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Municipal Solid Waste Mass Balance as a Tool for Calculation of the Possibility of Implementing the Circular Economy Concept

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Abstract: Municipal waste management system modeling based on the mass balance of individual waste streams allows us to answer the question of how the system will react to organizational changes, e.g., to the expected reduction in the amount of plastics or the introduction of a deposit for glass and/or plastic packaging. Based on the data on Polish municipal solid waste and the forecast of changes in its quantity and composition, as well as demographic data, a balance model was prepared to assess the impact of introducing higher and higher levels of recycling, in accordance with the circular economy assumptions on the waste management system. It has been shown that, for the Polish composition of municipal waste, even if the assumed recycling levels of individual streams are achieved, achieving the general target level of 65% recycling in 2025/30 may not be feasible. The possibility of achieving a higher level of recycling will be possible due the introduction of selective ash collection from individual home furnaces, while the impact of reducing the amount of plastics or introducing a deposit on packaging is minimal. The calculations also showed that, to complete the waste management system in Poland, we need at least 3.5 million Mg/year of incineration processing capacity and the present state (approx. 1.3 million Mg/year) is insufficient.

Keywords: MSW management; recycling; circular economy; mathematical modeling

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1. Introduction

In the introduction to the excellent textbook "Air Pollution Modeling", Paolo Zanetti [1] stated that "Contrary to popular belief that point measurements in the environment represent the real world, it must be firmly stated that only a well-tested and well-calibrated simulation model is a correct representation of the three-dimensional real world, its dynamics and responses to all possible future disturbances. Hence, only mathematical models can answer our question, what if . . . ?". One can hardly disagree with this statement. Mathematical modeling of processes occurring in the atmosphere, surface waters or soil (e.g., modeling of pollutant dispersion) has been widely practiced for years. Similarly, we use mathematical modeling to simulate gas or wastewater treatment processes—in this area, chemical engineering perfectly complements environmental engineering. However, modeling of waste management is still a big problem. The main reason is that we are most often dealing with very heterogeneous material, such as waste and with stochastic processes that are difficult to describe mathematically. Usually, we create a mass balance based on collected statistical data. However, it provides an opportunity to simulate the impact of various types of decisions (often political) and both systemic changes and changes in the behavior of residents on the final waste mass streams that we must manage.

The key question we pose when we start modeling a municipal solid waste (MSW) management system is how much waste will be generated today, in a year and in 10–20 years. Since the amount of municipal waste is closely related to the number of inhabitants, it is necessary to know not only demographic trends, but also changes in the amount and fractions of municipal waste and these amounts are closely related to the standard of living, i.e., the level of residents' income [2–6]. For many years, attempts have been made to model and predict the quantity and fractions of municipal waste [7–18]. Various types of models were used—regression [19,20], stochastic [21,22] or with the use of artificial neural networks [23,24], often with good results, close to reality. The use of mathematical modeling also allows for effective planning of waste management systems and assessment of the impact of changes in input parameters on the functioning of the system as a whole [25–36]. It has proved particularly useful in recent years in connection with the implementation of the circular economy concept [37–53]. Obviously, with the implementation of the circular economy concept, municipal waste will not disappear ("zero waste") and its amount will still depend on the standard of living of the inhabitants. This is evidenced by the latest forecasts of anticipated changes in the municipal waste management system [2].

The aim of the study was to analyze the possibilities of implementing the circular economy concept in Poland and the impact of possible changes in the system of collecting and managing specific groups of waste, such as glass, plastics or ash from household stoves, on the achievable recycling rate of all amount of MSW.

2. Materials and Methods

2.1. Circular Economy

It is obvious that the Earth's natural resources, including energy resources, are not inexhaustible. Therefore, saving raw materials, reusing products and recycling of used materials is an absolute necessity. The current model of economic development based on the so-called linear economy, which can be described by a simple scheme: obtain raw materials—produce a product—use it—get rid of waste, should be replaced with another model in which the obtained raw materials will be used as long as possible with multiple use of the produced products and the waste stream will be the lowest.

In making this a reality, the European Union adopted in July 2014 the communication "Towards a Circular Economy: A Zero Waste Program for Europe" [54], followed in December 2015 by the communication "Closing the Loop—An EU Action Plan for the Circular Economy" [55]. These two communications and changes introduced in the European legislation [56,57] are summarized in the document "A New Action Plan for the Circular Economy: For a Cleaner and More Competitive Europe" [58] published in 2020, which is in line with the new strategy [59].

In these documents, the most important tasks that need to be implemented include development of environmental standards for secondary raw materials, implementation of a strategy for plastics, measures to reduce food waste, implementation of a strategy for critical raw materials (metals), as well as rational waste management of construction and demolition materials. It was assumed that the implementation of the circular economy principles will enable a more complete implementation of the principles of sustainable development and at the same time will bring many benefits to the Member States, including savings of EUR 600 billion for EU companies, which corresponds to around 8% of annual turnover, the creation of around 700,000 new jobs, increasing the EU's GDP by an additional 0.5% by 2030 and reducing carbon dioxide emissions by approx. 450 million Mg also until 2030.

The consequence of adopting the circular economy model in the EU were detailed regulations on waste management introduced by the European Commission [57]. 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%. The waste recycling targets set by the European Commission for environmental organizations seem not ambitious enough while, at the same time, too high and often even impossible to achieve for practitioners dealing with municipal waste management. This is confirmed by the balance calculations, the results of which clearly indicate that some indicators may be technically or technologically unattainable. Moreover, following large protests from environmental organizations, in 2017 the European Commission adopted a document entitled "The importance of transforming waste into energy in a circular economy" [60], which in the circular economy system not only did not exclude incineration plants, but also provided an important place for municipal waste incineration plants (so-called residual waste after selective collection) with energy recovery.

The only country in the European Union that already meets the minimum requirements of the circular economy is Germany. There, the share of recycling and biological methods of MSW management is approximately 68%, with landfilling below 1% (EUROSTAT data for 2018). At the same time, 98 waste incineration plants are operating in Germany with a total capacity of about 27 million Mg/year (34 incinerators for the combustible fraction separated from municipal waste—the so-called RDF (refuse derived fuel), in Germany called EBS (Ersatzbrennstoffe), with a capacity of around 5 million Mg/year and 63 incineration plants for mixed waste, also known as residual waste, with a capacity of approximately 22 million Mg/year). The share of combustion amounts to 31–32%. Austria, the Netherlands, Belgium and Slovenia, as well as Switzerland, account for more than 50% of recycling and biological methods (2018), each with more than 30% of combustion (except Slovenia).

