Energy Recovery from Waste—Closing the Municipal Loop

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Abstract: Municipal waste management in the EU has been challenged to a thorough transformation towards a Circular Economy. It is addressed by a number of quantitative policy targets, including a restriction on municipal waste landfilling to 10% in 2035. This paper presents the data on municipal waste composition in a large Polish city, based on thorough waste sorting analyses. On average, 374 kg of municipal waste is collected per capita in Wroclaw, of which 41% are separately collected fractions. The approach to implement the EU recycling targets until 2035 is presented, including an increase of sorting and recycling efficiency and a significant share of recyclables being retrieved from the residual waste fraction. Notwithstanding the recycling targets, an important stream of residual waste remains, amounting to 200 k ton in 2020 and approx. 130 k ton in 2035, which is available for energy recovery. The respective LHV values range from 8.5 to 7.6 MJ/kg. The results indicate that the residual waste stream, after satisfying the recycling targets, is still suitable for energy recovery through the whole period until 2035. Moreover, it is a necessary step towards closing the materials cycling in the municipal sector and the only option so far to reduce landfilling sufficiently.

Keywords: municipal waste; circular economy; energy recovery; waste-to-energy; waste composition

1. Introduction

Global resources depletion, which has progressed since the industrial revolution, and climate change issues require moving towards more cautious and sustainable solutions. The circular economy (CE) has been identified with a system, in which the growth of the economy is decoupled from resource consumption, through material recovery and recirculation [1,2]. In order for the CE to be implemented, it is necessary to move from a linear (take–make–dispose) model, in which a large amount of waste is generated, to a circular system, where resources are preserved throughout the production cycles [3,4]. In the shift towards the CE, consolidated efforts need to be taken in virtually all business sectors. A Circular Economy Action Plan was adopted by the European Commission in March 2020 [5]. It focuses on preventing waste generation and its management in a way to enhance the EU global leadership in this area, its competitiveness and economic growth. It also underpins the EU’s 2050 climate neutrality goal proclaimed by the Green Deal [6], which stipulates that all 27 EU Member States contribute to turning the EU into the first climate neutral continent by 2050, with the intermediate goal of cutting at least 55% of emissions by 2030, related to 1990 levels. There is an important role of municipal systems in supporting the CE approach, as, according to the estimations of [7], globally, 75% of natural resources and 80% of the energy supply are consumed in cities. The circular economy adaptation in an urban context is subject to increased attention as well [8–12]. Within municipal waste management, clear targets have been set by the European waste policy by the amended, in 2018, Directive 2008/98/EC on waste, referred to as the Waste Framework Directive (WFD). The WFD imposes the following targets on the EU countries:
• preparation for re-use and recycling of municipal waste should reach at least 55%, 60% and 65% by weight by 2025, 2030 and 2035, respectively.
• by 2035 landfilling of municipal waste landfilled should be limited to 10%.

Considering that the current reuse and recycling targets in EU member states differ widely between MS, from 25% in Latvia and Croatia up to 67% in Germany (Eurostat), substantial efforts will be needed across Europe to transpose the directive and achieve the targets successfully.

The WFD has stipulated separate collections of paper, metal, plastic and glass since 2015; moreover, it has to be extended, by 31 December 2023, for biowaste, and by 1 January 2025, for textile and hazardous household waste. The recommended arrangements for separate collections include door-to-door collection and bring systems, as well as civic amenity sites. The separate collection of waste, according to the Opinion of 27 April 2016 from the European Economic and Social Committee, is crucial for achieving circularity. Besides, only if waste fractions are collected separately, a high quality of recyclables can be provided. On the other hand, implementation of an efficient separate collection system remains a challenge, especially in large cities where multifamily housing prevails. In the multifamily housing, the level of pollution is higher than in the single-family areas, which can be explained by higher anonymousness and generally worse waste segregation behaviour [13–15].

It should be also considered, that even if the ambitious reuse and recycling targets are fulfilled, there always remains a proportion of waste which remains in the residual fraction [16,17]. The quality of this fraction is changing as higher shares of recyclables are diverted for recycling.

