation for reuse and recycling of the entire municipal waste stream. This is required by the transformation of the world economy into a circular economy, which is oriented towards resource efficiency in the broad sense, i.e. obtaining raw materials from municipal waste, causes that the European Union (EU) policy in the field of municipal waste management to seek further changes and tightening of regulations in this area, which will primarily be oriented towards increasing recycling [5].

In 2018 the European Commission (EC) presented a revised Waste Framework Directive, setting ambitious targets for increasing the reuse and recycling of municipal waste to a minimum of 65% by 2035. Due to increasing amount of municipal waste, it is important to look for sustainable methods of waste management, taking into account the European waste hierarchy. However, there are clear differences in the amount and composition of waste generated as well as methods of its management in individual countries and regions, resulting from many socio-economic and technical factors, including the wealth level of the society as well as the development and application of modern recycling and disposal installations. Due to the fact that the main challenge in waste management for the coming years is the transition to the Circular Economy (CE) model, and the EC indicated waste management as one of the elements of the framework for monitoring the transformation process towards the circular economy, it is necessary to monitor both the changes in the management of municipal waste in individual Member States and their effects [6].

The waste recycling targets set by the European Commission (EC) for environmental organizations seem not ambitious enough while, at the same time, too high and often impossible to achieve for municipal waste management practitioners. Calculations concerning the mass balance of municipal solid waste clearly indicate that some indicators, such as the target level of recycling of 65% municipal solid waste to be achieved in 2035, may be technically or technologically unattainable in Poland. This is mainly hindered by the fractional (morphological) composition of municipal waste and lower content of recyclable packaging waste than in more developed EU countries [7].

The European Environmental Bureau, in its position paper, notes that data monitoring in waste policy is not ideal and supports the European Commission's intention to develop a special methodology for calculating recycling levels instead of the four currently existing ones [8]. In 2019, the European Commission presented a common method for calculating the indicated recycling rates for EU countries in order to improve the comparability of statistics between EU countries [9]. Until now, one of the methodologies allowed for the recognition of the entire mass of waste that was selectively collected as recycled, which resulted in some countries reporting overestimated recycling levels [10].

The main purpose of the paper is to propose an algorithm for determining the recycling rate in Polish conditions, adopted by the European Commission, and to analyse the sensitivity of the waste recycling rate depending on the type of municipal waste streams and the methods of determining the individual masses of waste adopted for calculations. The article proposes three scenarios describing different situations with respect to different municipal waste streams and different places for measuring the mass of waste for recycling. Within each of the scenarios, two variants were included, in which a different model of determining the mass of generated waste was adopted. The presented theoretical considerations were analyzed experimentally using statistical data from nine municipal governments in Poland, and the averaged results together with their discussion are presented in this paper.

2. PREVIOUS METHOD OF CALCULATING RECYCLING INDICATORS

Municipalities in Poland were obliged to achieve a 50% recycling rate, including preparation for reuse of such municipal waste fractions as **p**aper, **m**etals, plastics and **g**lass (PMPG) by 31 December 2020. The basis for the selection of the method of determining the recycling rate was the decision of the European Commission of November 18, 2011 establishing the principles and calculation methods for verifying compliance with the targets set out in Art. 11 sec. 2 of the Directive of the European Parliament and of the

Council, which left the Member States the freedom to choose municipal waste streams for which the recycling rates were calculated, but nevertheless specified the scope of solutions (4 methods of calculating the recycling rates) available to the Member States, whether or not they had achieved the recycling targets [11]. Poland chose the first method of calculating environmental targets to determine the recycling rate of waste paper; metal; household plastic and glass in percentage points (%) as a ratio of paper waste; metal; recycled household plastics and glass to the total amount of paper; metal; plastic and glass waste from households generated. The detailed method of determining the level of recycling has been determined by the Regulation of the Minister of the Environment [12–13] and is determined according to the equation (1):

$$P_{pmpg} = \frac{Mr_{pmpg}}{Mw_{pmpg}} \times 100\% \qquad (1)$$

where:

P_{pmpg} – the level of recycling and preparation for re-use of paper, metals, plastics and glass [%]

Mr_{pmpg} – total weight of recycled and prepared for re-use paper, metal, plastic and glass waste from the municipal waste stream from households and from other municipal waste producers [Mg]

Mw_{pmpg} – total mass of paper, metal, plastic and glass waste generated from the municipal waste stream from households and from other municipal waste producers [Mg]