There is no doubt that waste-to-energy is a supplement to the municipal waste management system. Recycling has its limits and as shown by the experience of many countries, even after the best separate collection, there is always some waste that needs to be incinerated, avoiding landfilling. If we approach the concept of "Circular Economy" orthodoxically and identify it with the concept of "zero waste", we will obviously fail. Achieving the "zero waste" status is possible for individual households in a short time. In the scale of small communities, it is probable for a short period, but completely unrealistic in the case of large urban agglomerations and multi-family residential buildings, which does not mean that activities aimed at reducing the amount of generated waste and implementing their selective collection and recycling should not be carried out.

2.2. Municipal Solid Waste Management in Poland

The Polish MSW management system is based on mechanical-biological waste treatment (MBT) installations. According to the data for 2018, there were about 179 such facilities in Poland with a total capacity of over 11.5 million Mg in the mechanical part. There were plans to increase their quantity by 2021 by another 47 facilities with a total capacity of almost 3.3 million Mg in the mechanical part and 1.6 million Mg in the biological part. This means that in the years 2021–2022 the total capacity of MBT installations should amount to approximately 13 million Mg, which is more than the currently, generated municipal waste (at least according to official data). According to the data from the Central Statistical Office (CSO), currently, around 12.75 million Mg of municipal waste is generated annually in Poland and since 2014 this amount has been systematically growing (Figure 1). It is assumed that, by 2025, it will reach the level of about 14.5–15.0 million Mg annually.

From a technical point of view, the MBT is a very simple installation. Its work consists in separating specific fractions of municipal waste. There are a huge number of technical variants of MBT installations [61], but in each case, at the output of such an installation, three streams are produced:

- plus-mesh fraction (calorific);
- minus-mesh fraction (biological);
- ballast fraction (non-flammable).

The operational data of the MBT facilities operating in Poland show that the so-called the plus-mesh fraction, often called refuse derived fuel (RDF) (code 19 12 12 or 19 12 10), accounts for about 30–40% of the initial weight of waste entering the installation. According to data from operating installations, the RDF fraction has a calorific value of 10–18 MJ/kg depending on moisture content. Most often, however, it is only 11–12 MJ/kg.

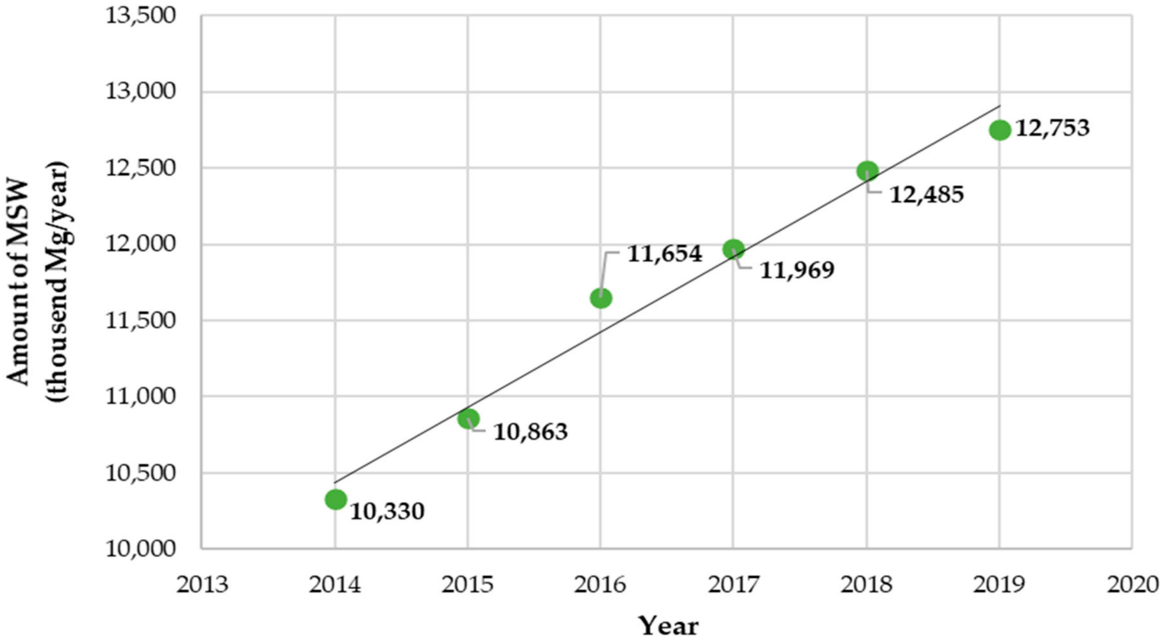

Figure 1. Increase in the amount of municipal waste generated in Poland in 2014–2019 (according to CSO).

So far, this system is supplemented by nine municipal waste incineration plants with a total capacity of approximately 1,374,000 Mg/year:

- Kraków—220,000 Mg/year;
- Poznań—210,000 Mg/year;
- Bydgoszcz—180,000 Mg/year;
- Szczecin—150,000 Mg/year;
- Białystok—120,000 Mg/year;
- Rzeszów—100,000 Mg/year;
- Konin—94,000 Mg/year;
- Warszawa—50,000 Mg/year;
- Zabrze—250,000 Mg/year (multi-fuel boiler for RDF).

The share of incineration is currently nearly 15–16% of the total mass of municipal waste generated.

It was hoped that RDF management could be associated with the cement industry, which has been using for years the so-called alternative fuels produced from waste. When 15 years ago our cement plants started co-firing alternative fuels in the amount of about 5% of the mass of fuel (coal) fed, they required that the supplied fuel has a calorific value of not less than 12 MJ/kg. Today, the average degree of replacement of fossil fuels with alternative fuels is over 50% and in some cement plants over 80% and they are not interested in an alternative fuel with a calorific value lower than 20–22 MJ/kg, because the use of less calorific fuels may not achieve the required clinker firing temperature exceeding 1450 °C. All Polish cement plants can consume a maximum of 1.5–1.8 million Mg of such fuel. In order to use RDF produced in MBT facilities to produce an alternative fuel for cement plants, it is necessary to "enrich" it with plastics or rubber. Taking into account the calorific value of plastics (maximum approx. 42 MJ/kg) and rubber (maximum 29–30 MJ/kg), a maximum of approx. 1.0 million Mg of RDF per year can be used for the production of fuel for cement plants.