Energy recovery from waste is the next recommended option after material recycling, according to waste hierarchy, and clearly provides a better alternative to landfilling [18]. According to the Joint Research Centre of the European Commission [19], in 2014, approximately 1.5% of the EU’s total final energy consumption was met by energy recovered from waste. Energy can be recovered directly from waste by mass combustion or through the production of waste-derived fuels, which in turn also can be used to produce electricity, heat or steam. The combustion of residual waste in incinerators itself, despite of strict emission limits, does lead to environmental burdens in the form of, mainly, emissions to air. This is, however, compensated by the production of energy (electricity, heat or steam) that is replacing traditionally generated energy. Thus waste combustion may lead to overall environmental relief, especially for the areas depending on energy from coal, as is the case in the city of Wrocław [20]. The overall waste incineration capacity should not exceed 25–30% of the total volume of municipal waste generated in a region, so that it does not compete with the options of a higher priority, such as recycling.

There has been much interest in the Circular Economy in the past years; however, as identified by [2], the empirical work on CE is scarce. Considering the abovementioned targets and deficiencies, this paper presents the results of a thorough municipal waste characterisation in a Polish city and discusses its approach to implement CE targets at a municipal level. The results of detailed composition studies with basic chemical characteristics, along with a waste generation prognosis, allow one to conceptualise future waste collection and treatment scenarios to implement the CE reuse and recycling targets. According to the CE philosophy materials, which are not suitable for recycling, should be used for energy recovery. Since the growth of recycling will affect the composition of the residual waste stream, the data of fuel properties of individual waste components are used to estimate the quality of the residual waste stream available for further treatment. The results of these considerations show how the future CE scenario will influence the fuel properties of the residual stream, and if the energy recovery will still be a plausible solution in a 15 years’ perspective.
2. Materials and Methods

2.1. Waste Sampling

Waste composition of the City of Wrocław was evaluated during a full year, on a monthly basis. Waste sorting analyses were performed in three characteristic residential areas and, from a number of non-residential sources, were investigated, including: hotels, restaurants, markets, allotment gardens and street bins. Both residual waste as well as separately collected waste fractions, including light recyclables (plastics, composites and metals), paper & cardboard, glass and biowaste, were examined. The samples were delivered by waste collection company. In case of residential areas, waste from three selected routes were delivered each month, namely from a single-family housing, high-rise multifamily district and city centre multifamily housing. In case of non-residential sources, waste samples were delivered from specified locations. Waste was discharged directly from the collection vehicle (approx. 10,000 kg batch), out of which the sorting sample of approx. 100 kg was formed by marching together 10 unit samples of 10 kg evenly distributed throughout the pile of waste batch.

2.2. Waste Composition Analyses

For the waste sorting analyses the modified method recommended by the Polish ministry of Environment was followed [21]. The method was adjusted to the needs of waste management planning for the municipality of Wrocław, in particular for the planning of advanced waste sorting technologies focused on implementation of the future recycling targets. In case of residual waste, 100 kg sample was sieved by each participant into particle sizes of >80 mm, 40–80 mm, 20–40 mm, 10–20 mm and <10 mm. Size fractions were collected and, except for fine fractions (<20 mm), separated into specified material categories. Samples of residual waste >80 mm were sorted into 33 material sub-categories, samples 40–80 mm and 20–40 mm were sorted into 22 material sub-categories, as shown. Each material fraction was weighted with an accuracy of 10 g. The scope of the granulometric and morphological analysis of residual waste is demonstrated in Figure 1.

In case of separately collected waste, the same granulometric fractions were distinguished; however, only fractions >40 mm were sorted. The scope of material sub-categories of the light recyclables waste analogical to the residual waste, respectively, for plastics, composites and ferrous and non-ferrous metals. In paper and cardboard, the following categories were distinguished: packaging paper, newspaper, and other paper (office paper, books and hygienic paper). Glass was sorted to packaging glass and non-packaging glass. In all separately collected fractions a sub-category of “contamination” was distinguished, which encompassed all materials not intended to be collected within the given fraction. In the fraction of biowaste, only the level of contamination was investigated.

2.3. Total Waste Quantities

Data on total yearly waste quantities was obtained from the municipal statistics. The municipality assesses and publishes yearly reports on waste management status [22].

