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Analysis and evaluation of plastics waste management using exergy analysis

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ABSTRACT

The possibility of using the exergy analysis for the assessment of management of plastic packaging waste contained in municipal waste was presented. Two variants of waste management were evaluated. One option considered the use of waste to produce heat and electricity. The second option considered processing the waste into regranulate. The study aimed to identify which waste management option, in terms of the use of the raw materials it contains, is more favorable in terms of exergy. An index of cumulative exergy demand was used to assess the variants. The value of the indicator is the sum of the exergy of the raw material resources that need to be consumed in waste management. The functional unit is 1 Mg of waste, which consists of municipal plastic packaging waste and mixed municipal waste. The quantitative description of the functional unit is based on the results of surveys of municipal waste in Poland and data from the waste collection company. For each of the waste handling options, an analysis of the processes implemented in them in terms of material and energy flows and exergy requirements was carried out. The data on efficiency, energy needs, calorific value of fuels used in these processes were taken from the literature. The substitution coefficient was calculated to be 0.95. The option involving material recycling of plastic waste will be more favorable in terms of exergy consumption if the resulting regranulate from the waste has a substitution coefficient above 0.95. If the regranulate produced has a substitution coefficient below 0.95, the option involving exergy use of the waste will be better in terms of energy consumption.

Keywords: recycling, plastic waste, exergy consumption, exergy analysis, energy recovery from waste, waste utilization.

INTRODUCTION

Plastic waste is a source of secondary raw materials. This implies it is to subjection to processes aimed at the recovery of recyclable materials or converting it into fuels, heat or electricity. According to Eurostat (2025), the recycling rate of plastic packaging waste in the EU reached 40.7% in 2022 (an increase of 15.5% compared to 2005), while the energy recovery rate from this waste was 35%. Further efforts are being made to achieve even higher levels of plastic waste utilization. The efforts are justified by the resulting benefits for both the economy and the environment. Using plastic waste as a substitute for primary raw materials contributes particularly to the conservation of natural resources and the reduction of waste in the environment. A key objective of research in the field of plastic waste recycling is to develop solutions that enable the effective separation of plastic waste from other types of waste. Currently, attention is focused on municipal waste, for which EU Member States are required to achieve a recycling rate of 55% by weight by 2025 (Directive (EU), 2018). Priority is given to improving the efficiency and effectiveness of selective plastic waste collection at the point of municipal waste generation. Research and development activities are also crucial, particularly those aimed at cleaning selectively collected waste and separating plastic fractions from mixed municipal waste for subsequent recycling. Among the recycling methods, material recycling is currently more commonly used for processing plastic packaging waste than chemical recycling (Jędrczak et al., 2021).

Both the processing of plastic waste for material recovery and its thermal treatment involve multiple unit operations, which require investment, appropriate technological infrastructure and financial resources to cover operational costs. Recoverable municipal waste can enter recovery facilities in various forms, including mixed recyclable waste streams or mixture of recyclable and non-recyclable waste. The type of incoming waste stream determines the configuration of the machinery and equipment in the facility. To compare different municipal waste management scenarios, Pressley et al. (2015) analyzed the costs and energy inputs associated with recovery facilities. They developed a model that assesses the impact of different types of municipal solid waste streams on costs and energy requirements.

The research problem addressed in this article was the impact of the plastic waste management variant on exergy consumption. The study aimed to answer the following questions: How can exergy analysis support the assessment of waste management methods? Which waste management variant is more favorable in terms of exergy consumption, considering the use of resources contained in the waste?

The study considered a variant involving the collection, transport, and mechanical processing of plastic packaging waste together with a fraction of mixed municipal waste, followed by incineration. Additionally, a variant involving the production of regranulate was analyzed. The cumulative exergy demand indicator was used as the criterion for evaluating the plastic packaging waste processing variants. This indicator represents the sum of exergy of natural raw material resources used in the waste processing process.