2.3. Mass Balance for Municipal Solid Waste in Poland

Planning in MSW management consists in drawing up a balance of generated waste, taking into account the efficiency of selective collection and recycling and planning the necessary processing capacity of waste management facilities. The key to a reliable balance is knowledge of the amount of waste generated and its morphological composition. The amount of municipal waste is estimated on the basis of the indicators of its generation (depending on the place of its generation) and the number of inhabitants. The main source of data here is the forecast of changes in waste management prepared by Szpadt in 2010 [62]. This forecast covers the period until 2022. In this forecast, as in the methodology adopted in the National Waste Management Plan [63], differentiation was made in the amount of generated waste and its morphology between large cities (over 50,000 inhabitants), small towns (less than 50,000 inhabitants) and rural areas. For three groups of inhabitants defined in this way, it was assumed [64] that in the coming years, the number of inhabitants of Poland will slowly but steadily decrease. The loss (compared to 2007) will amount to approx. 2223 thousand people in 2035. It is estimated that in 2022, the population will amount to about 37.670 million and at the end of 2035 the population of Poland will reach 35.993 million, which is 94.4% of the 2007 figure. The decline in population will mainly affect cities. The number of urban residents is expected to decrease from about 23.317 million in 2007 to approximately 22.5 million in 2022. During this time, a slight increase is expected in the number of rural residents from 14.788 million in 2007 to about 15.160 million in 2022. In the longer term—in 2035, the number of rural inhabitants will also slightly decrease to approx. 14.778 million. Economic forecasts for the analyzed period assumed that Poland's economic growth until 2022 would not exceed the average annual value of 3.5%. The author of the Forecast [62] also assumed that in the period until 2022 there will be no significant changes in the quantity and composition of municipal waste generated—the increase in quantitative indicators of generated waste will be at the level of approx. 5% in 5 year periods. With such assumptions, tables were developed to show the expected changes in the index of municipal waste generated and its morphological composition (Tables 1–4).

Table 1. Projected changes in the unit index of municipal waste generation (in kg/M/year) [62].

Types of Waste	2008	2011	2014	2017	2020	2022
Big cities (over 50,000 inhabitants)	386	402	420	440	463	479
Small towns (less than 50,000 inhabitants)	346	358	374	391	412	428
Rural areas	234	243	253	265	280	291

According to the latest data of the Central Statistical Office (for 2019), the number of inhabitants of Poland amounted to 38,411,148 people. Table 5 shows the division into individual categories of places of residence (analogous to the one presented for municipal waste).

Table 2. Projected changes in the morphological composition of municipal waste from large cities (%) [63].

Types of Waste	2008	2011	2014	2017	2020	2022
Paper	19.09	19.33	19.71	20.25	20.48	20.56
Glass	9.97	9.90	9.93	9.89	9.81	9.81
Metals	2.67	2.64	2.57	2.48	2.35	2.28
Plastics	15.17	15.34	15.52	15.56	15.88	16.16
Multi-material waste	2.47	2.50	2.53	2.53	2.59	2.63
Kitchen and garden waste	28.91	28.41	27.76	27.09	26.48	25.93
Mineral waste	3.16	3.13	3.10	3.07	3.02	3.03
Fraction < 10 mm	4.20	4.08	3.95	3.86	3.80	3.80
Textiles	2.28	2.29	2.29	2.27	2.27	2.30
Wood	0.23	0.30	0.36	0.41	0.45	0.50
Hazardous waste	0.75	0.77	0.79	0.80	0.80	0.84
Other waste	3.16	3.36	3.64	3.84	4.08	4.24
Bulky waste	2.59	2.61	2.55	2.59	2.63	2.61
Waste from green areas	5.34	5.35	5.31	5.36	5.36	5.32

Table 3. Projected changes in the morphological composition of municipal waste from small towns (%) [63].

Types of Waste	2008	2011	2014	2017	2020	2022
Paper	9.60	9.74	9.96	10.27	10.38	10.46
Glass	10.21	10.16	10.20	10.19	10.11	10.06
Metals	1.54	1.51	1.47	1.43	1.36	1.31
Plastics	10.98	11.13	11.30	11.34	11.61	11.79
Multi-material waste	3.95	4.02	4.07	4.09	4.17	4.25
Kitchen and garden waste	36.70	36.13	35.33	34.72	34.17	33.81
Mineral waste	2.83	2.67	2.89	2.89	2.86	2.90
Fraction < 10 mm	6.84	6.81	6.72	6.59	6.43	6.35
Textiles	4.02	4.10	4.15	4.16	4.17	4.23
Wood	0.29	0.31	0.32	0.33	0.34	0.35
Hazardous waste	0.64	0.67	0.70	0.72	0.73	0.75
Other waste	4.52	4.63	4.90	5.29	5.70	5.84
Bulky waste	2.60	2.62	2.62	2.63	2.62	2.61
Waste from green areas	5.29	5.30	5.35	5.34	5.33	5.30

Table 4. Projected changes in the morphological composition of municipal waste from rural areas (%) [63].

Types of Waste	2008	2011	2014	2017	2020	2022
Paper	4.98	5.03	5.14	5.31	5.36	5.39
Glass	9.99	9.93	9.96	9.95	9.86	9.79
Metals	2.43	2.39	2.33	2.26	2.14	2.06
Plastics	10.26	10.39	10.55	10.59	10.82	10.96
Multi-material waste	4.09	4.12	4.19	4.22	4.29	4.36
Kitchen and garden waste	33.09	32.56	31.85	31.24	30.68	30.33
Mineral waste	5.92	6.48	6.80	7.23	7.75	8.11
Fraction < 10 mm	16.85	16.65	16.63	16.50	16.39	16.21
Textiles	2.14	2.14	2.13	2.11	2.07	2.06
Wood	0.65	0.66	0.67	0.68	0.68	0.69
Hazardous waste	0.81	0.82	0.87	0.94	1.00	1.03
Other waste	4.90	4.99	4.98	5.05	5.07	5.12
Bulky waste	1.28	1.28	1.30	1.28	1.29	1.27
Waste from green areas	2.61	2.60	2.61	2.64	2.61	2.61

Table 5. Population of Poland in 2018 according to CSO data [64].