The current method of calculating the levels of recycling and preparing for re-use of PMPG waste provided flexibility based on the data from the Central Statistical Office (CSO) in determining the mass of PMPG waste generated, i.e. Mw_{pmpg}, which is calculated according to the equation (2):

$$Mw_{pmpg} = Lm \times Mw_{CSO} \times Um_{pmpg} \qquad (2)$$

where:

Lm – number of inhabitants – data from the register of inhabitants or from the declaration of the amount of the fee for municipal waste management

Mw_{CSO} – mass of municipal waste generated by one inhabitant in the voivodship – CSO index averaged for the voivodship

Um_{pmpg} – the share of PMPG waste in the morphological composition of municipal waste, determined on the basis of indicators from National Waste Management Plan 2022 (Polish – Krajowy Plan Gospodarki Odpadami 2022 (KPGO 2022)) (49.3% for cities with more than 50 thousand inhabitants) or according to morphological studies carried out for a given commune (39% – average indicator for large cities).

3. NEW METHOD OF CALCULATING RECYCLING INDICATORS

The first CE document published in 2014 by the EC was the vision of the "zero waste program" for Europe in 2014. This communication is a key document in the implementation of the CE model in the EU because it clearly outlines the steps to be taken to move from a linear economy to a circular economy. In 2015, the second document on CE was published, the so-called CE Action Plan or CE Package. The CE Action Plan included the propositions of long-term actions to reduce landfilling of waste (including illegal landfill sites) and to increase its preparation for reuse and recycling [6].

The European Commission presented the Circular Economy Package as an action plan to extend the life cycle of products by keeping them in circulation as long as possible, making waste prevention and recycling the main action. As part of the CE Package, the European Commission amended most of the legal acts related to waste management [14]. They include:

- Directive of the European Parliament and of the Council amending Directive 2008/98 / EC on waste,
- Directive of the European Parliament and of the Council amending Directive 94/62 / EC on packaging and packaging waste,
- Directive of the European Parliament and of the Council amending Directive 1999/31 / EC on the landfill of waste,
- Directive of the European Parliament and of the Council amending Directives 2000/53 / EC on end-of-life vehicles, 2006/66 / EC on batteries and accumulators and waste batteries and accumulators and 2012/19 / EU on waste electrical and electronic equipment.

The consequence of adopting the circular economy model in the EU were detailed regulations on waste management introduced by the European Commission. In line with them, the following restrictions were adopted:

- achieving 65% recycling of municipal waste by 2035;

- achieving 75% recycling of packaging waste by 2035;
- reducing municipal waste landfilling to a maximum of 10% by 2030;
- a ban on the landfilling of selectively collected waste.

In terms of packaging waste, detailed, target recycling levels have been adopted, different for different types of waste: paper and cardboard – 85%; ferrous metals – 80%; aluminum – 60%; glass – 75%; plastics – 55%; wood – 30% [7].

As part of the 2015 Circular Economy Package and the Commission's extensive efforts to improve the quality of EU waste statistics, the European Commission has also proposed to harmonize the methodology for calculating recycling rates for municipal waste and packaging waste. According to the Commission, the adoption of these proposals by the Council and the European Parliament and their implementation by the Member States will result in more reliable and comparable statistics [15].

The ambitious goals have been transposed into national law, setting new levels of environmental indicators for municipal governments in the field of municipal waste management [4]. In Art. 3b paragraph 1 of the Act on maintaining cleanliness and order in municipalities, as the municipalities' own task, achieving the level of preparation for re-use and recycling of municipal waste in the amount of at least:

- 20% by weight – in a year 2021;
- 25% by weight – in a year 2022;
- 35% by weight – in a year 2023;
- 45% by weight – in a year 2024;
- 55% by weight – in a year 2025;
- 56% by weight – in a year 2026;
- 57% by weight – in a year 2027;
- 58% by weight – in a year 2028;
- 59% by weight – in a year 2029;
- 60% by weight – in a year 2030;
- 61% by weight – in a year 2031;
- 62% by weight – in a year 2032;
- 63% by weight – in a year 2033;
- 64% by weight – in a year 2034;
- 65% by weight – in a year 2035 and for each subsequent year.