Table 1. Mass of municipal waste collected by Kom-Eko S.A. from owners of residential and non-residential properties in 2021 (ESG Report, 2021)

Specification	Mass,Mg
Total waste collected	89094.59
Of which mixed waste	44290.63
Packaging waste	18326.37
Bio waste	5764.82
Green waste	8441.76
Bulky waste	4935.26
Construction waste	5943.32
Other waste	1392.43

MATERIALS AND METHODS

The functional unit in the study is 1 Mg of waste, which consists of municipal plastic packaging waste and mixed municipal waste. The object of the study was to analyze two waste treatment options in terms of energy input and exergy consumption. The spatial scope of the study considers the area of a city with a municipal waste management system. The time scope of the study is 1 year. In order to quantitatively describe the functional unit, the results of the study of the morphological composition of municipal waste in Poland and data (Table 1) on the mass of municipal waste collected in 2021 by the Kom-Eko S.A. company from the owners of residential and non-residential properties in the city of Lublin, Poland were used. Kom-Eko S.A. collects, transports and processes municipal waste from three sectors of the city of Lublin. These sectors cover 13 districts of the city (27 districts grouped into 7 sectors in Lublin).

Plastic packaging waste is collected in Poland separately (waste code 150102) or together with packaging waste code 150106 (mixed packaging waste; collected in a yellow container/bag). A study (Szczepański et al., 2020) shows that in the total weight of collected municipal packaging waste in Poland in 2020, the share of waste code 150102 was 16.3% and that of waste code 150106 was 31.2%. The weight share of plastic waste in the weight of municipal packaging waste with code 150106 was 53.6% and in the weight of waste with code 150102 – 90%.

On the basis of the above data, it was determined that Kom-Eko S.A. collected 5753.23 Mg of plastic packaging in 2021 – this mass represented approximately 6.4% of the total mass of municipal waste collected by the company.

The share of the mass of mixed waste in the total mass of municipal waste collected by this company in 2021 was 49.7% (Table 1).

The data presented shows that for every 1.78 Mg of municipal waste collected, there is 1 Mg of mixed waste and plastic packaging waste combined (0.885 Mg of mixed waste and 0.115 Mg of plastic waste). These two fractions of municipal waste (Figure 1) are the focus of this study.

For each waste treatment option, an analysis of the processes involved was carried out. The subject of the analysis is material and energy flows and exergy demand. Process data (yield, energy demand, calorific value of fuels) were taken from the literature, including scientific studies, reports

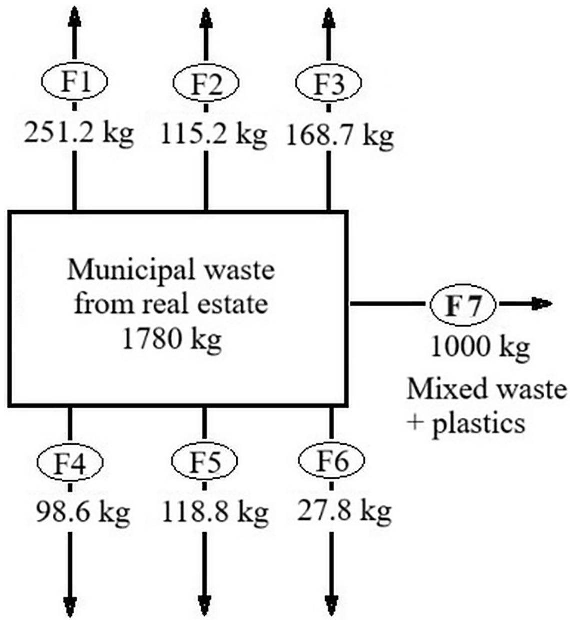

Figure 1. Functional unit and waste fractions omitted from the study; F1 – non-plastic packaging waste, F2 – bio waste, F3 – green waste, F4 – bulky waste, F5 – construction waste, F6 – other waste, F7 – mixed waste + plastic packaging waste

published by companies and reporting institutions, and the Life Cycle Database (Ecoinvent).

Waste treatment – option one

Waste treatment option one (P1) considers that plastic waste will be incinerated with energy recovery along with mixed municipal waste. The processes analyzed here were: collection and transport of waste from the property, mechanical treatment of waste and incineration of waste.

Collection and transport of waste

The energy demand of the waste collection and transport process was determined on the basis of data on the consumption of transport fuels by the waste collection company in 2021 (Table 2).