Population of Poland	38,411,148
Cities, total	23,094,970
Cities with more than 50,000 inhabitants	13,824,254
Cities with less than 50,000 inhabitants	9,270,716
Rural areas	15,316,178

Now, multiplying the number of residents of cities with more than 50,000 inhabitants, less than 50,000 inhabitants and rural areas (Table 5) by the appropriate unit indicator of municipal waste generation (Table 1) and summing up the products obtained, it is possible to calculate the total amount of municipal waste produced in Poland. As already mentioned, for the data predicted for 2025 it is approximately 14.5 million Mg. Taking into account the predicted economic growth and the inevitable increase in the amount of waste generated, this amount of waste will most likely be produced in 2025.

The amount of waste of each fraction (Q_i) was calculated as the sum of the products of the number of inhabitants of a given type of place of residence (large city, small town, village) M_1, M_2, M_3, the indicator of the amount of municipal waste generated for a given type of residence w_1, w_2 and w_3 and the share individual (14) fractions of municipal waste x_i. The total amount of municipal waste generated (Q) was calculated as the sum of the calculated amounts of waste from individual fractions.

$$Q_i = \sum_{i=1}^{14} (M_1 \cdot w_1 \cdot x_i + M_2 \cdot w_2 \cdot x_i + M_3 \cdot w_3 \cdot x_i) \quad (1)$$

$$Q = \sum_{i=1}^{14} Q_i \quad (2)$$

Results of these calculations are presented in Table 6.

Table 6. Calculation of the mass of individual fractions of municipal waste generated in Poland (calculations for 2025).

Types of Waste	Big Cities (kg/M/year)	Small Town (kg/M/year)	Rural Area (kg/M/year)	Big Cities (Mg)	Small Town (Mg)	Rural Area (Mg)	Total (Mg)	Percent (%)
Paper	94.8	42.8	15.0	1,310,849	396,853	229,865	1,937,567	13.35
Glass	45.4	41.7	27.6	627,902	386,530	422,849	1,437,281	9.90
Metals	10.9	5.6	6.0	150,415	51,996	91,775	294,185	2.03
Plastics	73.5	47.9	30.3	1,016,420	443,879	464,019	1,924,317	13.26
Multi-material waste	12.0	17.2	12.0	165,776	159,429	183,978	509,183	3.51
Kitchen and garden waste	122.6	140.9	85.9	1,694,887	1,306,402	1,315,721	4,317,010	29.75
Mineral waste	14.0	11.8	21.7	193,299	109,345	332,361	635,005	4.38
Fraction < 10 mm	17.6	26.5	45.9	243,224	245,835	702,890	1,191,949	8.21
Textiles	10.5	17.2	5.8	145,294	159,429	88,773	393,496	2.71
Wood	2.1	1.4	1.9	28,803	12,999	29,162	70,964	0.49
Hazardous waste	3.7	3.0	2.8	51,205	27,910	42,885	122,000	0.84
Other waste	18.9	23.5	14.2	261,146	217,925	217,428	696,499	4.80
Bulky waste	12.2	10.8	3.6	168,337	100,169	55,322	323,828	2.23
Waste from green areas	24.8	22.0	7.3	343,074	203,779	111,931	658,783	4.54
Total	463.0	412.3	280.0	6,400,630	3,822,479	4,288,959	14,512,067	100.00

In the absence of official data, both from the Central Statistical Office and the Provincial Offices, it was decided to estimate the amount of RDF generated in Poland. The simplest estimate may be based on the assumption that approx. 35–40% of the amount of municipal waste going to the MBT installation will be the plus-mesh fraction (RDF). This is confirmed by the results of research on 20 Polish MBT plants carried out in 2015 [65]. Formally analyzing the fractional composition of the entire waste stream shown in Table 6, it is easy to notice that the share of fractions that can be collected from the MBT installation as combustible (plus-mesh) fraction (paper, glass, plastics, multi-material waste, textiles, wood, bulky and other wastes) is approx. 50%, but not all are efficiently trimmed and not all have a value as a fuel.

This means that in 2018, approx. 3.1–3.5 million Mg RDF could have been produced. However, this method of estimation does not take into account the morphology of municipal waste generated in Poland. Thus, to more accurately estimate the amount of RDF, a methodology based on balancing the number of inhabitants, the indicator of the amount of municipal waste generated and its morphological composition was used. Table 7 summarizes the amounts of waste calculated in accordance with the above-mentioned method in individual provinces and compared with the amount reported by the CSO. The amount of RDF was calculated as the maximum value, assuming that the share of selective waste collection will be 33% and the total stream of the plus-mesh fraction (paper, glass, plastics, multi-material waste, textiles, wood, bulky and other wastes) will be the combustible fraction (RDF). The estimation of the amount of municipal waste and RDF were prepared for 2018 and 2025. When analyzing the data contained in Table 7, it is easy to notice a high compliance (for 2018) of the estimated amount of municipal waste generated with the data of the Central Statistical Office for the Dolnośląskie, Kujawsko-Pomorskie, Lubuskie, Małopolskie, Mazowieckie, Opolskie, Śląskie, Warmińsko-Mazurskie and Wielkopolskie Provinces, i.e., potentially richer provinces, with a higher per capita income. On the other hand, particularly large differences occurred in the Lubelskie, Podkarpackie, Podlaskie and Świętokrzyskie Provinces—the reason for this is most likely the large share of municipal waste burned in household stoves. According to the Central Statistical Office, the Pomorskie and Zachodniopomorskie Provinces show a surplus in relation to balance calculations, which is most likely associated with a large influx of tourists.

It seems, however, that the adopted methodology for estimating the amount of municipal waste based on balance calculations has confirmed its good accuracy. In this situation, for further considerations, the amount of RDF produced in Poland in 2018 can be assumed to be approximately 4.45 million Mg, with the forecast for 2025 amounting to approximately 5.35 million Mg. When supplementing the data on the calculation methodology, it should be noted that the compliance of the amount of municipal waste generated (according to the Central Statistical Office) with the estimated value for 2018 was obtained using the indicators for 2011. For the forecast for 2025, the indicators from Szpadt's study from 2020 were adopted, because the estimated amount of waste generated, based on the predicted economic growth, shows that in 2025 we will achieve the amount of municipal waste generated at the level of approximately 14.5 million Mg. This amount is likely to remain at the same level in the coming years.