2.4. Analysis of Technological Properties of Waste

Every month, laboratory samples from selected types of waste were derived for tests aimed at assessing the technological properties of the waste. The samples taken for the tests were comminuted and averaged using a high-speed mill, type. XC-GP230-5 HP. The scope of analyses included: humidity, based on PN-EN 15934:2013-2 [23] method A; loss of ignition (LOI), based on PN-EN 15935:2013-2 [24]; heat of combustion according to PN-EN 15400:2011 [25]. The analyses were performed by the Laboratory of Waste Technology and Land Remediation at the Faculty of Environmental Engineering of the Wrocław University of Science and Technology. The test results are presented in the following sections.
Figure 1. Sampling schedule according to modified SWA Tool methodology.

3. Results

Separate collections of municipal waste facilitate a high quality of recycling. It is basically proven that door-to-door separate collection schemes, which have already been successfully implemented in many MS, facilitate the increase of separate collection levels [26]. Since 2013, Polish municipalities are fully responsible for the organisation and performance of municipal waste management. Since then, the separate collection infrastructure has been significantly improved, by increasing the accessibility of waste collection points. To assess the possibility of implementing the circular economy targets the separate collection results achieved so far in Wrocław have been evaluated.

3.1. Quantities of Separately Collected and Residual Waste Fractions

In the city of Wrocław, by 2020 municipal waste was collected basically only in door-to-door schemes, i.e., directly from households. The door-to-door separate collection schemes are presented in Table 1. The table covers only the regularly collected fractions. Bulky waste and hazardous waste collection are provided in special drop-off containers and collected by a hazardous waste vehicle, as well as at the civil amenity sites.
Table 1. Door-to-door municipal waste collection scheme in the city of Wroclaw.

| Waste Fraction     | Introduction of Door-to-Door Collection                                                                 | Minimum Collection Frequency                  |
|--------------------|----------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| Paper & cardboard  | since 2013                                                                                              | since 2017, biweekly, before once per month     |
| Glass              | since 2017 (changed from common drop-off points)                                                         | since 2017, biweekly                           |
| Light recyclables  | since 2013, garden waste, since VIII 2020 includes kitchen waste                                      | biweekly                                      |
| Biowaste           | since 2013                                                                                              | weekly from IV to XI                           |
| Residual waste     | since 2013                                                                                              | weekly                                        |
| Bulky waste        | In containers provided in designated locations                                                        | every 2 months in each location               |
| Hazardous waste    | By a special vehicle                                                                                    | every 6 months in each location               |

Figure 2 presents results of waste collection in Wroclaw in the years 2013–2020 [22]. In 2020, 329.3 thousand tons of all municipal waste was collected, of which 191.5 thousand tons were residual waste. It can be seen that in the period 2013–2020, a significant increase of separate collection levels was achieved. The share of all separately collected materials in total waste has increased from 17.2% in 2013 to 41.8% in 2020. Out of this, the absolute amounts of separately collected fractions of plastics, composites and metals increased by a factor of 5.2, and of separately collected paper and cardboard by a factor of 4.8. However, at the same time, the total amount of waste has grown by 35%, so in the end, the absolute amount of residual waste collected in 2020 is only 5.0% lower than the amount collected in 2013. In more recent years, the total waste amount seems to have stabilised, accompanied with a continuing increase of amounts of separately collected waste fractions.

![Figure 2](image.png)

**Figure 2.** Results of municipal waste collection in Wroclaw in the period 2013–2020.

Individual waste collection results in different residential areas are presented in Table 2. The weighted average was determined, taking into account the shares of a given type of development (single-family housing—22%, multi-family housing—38%, multi-family housing in the center—40%). Approximately 75% of all municipal waste is contributed by residential areas (door-to-door collection). Within the remaining part are waste delivered to the collection points, mainly bulky waste, other waste collected in civil amenity sites, recyclables collected at metal scrap shops and green waste delivered by municipal services. On average, 373.6 kg of municipal waste per capita is collected in Wroclaw city. It can be clearly seen that the amount of municipal waste collected per capita is the highest in the single family area (581.3 kg) and the lowest in high-rise multifamily housing (308.9 kg), and that these differences are underlined by the significantly higher quantity of separately collected biowaste and of the residual waste.
Table 2. Individual waste collection rates for different types of housing [kg per capita and year].