The level of preparation for re-use and recycling of municipal waste is calculated as the ratio of the weight of municipal waste prepared for reuse and recycled to the weight of municipal waste generated [4]. For the calculation of the level of recycling, including reuse, the guidelines set out in the European Commission Implementing Decision setting out the rules for the calculation, verification and reporting of data on waste [9] the years 2025, 2030 and 2035, as referred to in Art. 11a of the Waste Framework Directive [16], waste entering the recycling process or waste that has ceased to be waste should be used. In general, recycled waste should be measured when it enters the recycling process. However, Member States may derogate and measure municipal waste at the exit of the sorting operation, provided that they deduct further losses from treatment prior to the recycling process and that the waste after the sorting operation is actually recycled.

The implementing decision, in order to ensure the uniform application of the calculation rules by all Member States, specified, for the most common types of waste and recycling processes, whose waste materials should be included in the calculation and at which stage of the waste treatment they should be measured. This defined the calculation points and the measurement points in the case of recycled municipal waste, and so in accordance with the provisions of the decision [9] as:

- the mass of waste prepared for re-use is only considered to be products or components of products that can be re-used after checking, cleaning or repair operations without further sorting or pretreatment;
- mass of glass waste – sorted glass, not subjected to other processing before being processed in a glass furnace or used for the production of filtration media, abrasive materials, glass insulating materials and building materials;
- mass of metal waste – sorted metals, not subjected to other processing prior to treatment in a metal melting furnace or a metal heat treatment furnace;
- weight of paper waste and cardboard – sorted paper, not subjected to other processing before being used for the preparation of pulp;
- weight of plastic waste – plastics divided by polymers, not subjected to other processing before being granulated, extruded or formed. Plastic flakes, not otherwise processed before being used in the final product;
- weight of wood waste – sorted wood, not subjected to other processing before being used in the production of chipboards. Sorted wood was composted;

- weight of textile waste – sorted textiles, not subjected to other processing before being used in the production of textile fibers, rags or granules;
- mass of multi-material waste (multi-material) – Plastics, glass, metal, wood, textiles, paper and cardboard and other constituent materials from the treatment of multi-material waste, not otherwise processed before being transferred to the calculation point established for the material in question in accordance with this Annex or with Art. 11a of Directive 2008/98 / EC and Art. 3 of this decision;
- weight of waste electrical and electronic equipment (WEEE) – WEEE admitted to the recycling facility after appropriate treatment and completion of preliminary activities in accordance with Art. 11 of Directive 2012/19 / EU of the European Parliament and of the Council;
- weight of waste from used batteries – Input fractions entering the battery recycling process according to Commission Regulation (EU) No 493/2012;
- mass of municipal bio-waste – bio-waste that is treated aerobically or anaerobically includes only materials that actually undergo an aerobic or anaerobic treatment, excluding any material that is mechanically removed during or after the recycling process. The mass of municipal bio-waste that is recycled also includes the mass of bio-waste that is separated and recycled at source, although the actual measurement of the input to the recycling process or its output is not always possible as it is usually managed by individual households. Therefore, a reasonable common approach has been established which should ensure a high level of reliability in the reported data. The decision develops a method for calculating municipal bio-waste sorted and recycled at source, with the requirement that the amount of municipal bio-waste separated and recycled at source should be included in both the amount of municipal waste recycled and the total amount of municipal waste generated;
- mass of metals separated after incineration of municipal waste – the amount of metals separated from bottom ash including only metals contained in the concentrate separated from raw municipal waste bottom ash and not including other materials in the concentrate.

Pursuant to the provisions of the Act of 13 September 1996 on maintaining cleanliness and order in municipalities [4], the level of preparation for re-use and recycling of municipal waste from 2021 will be calculated in accordance with the equation (3):

$$P = \frac{Mr}{Mw} \times 100\% \tag{3}$$

where:

P – level of preparation for reuse and recycling of waste municipalities, %,

Mr – total mass of municipal waste subject to preparation for reuse and recycling, Mg,

Mw – total mass of generated municipal waste, Mg.

The determination of individual values is limited by the rules described in the Waste Framework Directive [16] and the European Commission Implementing Decision [9]. Nevertheless, in the opinion of the authors of the paper, it is reasonable to maintain maximum flexibility in determining the Mr (mass of waste sent for recycling) and Mw (mass of generated municipal waste) values, at least at the level permitted by European Union regulations. The algorithm for determining the amount of generated waste and the amount of waste transferred for recycling will be crucial for Poland's recycling performance. Maintaining flexibility in determining the amount of waste generated is supported by the Implementing Decision of the European Commission, which in Annex V allows for the estimation of the amount of waste generated according to morphological tests by indicating that the amount of waste generated for each material may be based on data on selectively collected waste and on estimated data from regularly updated municipal waste composition surveys [9].