Using the data in Table 8 and knowing the morphological composition of municipal waste, it is easy to estimate the average value of the heat of combustion, moisture content or ash content, using the weighted average method. For instance, for the heat of combustion:

$$H_o = \sum H_o^i \cdot x_i \tag{3}$$

where:

H_o^i—heat of combustion of the 'i' fraction in the waste
x_i—mass fraction of 'i' in the waste.

Table 7. Balance of municipal waste and RDF for 2018 with the perspective of 2025 based on CSO data and the authors' own calculations.

Province	According to CSO for 2018				Data based on the Balance			
	Number of Inhabitants	Amount of Municipal waste	Quantity Collected Selectively	Amount of Residual Waste	Calculated Amount of Municipal Waste 2018	Calculated Amount of Municipal Waste 2025	Calculated Amount of RDF 2018	Calculated Amount of RDF 2025
Dolnośląskie	2,899,986	1,142,084	277,000	865,084	982,359	1,132,140	352,577	425,139
Kujawsko-Pomorskie	2,074,517	665,785	190,000	475,785	680,956	784,817	241,919	291,072
Lubelskie	2,112,216	470,198	153,000	317,198	648,642	747,778	220,280	264,360
Lubuskie	1,013,031	366,596	86,000	280,596	333,238	384,112	116,593	140,565
Łódzkie	2,460,170	788,497	241,000	547,497	815,547	942,757	291,463	351,808
Małopolskie	3,404,863	1,073,430	348,000	725,430	1,057,968	1,219,591	362,772	435,510
Mazowieckie	5,411,446	1,811,834	479,000	1,332,834	1,819,082	2,096,376	654,535	788,372
Opolskie	984,345	322,621	106,000	216,621	307,591	354,608	104,499	125,670
Podkarpackie	2,127,462	497,523	136,000	361,523	634,350	731,399	210,636	252,489
Podlaskie	1,179,430	298,958	80,000	218,958	387,819	446,983	137,315	165,310
Pomorskie	2,337,769	826,652	239,000	587,652	776,651	895,113	276,206	332,719
Śląskie	4,524,091	1,664,060	650,000	1,014,060	1,614,282	1,859,939	601,709	726,085
Świętokrzyskie	1,237,369	250,085	70,000	180,085	376,660	434,249	126,857	152,219
Warmińsko-Mazurskie	1,425,967	441,392	86,000	355,392	458,847	528,926	158,902	191,328
Wielkopolskie	3,495,470	1,223,725	316,000	907,725	1,109,755	1,279,238	383,832	461,509
Zachodnio-Pomorskie	1,698,344	641,987	148,000	493,987	571,491	658,663	203,496	245,431
Total	38,386,476	12,485,425	3,605,000	8,880,425	12,575,237	14,496,688	4,443,593	5,349,583

Table 8. Typical heat of combustion and the average content of moisture and non-flammable substances (ash) in selected components of municipal waste (private information).

Types of Waste	Heat of Combustion (kJ/kg)	Moisture Content (%)	Ash Content (%)
Paper/cardboard	12,300	19.00	12.00
Plastics	31,500	9.00	8.00
Rubber/Leather	23,300	9.00	20.00
Wood	16,300	19.00	5.00
Textiles	15,900	22.00	7.00
Organic waste	4300	65.00	11.00
Kitchen waste	10,700	40.00	9.00
Garden waste	9500	50.00	5.00
Fine fraction (below 10 mm)	5000	20.00	50.00
Metals	0	5.00	93.00
Inert waste	0	2.00	98.00
Other waste	6700	30.00	30.00

In a simplified way, we can also estimate the calorific value of waste from the relationship:

$$H_u = \frac{(100 - w) \cdot H_o - w \cdot r_W}{100} \tag{4}$$

where:

H_u—calorific value [MJ/kg]
w—moisture content of the fuel [%]
H_o—fuel combustion heat [MJ/kg]
r_W—heat of water evaporation [MJ/kg] (r_W = 2250 MJ/kg)

3. Results and Discussion

3.1. Implementation of Circular Economy Concept

In Poland, it will not be possible to achieve the above-mentioned high recycling rates provided for in the Circular Economy Package (in particular for raw materials) using only MBT installations. These raw materials should be collected selectively. The reason for this is simple. Unfortunately, the waste separated in the MBT installation is only theoretically suitable for recycling because of the content of moisture and contaminants. According to the data of the Regional Municipal Waste Processing Plants Council (RIPOK Council) and the Rekopol Recovery Organization, we are currently able to selectively collect about 32% of the mass of generated municipal waste. Is it possible to achieve the 65% recycling in Polish conditions?

Therefore, it was decided to make a mass balance of municipal waste collected and processed in Poland on the basis of the known morphology of municipal waste, the amount of municipal waste generated in the country per capita and demographic data on the number of residents.

Taking into account the current dynamics of the increase in the amount of municipal waste generated in Poland, it has been assumed that around 2025 we will achieve the level of municipal waste generation at approximately 14.5 million Mg and that, similarly to the more developed EU countries, its production will stabilize at this level.

Then, three variants of the implementation of the circular economy assumptions in the field of municipal waste in Poland were analyzed:

- Variant I—achieving a level of separate collection equal to the required recycling targets for individual waste fractions in line with the requirements of the circular economy (paper and cardboard—85%, ferrous metals—80%, aluminum—60%, glass—75%, plastics—55%, wood—30%.);

- Variant II—achieving 65% separate collection with the assumption that all separate collected fractions will be recycled for whole stream of municipal waste (circular economy target for 2035);
- Variant III—achieving 65% real recycling of all municipal waste, assuming that only 90% of the separate collected fractions of municipal waste can be recycled.

As a result of the calculations carried out for Variant I, it was found that assuming the required recycling rates specified in the circular economy assumptions for individual fractions of municipal waste, it is not possible to obtain 65% recycling. Therefore, Variant II was adopted for the calculations, in which all individual recycling rates for individual fractions were increased so as to obtain a total of 65% selective collection rate (so far equated with recycling) of total municipal waste. Variant III additionally assumes that the selectively collected waste fractions will be contaminated and only approximately 90% of the collected fraction is recyclable. The adopted individual recycling rates for individual fractions in the analyzed variants are shown in Table 9.

Table 9. The required level of recycling of individual fractions of municipal waste according to circular economy assumptions (%).