| Waste Fraction     | Single-Family Area | High-Rise Multifamily Housing | City Centre Multifamily Housing | Weighted Average |
|--------------------|--------------------|-------------------------------|---------------------------------|------------------|
| Paper & cardboard  | 17.3               | 36.0                          | 21.8                            | 26.2             |
| Plastics, composites & metals | 39.4       | 34.6                          | 20.0                            | 29.8             |
| Glass              | 77.1               | 12.3                          | 6.7                             | 24.3             |
| Biowaste           | 88.3               | 13.1                          | 1.9                             | 25.2             |
| Residual waste     | 359.2              | 212.9                         | 270.6                           | 268.2            |
| Total              | 581.3              | 308.9                         | 321.0                           | 373.6            |

3.2. Composition of Separately Collected and Residual Waste Fractions

The results of the analyses were obtained for individual months and types of buildings and non-residential buildings. The results were then aggregated, taking into account shares of individual sources. The composition of the waste is crucial for assessing the recycling potential. Thus, the obtained weighted average data for the whole city for each of the separately collected fractions are presented in the following sections.

3.2.1. Separately Collected Light Recyclables

Figure 3 presents the composition of the separately collected light recyclables fraction by main material categories. Plastics is by far the most dominating fraction (60.5%), followed by composites (10.3%), ferrous metals (4.1%) and non-ferrous metals (2.1%). This fraction shows highest contamination level out of all investigated materials, amounting to 17.0%.

![Composition of separately collected light recyclables—main categories.](image-url)

The light recyclables fraction covers the widest spectrum of sub-categories, which can be derived for recycling in a sorting process. The detailed composition of fractions >80 mm and 40–80 mm are shown in Figure 4. The percentage values are related to the total mass of separately collected light recyclables. The total share of fraction >80 mm amounted to 77.4% and it included 11.5% of contaminants, which are not included in the graph. The share of
the fractions that were 40–80 mm was 16.7% (with 5.5% of contaminants). It means that the share of fractions <40 mm was only 5.9% of all separately collected light recyclables.

Figure 4. Detailed composition of >40 mm fractions of separately collected light recyclables.

3.2.2. Separately Collected Paper and Cardboard

Figure 5 shows the composition of separately collected paper & cardboard waste. In this case, fractions >80 mm constitute 92% of the total fraction, including 6.6% of contaminants. Cardboard is clearly the dominating material (54.6%), with significantly
lower shares of newspapers (16.0%), other paper, consisting mostly of office and hygiene paper (11.8%) and packaging paper (7.7%). Over the past several years, already there has been a decline of printed paper use, mostly due to the extensive growth and advancement of the Internet and e-businesses [27]. However, it is partly compensated by the growth in demand for paper, and especially cardboard, as a primary and secondary packing material for the shipment of the products. This global consumption change is also reflected by paper waste composition.

![Composition of separately collected paper and cardboard—main categories.](image)

3.2.3. Separately Collected Glass

Figure 6 presents the general composition of separately collected glass. It is dominated by packaging glass of a size >40 mm (57.4%), with a much lower share of non-packaging glass (5.7%). In contrast to paper and plastics, a significant amount of the desired material is contained in fractions <40 mm (glass cullet). The contamination level amounts to 9.7%.

3.2.4. Separately Collected Biowaste

The composition of separately collected biowaste is shown in Figure 7. At the time of the sorting campaign, kitchen biowaste was not collected separately from households yet. Thus, the prevailing fraction is garden waste >40 mm (69.9%), followed by the “fines” (<40 mm), also consisting of garden waste. The contamination level of the total fraction, with a 1.7% share, was lowest out of all fractions and consisted mainly of plastic bags used for biowaste collection.