Fuel consumption for the collection and transport of individual municipal waste fractions (Figure 1) was calculated assuming that it is proportional to the weight of the fractions. This is a simplification, as the amount of fuel consumed depends on the frequency of collection of a given waste fraction, vehicle payload and its use, engine power, age and travel time of the vehicles (Malinowski, 2014). In addition, different fractions of selectively collected waste can be transported by a single multi-compartment vehicle. Taking this assumption into account, it was calculated that the fuel energy demand for collection and transport of mixed municipal waste and plastic packaging waste has a value of 574 MJ/Mg (Table 2).

Mechanical waste treatment

The process starts with the loading of waste from the buffer zone into a hopper connected to a bag bursting machine by means of a wheel loader. With a moving floor in the hopper, the waste is transported from the hopper to an ascending conveyor and then to a disc sifter. The screen separates the waste stream into two fractions: up to 80 mm and over 80 mm. The fraction up to 80 mm is discharged via a belt conveyor into a container and is then transferred to undergo biological treatment.

The fraction above 80 mm is transported by conveyor to the sorting cabin. An electromagnet located above the conveyor separates iron from this waste. In the sorting cabin, glass packaging and the waste that could damage the shredders is manually separated. The remainder of this fraction goes from the sorting conveyor to a reverse conveyor and from there to two single-shaft shredders. The shredded waste constitutes the combustible fraction (alternative fuel), which is transported to the collection container by a paddle conveyor.

Option P1 assumes that the entire mass of plastic waste contained in the functional unit (115 kg) will be in the combustible fraction. The mass of the combustible fraction that can be separated from mixed municipal waste was determined using data (Szczepański et al, 2022): the average share of the fraction up to 80 mm in the total mass of mixed municipal waste in Poland is 34.2%, and

Table 2. Energy demand of fuels for municipal waste collection and transport

Fuel type	Fuel consumption	Density, kg/m^3	Lower calorific value[(1)], MJ/kg	Amount of energy delivered in fuel, MJ/year	Fuel delivered energy per functional unit, MJ/Mg
CNG natural gas	134016.250 m^3/year	0.79	45.1	4774865	95.4
Diesel	646.244 m^3/year	832.0	43.1	23173800	463.0
Propane-butane gas	16.929 Mg/year	550.0	46.0	778734	15.6

Note: [(1)] Hass et al. (2014), based on ESG Report (2021).

of the fraction above 80 mm – 65.8%, the average share of glass in the mass of mixed municipal waste accepted at the mechanical processing facility is 9.7% (of which the mass of glass packaging accounts for 99%), and metals – 2.2% (of which the mass of packaging accounts for 90.9%). On the basis of these data, it was calculated that the mechanical treatment of mixed municipal waste contained in the functional unit could produce almost 480 kg of waste for incineration. This value was obtained by subtracting the weight of glass and metal packaging from the weight of the fraction above 80 mm in the functional unit and assuming a separation efficiency of 100% for glass and metal packaging.

The total electricity consumption to operate the equipment used was calculated by adding up the energy consumption of each piece of equipment included in the waste treatment facility. The result of the calculation is 10 kWh/Mg of waste entering the facility. The electricity consumption of each piece of equipment was calculated in two stages. In the first step, the electrical energy demand of the equipment per unit mass was calculated (based on the motor power and throughput of the equipment), then the result obtained was multiplied by the mass of waste entering the equipment. Pressley et al. (2015) reported an electricity consumption for sorting municipal waste amounting to 4.7–7.8 kWh/Mg of waste entering the process, depending on the composition of the waste and the sorting technology used.

Waste incineration

The energy resource in the waste to be incinerated was calculated from the formula:

$$E = E_{PW} + E_{MW} \quad (1)$$

where: E – energy resources in waste, E_{PW} – energy resources in plastic packaging, E_{MW} – energy resources in mixed municipal waste.

If the calorific value of mixed municipal waste is assumed to be 12 MJ/kg (Woelders et al., 2011) and that of plastics 40 MJ/kg (Astrup et al., 2009; Klimek, 2013), the amount of chemical energy in the waste to be incinerated will be 10360 MJ per functional unit. The value of the energy efficiency factor of a waste incineration plant operating in cogeneration mode in Vienna (Spittelau) reaches 0.78 (Cyranka et al., 2016; Wood et al., 2013), in Krakow 0.873, in Białystok 0.813 (Jędrzejowski et al., 2018). This factor is expressed by the formula (Waste Act, 2023; Reimann, 2006):