4. PROPOSITION OF ALGORITHMS FOR DETERMINATION OF RECYCLING RATE IN POLAND

Currently in Poland, at the legislative level, there is a discussion on the method of determining the recycling rates. The purpose of this paper is to analyze the sensitivity of the waste recycling rate depending on the type of municipal waste streams included and the methods of determining the weight of waste adopted for calculations. Data from 2018, included in the reports on the implementation of tasks in the field of municipal waste management, were adopted for the analysis. Reports prepared and published on websites by the following municipalities were analyzed:

Kraków, Wrocław, Gdańsk, Szczecin, Białystok, Gliwice, Tomaszów Mazowiecki, Sieradz, Dzierżoniów.

The basis for determining the recycling rate was the method specified in Art. 3b of the Act on the maintenance and order in municipalities [4], defining the level of preparation for re-use and recycling of municipal waste as the ratio of the weight of municipal waste prepared for reuse and recycled to the weight of municipal waste generated, while when calculating the level of preparation for re-use and recycling of municipal waste construction and demolition waste other than hazardous waste, constituting municipal waste, is not taken into account [4].

Three scenarios for determining the recycling rate were designed, different in terms of the type of municipal waste streams considered as entering the recycling process and differentiated in terms of measuring points, i.e. points / places where the mass of waste materials was measured to determine the amount of waste considered as recycled. Additionally, in all scenarios, it was proposed to examine the variability of the recycling rate in terms of the method of determining the mass of generated municipal waste, adopting two variant solutions.

In addition, due to the development and standardization of selective municipal waste collection systems, systematized in 2016 [12–13] the change in the recycling rate in 2018-2020 was analysed on the example of one municipal government (Municipality of Krakow), taking into account all described situations.

Scenario 1 assumes that the recycling rate is calculated as the ratio of the mass of paper, metal, plastic and glass waste prepared for re-use and recycling (Mr_{pmpg}) to the mass of total municipal waste generated (Mw). The mass of waste paper, metal, plastic and glass (Mr_{pmpg}) introduced into the recycling process was adopted as the measuring point.

Scenario 2 assumes that the recycling rate is calculated as the ratio of the mass of paper, metal, plastic, and glass prepared for reuse and recycling and the bio-waste sent to the recycling process, i.e. the bio-waste input into the recycling process (Mr_{pmpg} + BIO), to the total mass of municipal waste generated (Mw). The mass of paper, metal, plastic and glass waste put into the recycling processes and the mass of municipal bio-waste put into the recycling process at the beginning of the recycling process (composting or anaerobic digestion) were taken as the measuring point.

Scenario 3 assumes that the level of recycling is calculated as the ratio of the weight of paper, metal, plastic and glass waste and bio-waste collected selectively in municipal waste management systems ($Mr_{sel(pmpg\ +\ BIO)}$) to the total weight of municipal waste generated (Mw). The mass of paper, metal, plastic and glass waste as well as municipal bio-waste actually separately gathered in municipal waste management systems, that are planned to be collected in the "at source" system was adopted as the measurement point.

Additionally, in all three scenarios, two variants of determining the total mass of generated municipal waste (Mw) were adopted:

– Variant I – the mass of generated municipal waste is the mass of municipal waste actually collected under municipal waste management systems (Mw_{REAL});
– Variant II – the mass of generated municipal waste is calculated according to statistical data as the product of the number of inhabitants and the CSO index averaged for the province concerning the mass of municipal waste generated per one inhabitant in the given province (Mw_{CSO}). The mass of generated municipal waste (Mw_{CSO}) is calculated according to the equation (4):

$$Mw_{CSO} = L_m \times W_{CSO} \tag{4}$$

where:

L_m – number of inhabitants from the municipal register of residents or from the declaration on the amount of the fee for municipal waste management;

W_{CSO} – mass of municipal waste generated by one inhabitant in the given province, Mg.

Table 1 presents a summary of the three scenarios with their descriptions and the determination of the equations for the two variants adopted.