3.2.5. Residual Waste Composition

The average residual (mixed) waste composition by main materials is presented in Figure 8. The fraction >80 mm constitutes 55.9% of the total mass of residual waste and contains the majority of recyclables, such as plastics, paper and textiles. It also contains a significant share of the shares of kitchen and garden waste as well as hygiene waste. The fraction that is 40–80 mm is dominated by biodegradable fractions—kitchen and garden waste and paper. It also contains some plastics and metals. The fraction of 20–40 mm is strongly dominated by the kitchen and garden waste.
The fraction >80 mm is the most interesting from the point of view of material recycling. Its detailed composition is presented in Figure 9. Except for the kitchen waste and hygiene waste, some of the prevailing categories include textiles (5.7%) of the total residual waste stream. The share of this category has significantly grown in the past decade, as compared to the previous research [28]. Other paper and packaging glass contribute a further 4.4% and 4.0% mass. Out of all plastics, the dominating sub-fractions are coloured and transparent foil (4.1% and 2.3%) and PET bottles (2.2%). Thus, it can be concluded that the share of potentially recyclable materials is still high in the residual waste stream.
Figure 8. Residual waste composition by major fractions in Wrocław.

3.3. The Overall Recycling Potential of the Collected Waste Fractions

By 2020 it was required to obtain a 50% recycling rate of at least paper, metals, glass and plastics contained in municipal waste. This calculation method was chosen by Poland in agreement with “calculation method 2”, as defined in the EU Commission Decision COM 2011/753/EU [29]. From the current separate collection results, it is clear that the 50% recycling target cannot be achieved only by recycling the separately collected materials. Furthermore, the most precious recyclables from residual waste need to be diverted for recycling. It should be done in the mechanical-biological treatment plants, which currently process the residual waste stream.

By far the most challenging out of all separately collected waste streams is the fraction of light recyclables. As demonstrated in Figure 3, plastics are currently the dominating material contained in the light recyclables fraction. However, the group of plastics in municipal waste consists of a wide variety of various polymers, predominantly used as packaging materials (see Figure 4). Currently, only for some of the polymers, mainly PET and HDPE bottles, a relatively stable demand exists. There is lack of recycling capacity in Europe for many other packaging materials, e.g., PE/PS, packaging foil and composite packaging materials.

In principal, larger items (in practice objects >80 mm) can be more easily separated from the mixed recyclables stream, thus it is more likely to be recycled. PET is the dominating polymer within the >80 mm fraction. To be suited for recycling it needs to be further classified according to colours and separated from contaminants (caps, labels, etc.). In the majority of cases, one piece of packaging is composed of two or more different polymers, which need to be separated before recycling. It requires additional efforts and treatment steps, which often render material recycling not an economically viable option at the moment. Data from the Polish sorting plants indicate that only approx. 49% of the whole light recyclables stream is fed to actual recycling.

Based on the qualitative assessment, shares of individual material fractions assumed to be diverted for recycling from the light recyclables and residual waste streams are presented in Figure 10. The “shares of fractions derived for recycling” were constructed as a combination of the recyclability/demand of a given material, the degree of its contamination and its suitability for (automated) sorting. It is obvious that the highest diversion rates
can be attributed to the separately collected waste fractions (especially >80 mm). Lower diversion rates for materials contained in the residual waste fraction can be attributed to its higher contamination (lower value) and impaired sorting ability, by automated separators, as compared to the separately collected fractions.

Figure 9. Composition of the >80 mm fraction of residual waste in Wroclaw by detailed categories.
Similar assumptions were made for other recyclables (paper & cardboard and glass) and finally they were applied to calculate the potential shares of recyclables to be derived from separately collected and residual waste to achieve 50% recycling of all recyclables. The relative shares of materials from those fractions are presented in Figure 11. It can
be seen that, despite relatively high separate collection levels obtained, it is by far not possible to satisfy the 50% recycling level by separately collected fractions only. In the presented example, 43% of materials for recycling is derived from residual waste. It can be seen that in both cases, the fraction >80 mm delivers most of the recyclables, especially paper and plastics, while especially high rates of glass are harvested from fractions 40–80 mm and <40 mm. It can also be concluded that achieving 50% recycling targets requires advanced sorting of both separately collected and residual waste streams to recover the targeted materials, as well as further development of recycling technologies for the less valuable materials.

![Figure 11](image-url)

**Figure 11.** Contribution of materials derived from different waste fractions to obtain 50% recycling of all recyclables.