Types of Waste	Variant I	Variant II	Variant III
Paper	85	85	95
Glass	75	90	99
Metals	65	70	80
Plastics	55	80	90
Multi-material waste	50	50	60
Kitchen and garden waste	70	80	90
Mineral waste	-	-	-
Fraction < 10 mm	-	-	-
Textiles	70	70	80
Wood	30	70	80
Hazardous waste	-	-	-
Other waste	-	-	-
Bulky waste	70	80	90
Waste from green areas	70	80	90

In addition, in the further part of the work for Variant I, calculations were also made in which the impact of withdrawing some plastic and glass waste from the waste market, e.g., as a result of the introduction of a deposit for glass and plastic packaging, was analyzed. This is how subsequent sub-variants were created, in which it was assumed that the amount of plastic waste (e.g., packaging waste) would be reduced by 50%. Similarly, the effects of implementing a glass bottle deposit were analyzed, as a result of which 50% of glass waste would not appear in the municipal waste management system. These variants were confronted with the situation in 2018, assuming that the entire stream of municipal waste generated after subtracting the streams of selective collection and part of the waste stream that went to operating waste incineration plants constituting the so-called residual waste was directed to the MBT installation. Finally, as an alternative, in Variant I, the effects of introducing a possible selective ash collection from home furnaces were analyzed. According to statistical data, in Poland, in this type of furnaces, approx. 11.2 million Mg of coal is burned annually (approx. 84% of the total in the EU), which results in a stream of nearly 1.2–1.5 million Mg of ash in the mass of generated municipal waste. The results of the balance calculations for the three basic variants are shown in Table 10.

Table 10. The amount and calorific value of residual waste and RDF for various variants of the implementation of the Circular Economy Package.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to the Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant II—target recycling of 65% of municipal waste according to circular economy assumptions	65.49	5,003,463	5.8	2,182,253	11.2
Variant III—target recycling of 65% of municipal waste, including about 90% use of waste collected selectively	73.56	3,832,634	4.9	1,508,587	10.2

When analyzing the presented data, it must be clearly stated that achieving individual recycling levels of some fractions of municipal waste provided for under the circular economy implementation will not ensure 65% recycling of all municipal waste in Poland. In this variant (Variant I), the maximum level of recycling of all waste is approx. 55%. Moreover, the planned and postulated by environmental organizations limitation on the use of plastics and introduction of a deposit system for glass packaging and plastic bottles, as a result of which glass and plastic bottles will not end up in the waste stream, will reduce the recycling rate of all municipal waste. A necessary condition for obtaining 65% recycling of all municipal waste is to achieve much higher levels of selective collection of individual waste fractions (Variant II). In fact, the levels of selective collection must be even higher, because not the entire stream of selectively collected waste fraction will be recyclable. Assuming about 90% use of selectively collected fractions of municipal waste, the rates of selective collection must be even higher (Variant III). However, there is no doubt that an interesting proposition is the selective collection of ashes from domestic furnaces. The calculations show that its implementation (at the level of 90%) significantly improves the total municipal waste recycling rate. So maybe it is worth considering a 6-container selective collection?

Individual recycling rates for certain fractions of municipal waste have been the subject of long discussions in the European Commission and the European Parliament, as a result of which some of them have been changed and made less stringent because of technical possibilities. There is no doubt for specialists dealing with waste management and recycling technologies that achieving the rates of selective collection and recycling required for Variants II and III is impossible under Polish conditions. The reason for this is the specific morphology of municipal waste. Compared to waste from more developed countries (e.g., Germany, France, Belgium, the Netherlands, Sweden or Denmark), our waste contains less plastic or paper and generally less packaging waste. As a consequence, this means that the objectives of the EU Circular Economy Package, i.e., the requirements of circular economy, cannot be achieved in Polish conditions.

It only seems realistic to achieve the total recycling rate for the entire municipal waste stream in Poland at the level of 50–55%. This means that a stream of approximately 6.5 million Mg of residual waste with a calorific value of about 7 MJ/kg, i.e., suitable for incineration, will have to be managed. If we take into account that the statutory (the Waste Act) level of municipal waste incineration of 30% is 4.35 million Mg (for the total mass of municipal waste in 2025 equal to approx. 14.5 million Mg), we have a huge deficit in the processing capacity of waste incineration plants. If the above-mentioned stream of 6.5 million Mg of residual waste is directed to the existing MBT installations, we can obtain from it about 3 million Mg of RDF with a calorific value of around 13.2 MJ/kg.

3.2. Effect of a Changing Waste Management System on Waste Streams

As described in Section 2, the idea of circular economy has gained a legal framework in the form of changes to several EU directives, while in Poland the response to this was the creation of the "Roadmap for Transformation towards a circular economy" (September 2019) [66]. The first milestone for meeting some circular economy requirements is set for 2025, the next one 33for 2030 and full achievement of the circular economy targets for waste management is scheduled for 2035.

As shown in the previous section, it is impossible to achieve the target requirements of circular economy with the current morphological composition and the amount of municipal waste generated in Poland. However, there is no doubt that measures will be taken to at least approach the recycling levels set in the assumptions of the circular economy.

Currently, (for 2020) we are committed to achieve 50% recycling of 4 fractions of municipal waste (paper, glass, metals and plastics) provided for in EU directives. According to data from the RIPOK Council, about 34% recycling was achieved in 2019. Therefore, reaching the recycling target for 2020 is virtually impossible.

On the basis of the municipal waste morphology predicted by Szpadt and total waste quantity estimated for 2025, the previous section presented the effects of implementing the high recycling rates provided for in the circular economy assumptions. In the first variant (achieving the assumed individual recycling levels planned for 2030), a stream of about 6.3 million Mg of residual waste with a calorific value amounting to 7 MJ/kg is obtained, most of which can be directed to waste incineration plants. If this stream is directed to the MBT installation—approximately 3 million Mg of calorific fraction (RDF) with a calorific value of about 13 MJ/kg will be obtained. With this waste management model, the operation of MBT installations is essential, although almost half of the existing installations qualify for shutdown. Most likely, the RDF stream will be slightly bigger, as it will not be possible to eliminate the entire biological and ballast fraction from the plus-mesh fraction. Therefore, it can be expected that about 3.2–3.5 million Mg of waste per year with a calorific value close to 12 MJ/kg will be incinerated. In fact, this variant only slightly changes the current situation in municipal waste management and will most likely continue to function in Poland for another 10 years—until the end of the 2020s.