5. RESULTS AND DISCUSSION

Based on the reports of communal self-governments, an analysis of statistical data on municipal waste management in nine communal self-governments in Poland, diverse in terms of demographics, was carried out. The recycling levels achieved by these local governments in 2018 (determined according to the existing rules) are as follows: Kraków – 42%, Wrocław – 35%, Gdańsk – 44%, Szczecin – 46.46%, Białystok – 58.96%, Gliwice – 39%, Tomaszów Mazowiecki – 61.96%, Sieradz – 30.21%, Dzierżoniów – 53%. The results in terms of the cal-

Table 1.
Summary of scenarios and determination of the patterns of the recycling rate in the developed variants

Scenario number	Scenario description	Determining the pattern – variant I	Determining the pattern – variant II
Scenario 1	the recycling rate is calculated as the ratio of the weight of paper, metal, plastic and glass (PMPG) prepared for reuse and recycling to the weight of total municipal waste generated	$P = \frac{Mr_{pmpg}}{Mw_{REAL}} \times 100\%$ where: P – level of preparation for re-use and recycling of municipal waste, %, Mr_{pmpg} – total mass of paper, metal, plastic and glass waste prepared for reuse and recycling, Mg, Mw_{REAL} – total mass of generated (collected) municipal waste, Mg	$P = \frac{Mr_{pmpg}}{Mw_{CSO}} \times 100\%$ where: P – level of preparation for re-use and recycling of municipal waste, %, Mr_{pmpg} – total mass of paper, metal, plastic and glass waste prepared for reuse and recycling, Mg, Mw_{CSO} – total mass of generated municipal waste, Mg
Scenario 2	the recycling rate is calculated as the ratio of the weight of paper, metal, plastic and glass waste prepared for reuse and recycling, and bio-waste transferred to the recycling process (input into the recycling process) to the total weight of municipal waste generated	$P = \frac{Mr_{pmpg+BIO}}{Mw_{REAL}} \times 100\%$ where: P – level of preparation for re-use and recycling of municipal waste,%, $Mr_{pmpg+BIOrec}$ – total weight of paper, metal, plastic, glass and recycled bio-waste, Mg, Mw_{REAL} – total mass of generated (collected) municipal waste, Mg	$P = \frac{Mr_{pmpg+BIO}}{Mw_{CSO}} \times 100\%$ where: P – level of preparation for re-use and recycling of municipal waste, %, $Mr_{pmpg+BIOrec}$ – total weight of paper, metal, plastic, glass and recycled bio-waste, Mg, Mw_{CSO} – total mass of generated municipal waste, Mg
Scenario 3	the recycling rate is calculated as the ratio of the weight of paper, metal, plastic and glass waste and bio-waste collected and collected selectively in municipal waste management systems to the total weight of municipal waste generated	$P = \frac{Mr_{sel(pmpg+BIO)}}{Mw_{REAL}} \times 100\%$ where: P – level of preparation for re-use and recycling of municipal waste, %, $Mr_{sel(pmpg+BIO)}$ – total mass of separately collected waste paper, metals, plastics, recycled glass and bio-waste, Mg, Mw_{REAL} – total mass of generated (collected) municipal waste, Mg	$P = \frac{Mr_{sel(pmpg+BIO)}}{Mw_{CSO}} \times 100\%$ where: P – the level of preparation for re-use and recycling of municipal waste, expressed in %, $Mr_{sel(pmpg+BIO)}$ – total mass of separately collected waste paper, metals, plastics, recycled glass and bio-waste, Mg, Mw_{CSO} – total mass of generated municipal waste, Mg

Source: Own study

culated recycling rates were averaged and grouped into three groups, dividing the municipalities depending on the number of inhabitants, i.e. municipalities with a high number of inhabitants (400–800 thousand inhabitants), municipalities with an average number of inhabitants (150–250 thousand inhabitants), municipalities with a small number of inhabitants (20–50 thousand inhabitants). Table 2 shows the average results for the calculated recycling rates [%] in three groups of municipalities and the average values in the analyzed three scenarios and two variants in each scenario.

Recycling rates achieved in 2018, included in reports on the implementation of tasks in the field of municipal waste management. Reports prepared and published on websites by the following municipalities were analyzed: Kraków, Wrocław, Gdańsk, Szczecin, Białystok, Gliwice, Tomaszów Mazowiecki, Sieradz, Dzierżoniów. The lowest values of the recycling rate were achieved in the situation assigned to Scenario 1. In 2018, the mass of recycled paper, metal, plastic and glass waste, in relation to the total amount of municipal waste generated, das so low that the level of recycling, average for both variants did not exceed 17%. According to the currently used methodology of calculating the level of recycling, the mass of recycled paper, metal, plastic and glass waste is related to the mathematically determined mass of these types of waste (paper, metals, plastic and glass) generated by the inhabitants of municipalities. Hence, most municipalities in Poland have achieved the waste recycling rate required for 2018, i.e. the recycling rate of 30% [12].