Regarding the separately collected biowaste fraction, at the time this study was performed only green waste was collected, the kitchen waste remained still in the mixed waste stream. The level of contamination is low (1.7%) thus, after the elimination of plastic bags, the entire stream is directed to the composting process. The final product derived from the composting process is used as a fertiliser, thus it complies with the definition of organic recycling.

3.4. Implementing the CE Reuse and Recycling Targets until 2035

Articles 11, 20 and 22 of the revised WFD impose, at least, the separate collection of waste from metals, paper, plastics, glass, textiles, hazardous household waste (HHW) and biowaste. Moreover, the calculation method for the reuse and recycling levels has changed to comply with the EU Commission Implementing Decision COM 2019/1004 [30] as, from 2025, the target of 55% reuse and recycling of municipal waste must be met, with the eventual target of 65% reuse and recycling of municipal waste in 2035. Thus, the calculation method changes, referring now to the entire municipal waste stream. In Poland, the new calculation method is implemented already for the year 2021, with the national intermediate recycling targets, starting with the 20% reuse and recycling obligation of the entire municipal waste stream in 2021. To analyse the possibility of implementing new CE recycling targets, a municipal waste generation prognosis for Wroclaw until 2035 was done, based on the demographic prognoses and trends of specific waste generation indicators, according to the suggestions of national and regional waste management plans.

The future reuse and recycling targets require an industry-wide paradigm shift to a CE, involving changes in product design to allow for higher reusability and recyclability, and the development of, preferably local, markets for recyclates. In terms of waste management practices, an increase of the separate collection efficiency and advancement of sorting and recycling technologies are crucial. In Figure 12, a prognosis of future recycling rates of
different waste fractions is made. It was assumed that in the future, the reuse and recycling of standard recyclables, such as paper and cardboard, glass, metals, plastics and composite materials will be continued at enhanced levels. Moreover, organic recycling of biowaste will be boosted due to the intensification of the separate collection of kitchen waste. This fraction will eventually represent the highest share in the overall recycling. Moreover, other separately collected fractions, such as textiles, inerts, as well as part of hazardous and bulky waste, will provide complementary streams for recycling. The presented prognosis takes into account a gradual increase of separate collection, following the recent trends. However, as stated before, recycling of only separately collected streams is not sufficient, it needs to be completed by the recovery of additional materials from a residual waste stream. Analysing the data, it can be concluded that in the years 2021–2024, the prognosed recycling levels will exceed the required levels, which will change, in this period, from 20% in 2021 to 45% in 2024. It also becomes clear that to reach the 55% recycling target in 2025, a significant increase of sorting and recycling efficiency must be achieved. This increase concerns, foremost, the plastics fraction, which, is, at the moment, only partly recycled. However, the separation of residual waste composed of various, difficult to separate materials, e.g., packaging foils or small PP/PS food boxes (often being composites of various polymers), into recyclable fractions with an acceptable market value, seems technically and economically impossible [31]. Thus the graph presents also the quantity of residual waste, including waste sorting residues (remaining after reuse and recycling), which will be available for further recovery in this period. The residual waste stream is expected to decrease from approx. 200 k tons in 2020 to 128 k tons in 2035.

![Figure 12](image_url)  
**Figure 12.** Prognosis of the individual recycling rates to comply with CE targets.

The residual waste, which is not suitable for recycling should be used for energy recovery, either directly (in a waste incineration plant) or after its processing and conditioning to solid recovered fuels of a specified quality. The energy recovery of the residual
waste fraction, which is in line with the waste hierarchy, coincides with less waste going to landfill.

3.5. Suitability of the Residual Waste for Energy Recovery

Waste sorting analyses were accompanied by regular investigations of the fuel properties of materials contained in the residual waste stream. Results of the physical-chemical analyses of the theses waste fraction are presented in Figures 13 and 14. Each combustible material category was investigated on an individual basis. Figure 13 shows data on the water content and LOI, as yearly averages, with error bars representing the standard deviations. Clearly the highest water content is related to the hygiene waste (mostly consisting of disposable nappies) and biowaste fractions (kitchen and garden waste). Additionally, fines <40 mm contain a relatively high amount of moisture. Figure 14 presents results of the determined Higher Heating Value (HHV) and Lower Heating Values (LHV) for the respective fractions. Basically, the HHV of all investigated waste materials, except for hazardous waste, exceed the current landfill admission limit in Poland, (HHV < 6 MJ/kg dm). Thus, the residual waste cannot be landfilled. The LHV is the crucial parameter determining the suitability of waste for energy recovery. It is clear the plastics and other organics (rubber, leather) show the most advantageous LHVs, due to high HHV and low water contents. The properties of the whole residual waste fraction, calculated as the weighted average amounted to app. 8.5 MJ/kg residual waste in 2020.