It is expected that in the early 2030s the higher recycling rates described in the second variant (in which total recycling will be over 65%) will be achieved. In this variant, about 5 million Mg of residual waste with a calorific value of approximately 5.8 MJ/kg will be offered for management. This calorific value is too low to direct the entire stream to incineration, but at the same time it allows for the landfilling of this waste. However, its amount is too large to be acceptable (it exceeds 10% of the circular economy assumptions). This means that this stream should be directed to the MBT installation, where approximately 2.2 million Mg RDF will be produced with a calorific value of about 11.1 MJ/kg. Taking into account the realities, a maximum of 2.4 million Mg of RDF with a calorific value of 10.5 MJ/kg should be available. In the second variant, one should take into account the strong pressure of "green" organizations against allowing the entire residual fraction to be landfilled, instead of sending it to the MBT installation, producing RDF and then incinerating it in the installations for thermal processing of municipal waste.

The third variant described in the previous section, in which only around 90% of selectively collected fractions will be recyclable, is completely unrealistic, but as it results from calculations, in this variant a maximum of only about 1.5–1.6 Mg RDF per year with a calorific value of approximately 10 MJ/kg will remain for combustion.

Summing up, the implementation of the circular economy assumptions will certainly reduce the amount of fraction suitable for incineration, and thus, a significant question arises whether after 2030 it will not turn out that Poland has excess processing capacity in municipal waste incineration plants. Therefore, it seems that 30% of waste acceptable for incineration (in accordance with the Waste Act) may turn out to be too high after 2030. In real terms, a maximum of 2.5 million Mg of RDF per year with a calorific value of around 12 MJ/kg will be available in this period.

3.3. Plastic Reduction

The 2019/904/EC Directive [56] on plastics adopted in 2019 provides for the systematic withdrawal of certain plastic products from the market. Aggressive propaganda of environmental organizations calls for a complete ban on the production of plastic products. As part of the circular economy there is increasing pressure to ban the production of non-recyclable plastics. The most common plastics today are polyethylene (PE) and polypropylene (PP). From a technical point of view, these plastics are practically unsuitable for classical recycling. Regranulation of plastic waste and repeated extrusion means that new products are of much lower quality than those made from primary raw materials. Repeated use of raw materials in this way renders the obtained products unusable. In order to produce a full-value product from PE or PP waste, these plastics must be depolymerized, cleaned and re-polymerized. This technology is very expensive and therefore unprofitable. On the other hand, for example, PET (polyethylene terephthalate) is fully recyclable. Despite all the difficulties, intensive research work on the development of new methods of processing plastics should be expected, so that the products made of them can be fully recycled. It is also expected to reduce the amount of plastic used as packaging and then contained in municipal waste. In Poland, the share of plastics in waste is approximately 13% (in richer EU countries it is higher), which gives a total stream of about 1.8–2.0 million Mg.

When performing simulation calculations, e.g., for the first variant described in the previous section, it can be easily noticed that a 25% reduction in the amount of plastics in municipal waste will not cause a significant change in the calculated total recycling, while the residual fraction stream will decrease by about 3% and its calorific value will decrease to 6.3 MJ/kg (from 7 MJ/kg). On the other hand, the RDF stream from the MBT installation will decrease by approximately 7% and its calorific value will drop to 12 MJ/kg (from 13.1 MJ/kg). Reducing the amount of plastics in the total municipal waste stream by around 50% will reduce the residual fraction by 6% and RDF by 15%. The calorific value of the residual fraction is expected to drop to approximately 5.6 MJ/kg and the RDF to about 10.7 MJ/k. The most important results of the calculations of the impact of reducing the amount of plastics in municipal waste are presented in Table 11.

Thus, there is no doubt that the expected reduction in the amount of plastics (in particular in the form of packaging waste) will have an impact on the amount of municipal waste (in the form of residual waste or RDF) that can be sent for incineration. The calorific value of this waste should also be expected to decline.

Reduction in the amount of plastics in municipal waste, as well as increase of the recycling rate will certainly affect the availability of a flammable fraction of municipal waste that can be sent for incineration. Along with the implementation of circular economy, changes in the morphology of municipal waste itself, as well as in the amount of waste generated annually should also be expected. What will these changes be like? It is impossible to predict today. Thus, this element represents now the greatest risk in planning the construction of new installations for thermal treatment of municipal waste.

3.4. Reduction of the Amount of Glass Waste Due to the Introduction of a Deposit

Deposits for some glass packaging (and perhaps some plastic packaging) discussed and planned to be introduced since 2021 will certainly affect the municipal waste management. The deposit system is to refer primarily to bottles (glass and plastic—mainly PET). However, this means that a certain amount of glass and plastic waste may disappear from the market, reducing the municipal waste input stream and affecting the calculated recycling rates. Collecting deposit packaging for reuse will make it much more difficult to achieve the main goal of circular economy, i.e., 65% recycling of municipal waste. It can be calculated that a 50% reduction in the amount of glass waste in the stream of municipal waste generated in households will reduce the amount of the residual fraction by about 3% and RDF by roughly 6%. A slight increase in the calorific value of the residual fraction to about 7.2 MJ/kg and the RDF to 13.8 MJ/kg is expected. However, if we assume a 50% reduction in the amount of glass and about a 25% reduction in the amount of plastics (after the introduction of bottle deposit), we can expect a decrease in the amount of residual fraction by about 6.3% and RDF by 13.4%. A slight decrease in the calorific value amounting to around 6.5 MJ/kg for residual waste and 12.7 MJ/kg for RDF will be expected. Table 12 presents the results of calculations of the effect of glass reduction in municipal waste due to the deposit of bottles.

Table 11. The amount and calorific value of residual waste and the calorific fraction for various implementation variants of the Circular Economy Package—the impact of reducing the amount of plastics in municipal waste.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant Ia1—with a 25% reduction in the amount of plastics in municipal waste	56.80	6,055,553	6.3	2,737,180	12.0
Variant Ia2—with a 50% reduction in the amount of plastics in municipal waste	56.86	5,839,409	5.6	2,521,036	10.7
Variant Ia3—with a 75% reduction in the amount of plastics in municipal waste	56.93	5,623,265	4.8	2,304,892	9.2

Table 12. The amount and calorific value of residual waste and the caloric fraction for various variants of the implementation of the Circular Economy Package—the effect of glass reduction in municipal waste.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant Ia1—with a 25% reduction in the amount of plastics in municipal waste	56.27	6,181,959	7.1	2,863,586	13.5
Variant Ia2—with a 50% reduction in the amount of plastics in municipal waste	55.79	6,092,222	7.1	2,773,848	13.8
Variant Ia3—with a 75% reduction in the amount of plastics in municipal waste	56.27	6,002,484	7.2	2,684,111	14.2

The deposit system can cover both glass and plastic packaging (this is the case, for example, in Germany). However, introducing it and thus removing a large amount of plastics and glass from municipal waste does not significantly improve the recycling rate of the entire municipal waste stream in Poland. The effect of simultaneous removal of some plastics and glass from the municipal waste stream as a result of the introduction of the deposit system is shown in Table 13.