Table 2.
Recycling rates [%] in the analyzed scenarios in two variants

Description		Large municipalities Recycling rate [%]	Medium municipalities Recycling rate [%]	Small municipalities Recycling rate [%]	Average value of the recycling rate [%]	
Scenario number	Variant Number					
Scenario 1	Variant I	12.96	15.08	12.22	13.42	16.65
	Variant II	18.48	21.20	19.94	19.87	
Scenario 2	Variant I	21.74	17.37	16.52	16.52	22.95
	Variant II	31.03	24.12	26.90	26.90	
Scenario 3	Variant I	29.38	33.12	18.26	18.26	33.55
	Variant II	42.72	47.99	29.81	29.81	

Source: Own study

The results presented in Scenario 2 show that after taking into account the additional stream of municipal waste, i.e. bio-waste (i.e. green waste and other biodegradable waste, e.g. kitchen waste) collected separately in municipal waste management systems, the recycling rate increased by an average of 6% reaching an average value of approx. 23%. Due to the harmonization of the method of calculating the recycling rate among the Member States, the European Commission provides for the possibility of taking into account other municipal waste streams, including bio-waste, in determining the recycling rates [9].

The results presented in Scenario No. 3 are the highest. For the calculations, the tonnage of municipal waste streams that were selectively collected in municipal waste management systems was assumed. The development and standardization of selective municipal waste collection systems, started in 2016, leads to an increase in the amount of selectively collected municipal waste, while increasing its recyclability [13]. The determination of measuring points in the case of raw material waste (paper, metals, plastics and glass) in the place where the mass of separately collected waste is determined, indicates the potential of this waste in terms of recycling it, and at the same time the lack of a domestic market for recyclers interested in the waste stream. In Poland, recycling of municipal waste is below the European average, and this deviation from the European average indicates a large potential for improvement. The low rates of municipal waste recycling in Poland compared to the European average are a consequence of the lack of sufficiently developed infrastructure for waste processing, efficient functioning like that in developed countries, such as Germany or Denmark. Poland faces significant challenges in obtaining the recycling rates, which assume reuse and recycling of municipal waste by up to 65% in 2035. In order to increase the demand and the value of recycled materials, improving the quality of the collected materials is necessary [6].

In the case of the municipal bio-waste stream, attention should be paid to two aspects. The law requires the creation of a separate bio-waste collection system [12–13], which increases the costs of municipal waste management systems [17], while at the national level we are struggling with a significant shortage of processing capacity in the field of installations conducting organic recycling [18]. Hence, a small mass of this waste is indicated as subject to recycling processes. At the same time, due to the properties of biodegradable waste and its typical weight loss, it would be reasonable to determine the measuring points (tonnage determination) at the time of selectively collected bio-waste. The recycling rate higher by approx. 11% compared to Scenario 2 justifies in particular the need to develop the processing capacity of installations in the field of recycling of raw material waste and biodegradable waste. An important area of bio-waste management is the development of methods based on anaerobic digestion and biogas production, which is a source of renewable energy. Currently in Poland the most commonly used method of biogas utilization is energy production in a cogeneration system. Out of concern for the natural environment, the search for alternative fuels for motor vehicles continues. As a result of the conversion of biogas created in the process of organic waste fermentation, biomethane can be obtained with a content of about 95% of methane, which is used in vehicles designed to burn gaseous fuel [19]. The treatment of bio-waste can facilitate the achievement of EU renewable energy targets. The link between the bioeconomy, the circular economy, bioproducts and bioenergy is observed worldwide. Municipal waste contains organic fractions with high energy potential for the