$$C = \frac{[E_p - (E_f + E_i)]}{[0.97(E_w + E_f)]} \quad (2)$$

where: C – energy efficiency factor of the waste incineration plant, E_p – total amount of heat and electricity produced annually from waste, calculated from the formula:

$$E_p = 1.1\,E_c + 2.6\,E_e \quad (3)$$

where: E_c, E_e – the amount of heat and electricity, respectively, produced per year at the waste incineration plant, E_f – the amount of fuel energy introduced per year into the incineration plant to produce steam, E_w – the amount of energy supplied per year with waste, E_i – the amount of energy, in addition to E_f and E_w, introduced per year into the incineration plant, 0.97 – a coefficient informing about energy losses caused by ash and radiation.

The energy efficiency coefficient of municipal waste incineration plants is also expressed in terms of the amount of energy removed from 1 Mg of thermally treated waste. Thus defined, the coefficient reaches a value of 3.415–7.163 GJ/Mg in Polish incineration plants operating in cogeneration mode (Waszczyłko-Miłkowska et al., 2021).

In this study, the energy efficiency coefficient of municipal waste incineration plants was assumed to be 0.70, expressed by the quotient of the amount of energy generated and the amount of energy delivered with the waste (the energy efficiency of electricity generation is 0.18 and that of heat generation is 0.52). Using this value of the coefficient, it was calculated that in the energy recovery process of the municipal waste under consideration, the amount of energy generated could be 7252 MJ/functional unit (1864.8 MJ of electricity and 5387.2 MJ of heat).

Waste incineration produces gases and secondary waste, including non-volatile ash, fly ash, ferrous scrap and waste from gas cleaning processes. According to studies (Brunner et al., 2004; Ramola, 2014), the average mass balance of the residues from the incineration of mixed municipal waste (without pre-sorting and treatment) is: gases – 70%, non-volatile ash – 25%, ferrous scrap – 3%, other components 2% (these are the proportions assumed in this article). Cyranka et al. (2016) report that the solid residues from the incineration of municipal waste in grate-fired furnaces account for 15 to 25% of the mass of incinerated waste. The results of a study (Krakow Municipal Holding) indicate that the mass of waste after the municipal waste incineration process (slag and bottom ash, boiler dust, fly ash, waste from flue gas cleaning processes) amounts to about 25% of the mass of waste entering the incineration plant.

Waste treatment – option two

In the second variant (P2) of waste management, it is assumed that the plastic packaging waste collected selectively will be processed in the material recycling process. Its purpose is to produce and use regranulated polymers to manufacture new plastic products. In option P2, five stages were considered: collection and transport of waste to the treatment facility, mechanical processing of mixed municipal waste, sorting and shredding of plastic packaging waste, production of polymer regranulate and incineration of the combustible fraction separated from the waste. It was assumed that all waste treatment stages would take place in one facility. In variant P2, the municipal waste stream was modeled as in variant P1. The functional unit was left unchanged.

Waste collection and transport

The energy demand for collection of municipal waste from properties and for transport to the treatment site was set in the same way as in variant P1 – at 574 MJ/Mg.

Mechanical treatment of mixed waste

Mixed municipal waste will first be sorted to separate the fraction above 80 mm. Glass and metal packaging will then be separated from this fraction. The residue will be shredded for incineration with energy recovery. On the basis of the assumptions (as in option P1) for the mechanical treatment of mixed municipal waste, it has been calculated that the following quantities of waste (per functional unit) will be separated as a result of this process: 480 kg combustible fraction, 17.7 kg metal packaging, 85 kg glass packaging and 302.67 kg fraction up to 80 mm. Electricity consumption for the mechanical treatment of mixed municipal waste was assumed to be 10 kWh per 1 Mg of waste (as in option P1).

Sorting and shredding of plastic waste

The composition of municipal plastic waste varies and depends on where the waste is generated and the waste collection system used (Table 3).

The study assumed that the sorting process will separate plastic packaging waste into film and hard plastics. Hard plastics will then be sorted by polymer type into four fractions: PET, PE, PP and PS. The separated fractions will be processed into regranulate in a material recycling process. Non-packaging and packaging plastics that are waste generated from sorting and processing into regranulate will be sent for incineration in a waste incineration plant after shredding. On the basis of the data in Table 3, it was determined that the following waste fractions can be separated from the 115 kg/functional unit plastic waste as a result of sorting with an efficiency of 60%: 31.4 kg PET, 19 kg PE (film), 4.4 kg PEHD (rigid packaging), 9 kg total fine PP, PS and PE packaging (weight of each fraction: 3 kg) and 51.2 kg residue from the sorting process.