![Figure 13. Water content and loss of ignition (LOI) of the residual waste fractions.](image)

![Figure 14. Higher and Lower Heating Values of material fractions contained in residual waste.](image)
Clearly, the future recycling levels will directly affect not only the amounts of residual waste, but also its composition and fuel properties. Based on the prognosis of waste generation until 2035 and the prognosis of recycling levels, the amount and characteristics of the residual waste stream was derived. Results of this analysis are presented in Figure 15. It was estimated that the volume of residual waste available for energy recovery will decrease from approx. 200 k ton in 2020 to 153 k ton in 2025, 142 k ton in 2030, and eventually approx. 130 k ton in 2035. The respective LHV will decrease from 8.5 to 7.6 MJ/kg in 2035. This analysis shows that the residual waste is suitable for energy recovery through the whole period, after satisfying the reuse and recycling targets. Moreover, it is a necessary step towards closing the materials cycling in the municipal sector. It is also the only option to allow to implement the target of landfilling not more than 10% of all municipal waste.

![Figure 15. Quantity and fuel properties of residual waste stream in the period 2020–2035.](image)

There are a few possibilities to turn waste into energy, including direct waste incineration with energy recovery, or processing to SRF and its co-/combustion in cement kilns or a dedicated power plant, or less developed processes such as pyrolysis or gasification.

Out of these, direct waste incineration is the most established energy recovery option with the lowest requirements of the input quality. There has been much progress in the energy recovery efficiency of waste incineration plants. According to the JRC study [19], the optimised energy efficiency for waste incineration, assuming CHP, amounts to 27% for electricity generation and 66% for heat generation (total of 93%). If those parameters are applied to the case of Wrocław, the incineration plant utilising residual waste of the presented quality could operate with the power capacity of app. 12 MW\textsubscript{el} and 29 MW\textsubscript{th} in 2025, and 10 MW\textsubscript{el} and 25 MW\textsubscript{th} in 2035.

The amount of produced electricity would be decreasing from 128 GWh\textsubscript{el} in 2020 to 92 GWh\textsubscript{el} in 2025 and 74 GWh\textsubscript{el} in 2035. The produced heat would fall from 1122 TJ in
2020 to 808 TJ in 2025 and 652 TJ in 2035. The electricity consumption in households in Wroclaw is strongly increasing and estimated at 678 GWh\(_e\) in 2020, 818 GWh\(_e\) in 2025 and 1086 GWh\(_e\) in 2035 [32]. The heat consumption in Wroclaw is more stable due to expected heat saving measures and will rise moderately from 9152 TJ in 2020 to 9225 TJ in 2025 and 9356 TJ in 2035. Assuming the above assumptions, an incineration plant could cover the electricity needs of approx. 18.8% of the population in 2020, 11.2% in 2025 and 6.8% in 2035. Similarly, it could cover approx. 12.3% in 2020, 8.8% in 2025 and 7.1% in 2035 of the population’s heat demand.

Use of waste to generate electricity and heat allows to replace the conventional resources which would otherwise need to be extracted. Moreover, residual waste contains a significant share of renewable materials. Default renewable energy content for residual waste in Poland is considered 42%. In this proportion the CO\(_2\) emissions are considered neutral for the climate. In Figure 16 values for CO\(_2\) emissions from the combustion of the considered waste fractions are given [33]. Due to changes in the residual waste composition, the average CO\(_2\) emissions per ton of combusted waste will be declining in time. The major contributor to CO\(_2\) emissions are plastics contained in the residual waste.