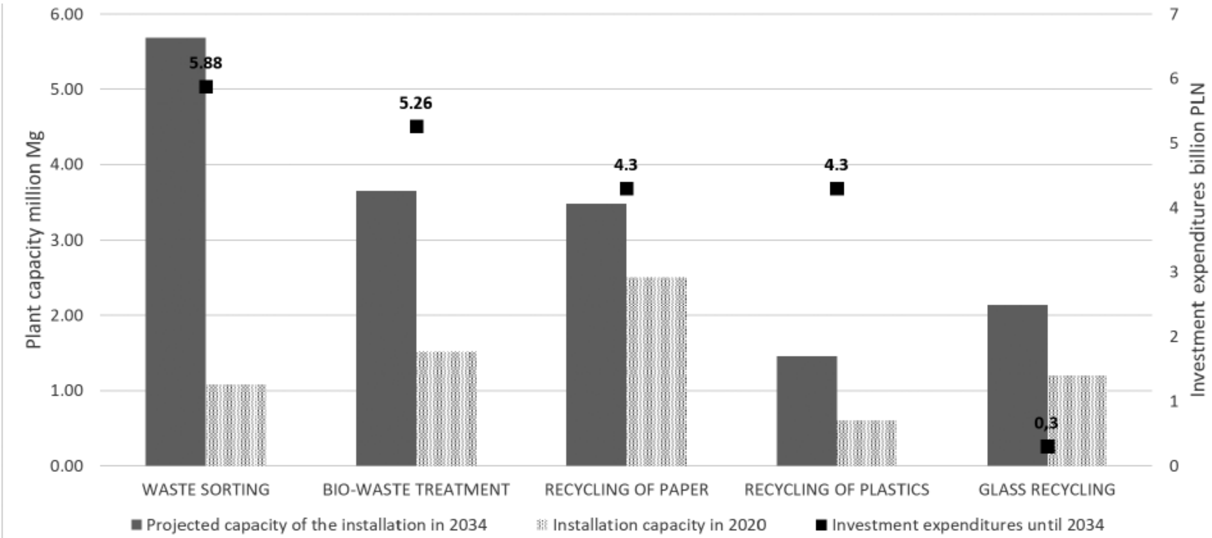

Figure 1.
Investment gap and investment outlays in the treatment of municipal waste. Source: Own study based on data from KPGO 2022 [18]

bioeconomy. However, limited time and financial resources can make it difficult to achieve ambitious sustainable development goals for climate change mitigation [20]. The Ministry of Climate and Environment in 2020, in the draft amendment to the National Waste Management Plan 2022, identified investment needs at the national level and estimated investment outlays by 2034 [18]. Figure 1 shows the processing capacity of municipal waste processing installations planned until 2034 and the investment outlays in this area.

In the Scenario No. 3, it was indicated that when determining the waste recycling rate, one should also take into account the situation in which municipal bio-waste is managed by the residents on their own in their own composters. In addition, organizing home composters is encouraged by the provisions of the Act on maintaining cleanliness and order in municipalities, which, in accordance with Art. 6k mouth. 4a obliges municipalities to establish an exemption in the fee for municipal waste management in the case of home composting of municipal bio-waste by the property owner [4]. The difference in recycling rates by several percent (11–18% depending on the variant) between large and medium-sized municipalities and small municipalities indicates that in small municipalities, less biodegradable waste is collected from property owners. The environments of small municipalities are characterized by less dense development, and thus the inhabitants have space for home composting of bio-waste. Hence, it is reasonable to include in the algorithm the recycling rate also bio-waste constituting municipal waste subjected to the composting processes "at the source", which will probably benefit the small east rural and rural-urban municipalities. The European Commission, in Annex II to the Implementing Decision, defined the methodology for determining the mass of separated and recycled bio-waste "at source" [9].

In all scenarios, there is a tendency to achieve higher recycling rates in the case assigned to Option II, i.e. a situation where the mass of generated municipal waste (M_W) is calculated on the basis of the registered number of inhabitants (Lm) and the CSO index concerning the mass of municipal waste generated per one inhabitant in a given voivodship (W_{CSO}), in accordance with the equation (4). The above conclusion, showing the trend of the recycling rate depending on the method of determining the mass of municipal waste generated, can guide the definition of the details of the determination of the recycling rate at the legislative level. Figure 2 shows the trend of the recycling rate in the analyzed scenarios depending on the method of determining the mass of generated municipal waste (M_W). In variant I, the mass of actually collected and collected municipal waste was assumed as the mass of M_W, in variant II – the mass of M_W was estimated based on statistical data.