The considerations take into account that plastic waste will be sorted manually and by an

Table 3. Composition of selectively collected municipal plastic packaging waste in Poland

Waste type		Share, % by weight
PET packaging	Colorless	17.3
	Blue	16.8
	Green	3.9
	Mixed	7.5
PE-HD rigid packaging		6.4
PE-HD, PE-LD film		27.5
PP, PS, PE small packaging		13.1
Other (non-packaging)		7.5
Total		100.0

Note: Jędrczak et al. (2021).

automatic method using separators, including optical and ballistic separators. In order to separate the different types of polymers using optical separators, a sequence of such separators is needed.

Liljenstrom et al. (2015) report that the electricity requirement for several stages of manual sorting of plastic waste is 44.44 kWh/Mg of sorted plastics. According to Ren (2012), the electricity consumption for optical sorting reaches 37.33 kWh/Mg of sorted plastics, and according to Swerec AB (2010): 43.9 kWh/Mg. As suggested by Bergsma et al. (2011), the electricity contribution to sorting plastic waste is 44.44–61.11 kWh per Mg of sorted waste. The literature also presents the results of studies of electricity consumption in relation to the amount of plastic waste entering the optical sorting process, with Shonfield (2008) indicating 51 kWh/Mg and Rhine (2012) indicating 26.64 kWh/Mg. This study assumed that the electricity demand for the sorting process is 43.88 kWh/Mg of waste entering the sorting process (the middle value of the set of study results cited above).

A study by Liljenstrom et al. (2015) indicated that the electricity demand in processes for shredding plastic waste to a particle size of less than 80 mm reaches a value of 16–32 kWh/Mg. According to a study by Swerec AB (2010), it is 40.5 kWh/Mg. For further considerations, a value of 28.25 kWh/Mg (middle value of the number range 16–40.5 kWh/Mg) was assumed. The total electricity requirement for the sorting and shredding of plastic waste will be 72.13 kWh/Mg of waste entering the process (259.67 MJ/Mg). This will equate to 29.86 MJ per functional unit (the mass of plastics in that unit).

Conversion to regranulate

This process consists of several steps, including washing, drying, extruding the polymers into pellet form. The results of a study (Rhine, 2012) indicate that the electricity demand for the washing process of plastic waste is 0.5 kWh/Mg and the heat consumption for heating the washing water: 3027.8 kWh/Mg. In contrast, the electricity consumption for extrusion and pellet molding is 270 kWh/Mg of plastic waste. For further considerations, the electricity input for washing and extrusion of plastic waste combined was assumed to be 270.5 kWh/Mg of plastic waste (974 MJ/Mg). In relation to the functional unit (mass of plastics granulated), this will be a value of almost 62.2 MJ.

Incineration of waste with energy recovery

The chemical energy contained in the waste to be incinerated was calculated from the formula:

$$E = E_1 + E_2 + E_3 \tag{4}$$

where: E – total chemical energy contained in the waste, E_1 – chemical energy contained in mixed municipal waste, E_2 – chemical energy contained in plastic waste not suitable for granulation, E_3 – chemical energy contained in polymer waste from the granulation process.

The values of E_1, E_2 and E_3 are 5760 MJ, 2048 MJ and 1024 MJ per functional unit, respectively. E_1 was calculated by multiplying the mass of the combustible fraction separated from mixed municipal waste of 480 kg by its calorific value of 12 MJ/kg (Cimpan et al., 2013; Woelders et al., 2011). The E_2 value is the result of multiplying the mass of residues from the mechanical processing of plastics of 51.2 kg by the calorific value of plastics of 40 MJ/kg (Astrup et al., 2009; Klimek, 2013). The E_3 value was calculated by multiplying the mass of the residue from the granulation process equal to 25.6 kg by the calorific value of plastics of 40 MJ/kg. The mass of the residue was determined by assuming, according to the literature (Shonfield, 2008), that the granulation process produces a waste equal to 40% of the waste entering the process. The amount of electricity and heat that will be generated from the combustible waste was calculated: 1590 MJ of electricity and 4592.6 MJ of heat. The calculations took into account an energy efficiency of electricity and heat generation of 0.18 and 0.52, respectively.