![Figure 16. CO\(_2\) emissions from residual waste combustion in the period 2020–2035.](image)

Despite waste incineration being the most widespread waste-to-energy option in Europe, the building of a new plant is almost always confronted with the conflict of interests and rejection by the local community. Finding the optimum location of such a plant remains a major challenge and the opponents of waste to energy plants do often refer to CE principles as opposing the energy recovery from waste. However, as shown in this study the energy recovery from residual waste may constitute an important and necessary element to close the municipal loop. According to [34], there is no general answer to the question “To which extent should material recycling be encouraged over energy recovery?”,
because it is subject to specific conditions and foremost specific market availability. In this paper, it was assumed that recycling will be achieved to the levels prescribed by the legislation. It was assumed that higher-quality materials will primarily undergo recycling, e.g., High-density polyethylene (HDPE) and Polyethylene terephthalate (PET) bottles, clean paper, especially cardboard, metals and glass. However, the future recycling targets imply that we have to reach also for the lower-quality waste fractions. Currently a significant portion of recyclables, including mixed plastics, can only be “downcycled” to lower-quality materials [31]. On the other hand, in the case of paper, the number of recycling cycles amounts, on average, to 3.5 in Europe and only 2.4 worldwide [35]. In this case, residual waste incineration with the recovery of thermal and electric energy becomes a competitive option [34]. Thus, the prerequisite for the CE to be implemented in the municipal waste management is a paradigmatic shift of the whole economy, including shifting towards sustainable product and packaging design as well as the development of more advanced recycling technologies.

3.6. Energy Recovery from Separately Collected Bio-waste

As mentioned before, the biowaste collected was limited to green waste only, thus mostly suitable for composting. In the longer term, after establishing the separate collection of kitchen biowaste it could be used for energy recovery. In 2025, approx. 30,000 Mg of biowaste could be available for anaerobic digestion, and by 2035 this amount could be doubled. The biogas potential of kitchen biowaste will be investigated in detail in a future study. However, assuming the average biogas generation from biowaste is at the level of 100 m$^3$/t with the methane content of 60%, as reported for a dry anaerobic digestion plant in Berlin [34], the Wroclaw plant could produce additionally 6 GW$_{el}$ in 2025 and 12 GW$_{el}$ in 2035, meaning a 6.5% and 16.2% increase of electricity generated by the waste-to-energy plant in 2025 and 2035, respectively.

4. Conclusions

The European waste policy establishes an order of waste treatment methods, prioritising prevention and material recycling over energy recovery, and finally disposal through landfilling, being the least preferred solution. This hierarchy has guided EU policies on waste over the last two decades, and has been recently reinforced by introducing very strict reuse and recycling targets under the wider concept of a Circular Economy.

In this paper, a summary of the main findings of the detailed waste sorting analyses has been presented and used to conceptualise the future of waste management, which will enable fulfilling the CE goals. When analysing the data, it becomes clear that the current separate collection levels are by far not high enough to allow for fulfilling the 65% recycling targets, neither were they for the 2020 targets for 50% recycling of paper, plastics, metals and glass. Assuming current sorting and recycling efficiencies, it has been estimated that in 2020, 43% of all resources needed to be recovered from residual waste. The future developments of separate collections should especially focus on the kitchen biowaste and textiles, which so far have not been fully utilised. By 2025, waste collection and recycling of these streams needs to be established to meet the 55% recycling target. On the other hand, the analysis shows that, throughout the whole period from 2020 to 2035, a significant share of municipal waste will remain as sorting residues and a residual mixed stream which will allow for energy recovery. It has been calculated that the incineration of residual waste could cover the electricity needs of approx. 18.8% of the population in 2020, 11.2% in 2025 and 6.8% in 2035 and, respectively, approx. 12.3%, 8.8% and 7.1% of the population’s heat demand. On the top of it, energy recovery from separately collected biowaste could cover a further 0.7% and 1.1% of the population electricity needs in 2025 and 2035. Thus, the study underpins the role of waste-to-energy as the justified alternative to waste landfilling. Thus, despite many critics from opponent groups, waste-to-energy will provide a long term solution to close the municipal CE loop. It is not a fully circular and climate neutral solution, as only part of the waste is biomass and CO$_2$-neutral, but having in mind that,
as reported by [36], our economy is just over 9% circular, it is clear that the CE needs to be approached step by step. For the municipal waste management the proposed solution could be considered as a significant step forward.

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