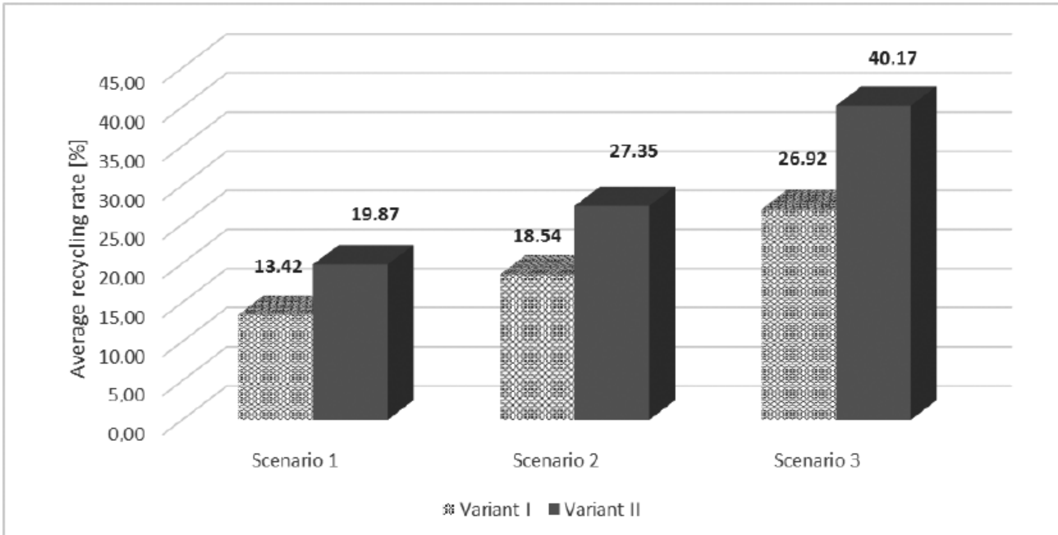

Figure 2.
Tendency of changes in the recycling rate [%] in the adopted variants. Source: Own study

Table 3.
Recycling rates [%] in the analysed scenarios according to two variants for GMK in 2018-2020

Description		2018	2019	2020
Recycling levels achieved by the City of Krakow		42.00	55.92	69.49
Scenario number	Variant Number	Recycling rate [%]	Recycling rate [%]	Recycling rate [%]
Scenario 1	Variant I	12.78	14.04	17.35
	Variant II	20.92	22.88	26.91
Scenario 2	Variant I	18.14	19.67	27.52
	Variant II	29.69	32.05	42.66
Scenario 3	Variant I	32.20	34.26	40.55
	Variant II	52.71	55.83	62.88

Source: Own study

Due to the availability of published statistical data on municipal waste management only for 2018 and taking into account the development of separate collection of municipal waste, in particular bio-waste, which took place in 2018–2020, it is reasonable, according to the authors, to present the variability of the results of the analyzes in one of the municipalities (the Municipality of Krakow) in all planned situations in 2018–2020. Table 3 presents the results obtained based on the statistical data of the Municipality of Krakow (GMK) in the scenarios analyzed above, according to two variants. Additionally, Table 3 presents the recycling levels achieved by the City of Krakow, calculated according to the existing rules. The analysis of the recycling rate [%] was carried out for the data covering the years 2018–2020.

The recycling rates set for 2020 are higher than the rates for 2018, which indicates the development of separate waste collection in the right direction leading to an increase in the amount of municipal waste recycled. The significant increase in the recycling rate took place when additional municipal waste streams, ie bio-waste, were taken into account. The reason for the increase in the recycling rate by an average of approx. 10% was also the fact that in 2020 the amount of green waste and biodegradable waste (bio-waste) collected selectively increased compared to 2018 [21].

In all the analysed scenarios in individual years, the trend that was observed earlier is maintained, i.e. the achievement of higher recycling rates in the case assigned to Option II, i.e. the situation where the mass of municipal waste generated (MW) is calculated on the basis of the registered number of inhabitants (Lm) and CSO index concerning the mass of municipal waste generated by one inhabitant in a given voivodship (M_{CSO}), in accordance with the equation (4). The results of the scenario 2 and 3 analysis both in 2019 and 2020 justify the need to develop the processing capacity of installations in the field of recycling of raw material waste and biodegradable waste.

6. SUMMARY

The proposed scenarios for determining the recycling rate allow for the assessment and selection of the best solution. The guidelines for the harmonization of reporting and methods of monitoring the progress towards the objectives of waste management [9] indicate that some flexibility is possible in formulating the calculation rules. The analyses show that in the case of Poland, at least in the first period, this flexibility should be used, as the recycling rates calculated according to the new methods will be low. This is due to the lack of an appropriate number of installations, both in terms of sorting raw material waste and recycling, and the necessary processing capacity of installations that carry out organic recycling of municipal bio-waste. Therefore, according to the authors, changes to the method of determining the recycling rate at the national level should be introduced in stages. As a first step, until the necessary waste treatment infrastructure is in place, the methodology for calculating the recycling rate should lead to the most favourable results, i.e. maximizing the levels achieved. This will allow for the proper development of municipal waste management systems, and in particular to avoid administrative penalties imposed on municipal governments for failure to achieve the recycling level.

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