RESULTS

The mass balance and the amount of energy supplied and produced for the options analyzed are shown in Figures 2 and 3. In order to compare the variants, the equal results (benefits) method was applied (Vandermeersch et al., 2014). This method involves expanding the options in a way that ensures that equal benefits are obtained for them.

The expansion of variant P1 consisted of adding the energy requirement for the production of plastic pellets from virgin raw materials. In variant P2, the electricity and heat generated

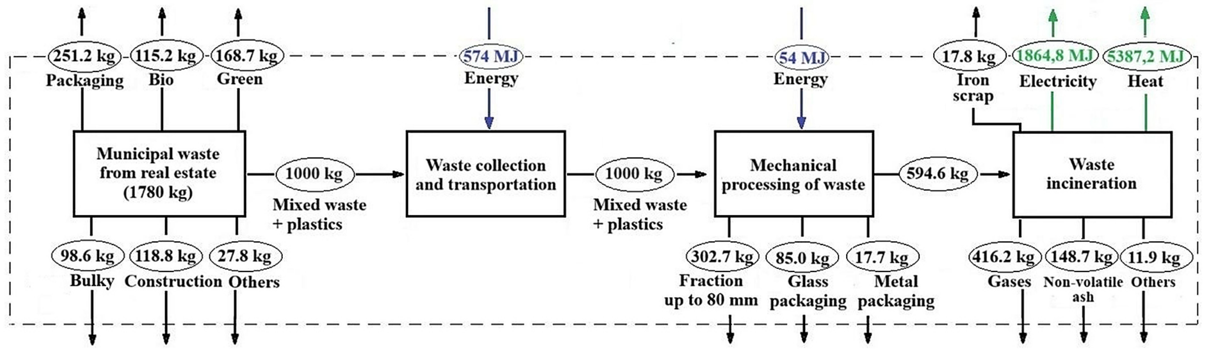

Figure 2. Waste streams and amount of energy input and output for variant P1

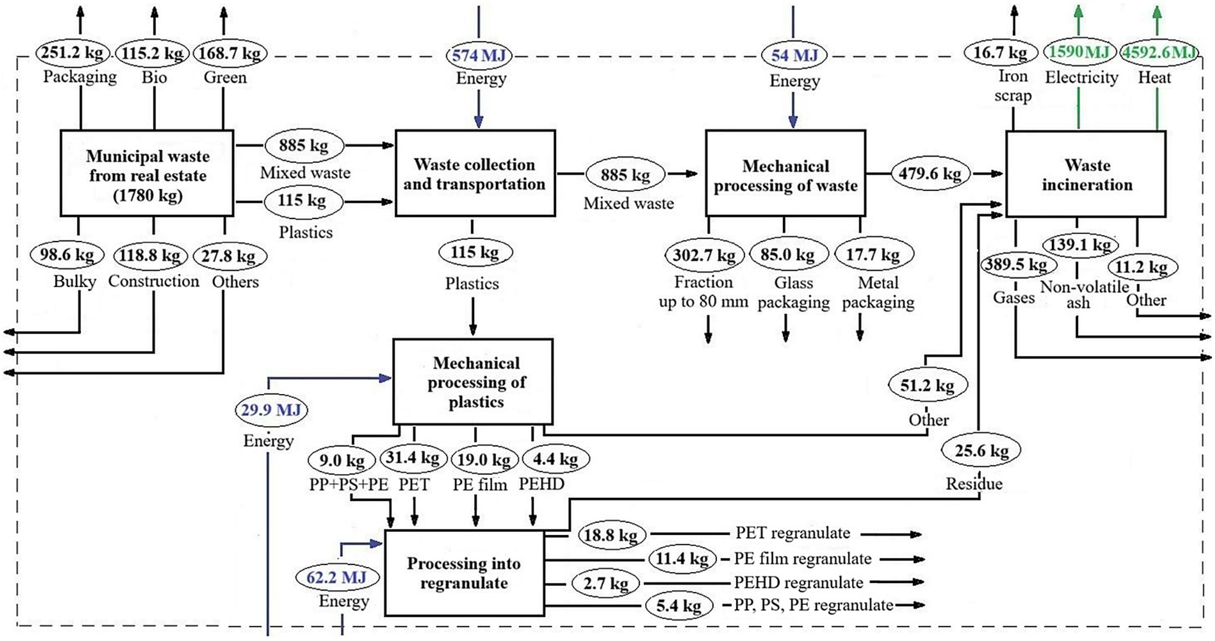

Figure 3. Waste streams and amount of energy input and output for variant P2

from the combustion of fossil fuels were added to give the resulting energy and heat values in variant P2 as in variant P1. Figure 4 indicates, using dashed lines with an arrow, the input data needed to align the results for the two variants.

The cumulative exergy demand ratio (CExD) (Bosch et al. 2007, Burchart-Korol 2017), denoting the sum of the exergy of the natural resources consumed in the waste management process, was used as a criterion for comparing the two variants. For the extended variant P1, this indicator was calculated as the sum of the exergy demand in the individual waste treatment steps and in the production of primary plastic pellets, and for the extended variant P2 as the sum of the exergy demand in the waste treatment steps and in the production of additional electricity and heat.

Exergy of energy carriers in the European energy mix

The study considered that electricity would be sourced from the European energy mix (Table 4).

Renewable energy carriers were considered as energy resources with free access. They were assumed to have zero exergy value. This had the effect of excluding from consideration the exergy requirement to generate electricity from renewable energy resources. The exergy of non-renewable energy carriers was calculated using the value of the exergy quotient and the lower heating value of these carriers (Table 5).

Table 6 shows the results of the exergy demand calculations of the energy carriers that make up the European energy mix. In addition, Table 6 shows the fossil fuel-to-electricity