3.5. Selective Collection of Bottom Ash

Many households still use individual heating systems, most often based on coal stoves. In Poland, heat from the district heating network accounts for a relatively large share, slightly exceeding 50%, but still, especially in city centers, individual coal heating dominates. In Poland, household stoves burn approximately 11.2 million Mg of coal, while in the entire EU it is slightly over 13 million, which makes us an infamous leader in this field. The consequence of burning such amount of coal (often of poor quality) in domestic stoves is the presence of approx. 1.2–1.5 million Mg of mineral (non-flammable) substance—bottom ash in the municipal waste stream. An interesting proposition is the selective collection of ashes from domestic stoves. As results from the calculations (Table 14), the implementation of selective collection of bottom ash significantly improves the total municipal waste recycling rate. So maybe a 6-container selective collection is worth considering?

Summarizing the section on threats to the development of the waste-to-energy sector in Poland, we analyzed the impact of the simultaneous introduction of a deposit (for re-use or recycling) of glass and plastic packaging contained in the municipal waste stream on the total municipal waste recycling rate, as well as the introduction of selective collection of ashes from home furnaces. Results of these calculations for variant I are presented in Table 15.

Summarizing the above presented considerations on the feasibility of implementing the circular economy assumptions into the municipal waste management system in Poland, it should be stated that the target level of recycling (and biological treatment) of 65% municipal solid waste (to be achieved in 2035) in Poland is unrealistic. This is mainly hindered by the fractional (morphological) composition of municipal waste and a lower content of recyclable packaging waste than in the more developed EU countries. Paradoxically, waste avoidance, which is at the top of the waste management hierarchy, in the case of, e.g., plastics and glass (packaging) may worsen the overall recycling rates and make impossible for Poland achieving one of the goals of the circular economy, i.e., the 65% recycling.

The idea of introducing selective collection of slags and bottom ashes from coal-fired household stoves in Poland gives a good chance of achieving the assumed, very high rates of municipal waste recycling. Compared to other EU countries, Poland is distinguished by a huge share of coal in heating flats and houses. In Poland, approx. 11.2 million Mg of hard coal is burned there, which constitutes about 84% of this fuel for heating residential houses in all EU countries. Such an organized collection should allow for the removal of nearly 1.2–1.5 million Mg of ash from the municipal solid waste stream and ultimately achieve the expected 65% recycling of the entire municipal waste stream.

Table 13. The amount and calorific value of residual waste and RDF for various variants of the Circular Economy Package implementation—the impact of simultaneous reduction in the amount of glass and plastics in municipal waste.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant Ic1—with a 50% reduction of glass and 25% reduction of plastics in municipal waste (bottle deposit system)	55.81	5,876,078	6.5	2,557,705	12.7
Variant Ic2—with a 75% reduction of glass and 50% reduction of plastics in municipal waste (bottle deposit system)	55.29	5,889,002	5.8	2,551,823	11.7

Table 14. The amount and calorific value of residual waste and RDF for various variants of the Circular Economy Package implementation—the impact of selective collection of bottom ash.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant Id1—with approx. 25% selective collection of ash	58.58	5,814,976	7.4	2,953,323	13.1
Variant Id2—with approx. 50% selective collection of ash	60.55	5,358,255	7.9	2,953,323	13.1
Variant Id3—with approx. 75% selective collection of ash	62.66	4,901,534	8.4	2,953,323	13.1
Variant Id4—with approx. 50% selective collection of ash and its recycling	63.04	5,358,255	7.9	2,953,323	13.1
Variant Id5—with approx. 75% selective collection of ash and its recycling	66.19	4,901,534	8.4	2,953,323	13.1

Table 15. The amount and calorific value of residual waste and RDF for various variants of the Circular Economy Package implementation.

Simulation for 2025 (Approx. 14.5 million Mg/year) Variant	Recycling Rate of All Waste (%)	Amount of Residual Waste (Mg/year)	Calorific Value (MJ/kg)	Amount of RDF from MBT Installation (Mg/year)	Calorific Value (MJ/kg)
Variant I—target recycling of individual fractions of municipal waste according to Circular Economy Package	56.74	6,271,697	7.0	2,953,323	13.1
Variant If1—with a 50% reduction in the amount of glass and 25% in the amount of plastics in municipal waste (bottle deposit) and a selective collection of approx. 50% of bottom ash from household stoves	59.93	4,962,363	7.3	2,557,705	12.7
Variant If2—with a 75% reduction in the amount of glass and 50% in the amount of plastics in municipal waste (bottle deposit) and a selective collection of approx. 75% of bottom ash from household stoves	62.12	4,200,033	7.0	2,851,823	11.7

4. Conclusions

There is also no doubt that regardless of the implementation of circular economy in the municipal waste management system, there will always be a stream of the so-called residual waste after selective collection, the fuel properties of which will have to be used to reduce the amount of deposited waste below 10%. The calculations show that in Poland this stream (most likely after the separation of biological residues and ash residues) will amount to about 3.0–3.5 million Mg, even with the implementation of the circular economy assumptions. According to the results of the presented calculations, this residual waste stream is flammable and should not be landfilled. In 2001, the first Polish municipal waste incineration plant started its works and now nine of them are already in operation. Their capacity (approx. 1.3 million Mg) is too small to incinerate the amount of waste remaining after selective collection. Even if we take into account the possibility of burning some of the waste in cement kilns, we still have 1.0–1.5 million Mg of waste left, for which we should build new installations. Several of them will be large waste-to-energy plants with a capacity of 100,000–200,000 Mg/year, but there are more than a dozen projects with a capacity of 15,000–30,000 Mg/year.

Summarizing, the creation of a mathematical model of municipal waste management in Poland allowed for the simulation of "what will happen when . . . ?". The results of these simulations make it possible to better plan the system and improve the municipal solid waste management system in Poland.

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