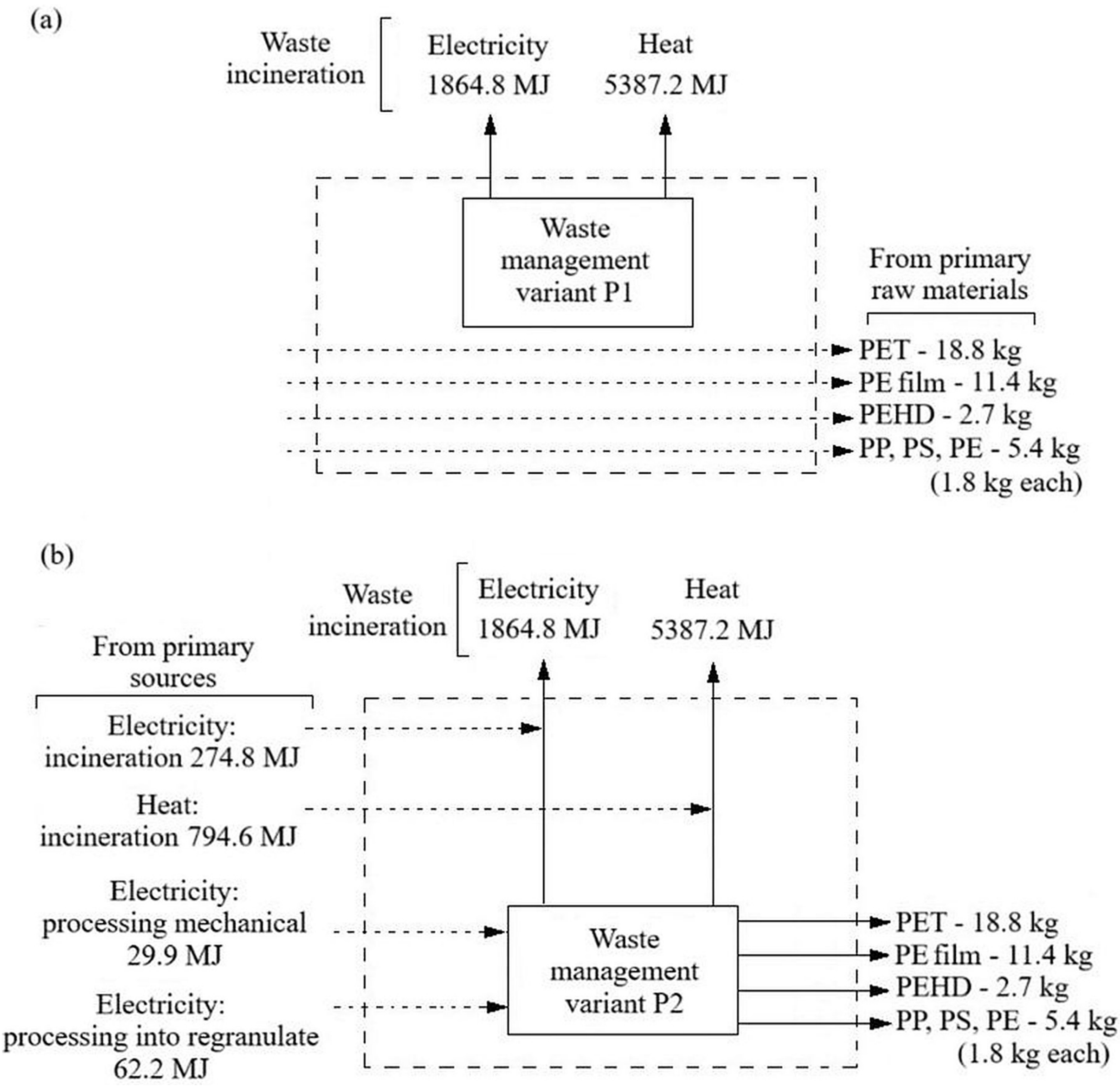

Figure 4. Variants P1 (a) and P2 (b) expanded to apply the equal benefit method

Table 4. Structure of electricity generation in 2022 in Europe

Energy type	Share, %
Renewable energy	34.94
Of which wind energy	11.08
Hydro power	14.56
Solar energy	4.99
Biomass energy	4.31
Other	0.30
Fossil fuels	44.24
Of which natural gas	26.23
Coal	15.15
Oil	2.86
Nuclear energy	20.53

Note: Energy Institute (2024).

conversion efficiency values used to calculate the exergy of these fuels. The exergy of nuclear energy is equal to this energy. The heat-to-electricity conversion efficiency of a nuclear power plant was assumed to be 33%. The calculation of the exergy of fuels of the European energy mix does not take into account the exergy inputs for fuel extraction and purification.

Exergy of fuels for waste collection and transport

In this study, the fuel exergy requirement for collection and transport of 1 Mg of waste has a value of 611.32 MJ. This value was calculated using the data in Table 2 and an exergy/LHV ratio value (Table 5) of 1.04 for natural gas, and 1.07 for diesel and propane-butane gas.

Exergy consumed in the production of primary polymers

The amount of primary energy and exergy required to produce 1 kg of primary polymers is shown in Table 7. Primary energy includes the energy contained in the hydrocarbon fractions that build the polymer molecules and the energy of the energy carriers used to generate electricity and heat for the polymer production process. The exergy inputs required to produce polymers were determined by assuming that crude oil is the raw material for polymer production and the energy carrier.

Table 5. The quotient of exergy and lower heating value of fuels (LHV) (Szargut, 2005) and LHV values for fuels (Boundy et al., 2010)

Fuel type	Exergy/LHV	LHV, MJ/kg
Hard coal	1.09	26.0
Lignite	1.17	22.7
Natural gas	1.04	47.1
Liquid hydrocarbon fuels	1.07	-
Crude oil	1.07	42.69
Typical diesel	1.07	42.79
Typical petrol	1.07	43.45

Exergy inputs for waste management

Table 8 shows the results of the cumulative exergy demand calculations for Option P1 and Table 9 for Option P2. The symbols α_1, α_2, α_3, α_4 denote the substitution factors for PE, PP, PS,

Table 6. Exergy of the energy carriers making up the European energy mix

European energy mix 2022	Carrier energy, MJ/1 MJ electricity	Efficiency	Primary energy, MJ/1 MJ electricity	Exergy, MJ/1 MJ electricity
Total renewables	0.349	-	-	-
Natural gas	0.262	0.5	0.524	0.545
Coal	0.152	0.35	0.434	0.473[(1)]
Oil	0.029	0.35	0.083	0.089
Nuclear	0.205	0.33	0.621	0.621
Total			1.662	1.728

Note: [(1)] exergy/LHV ratio for hard coal.

Table 7. Primary energy (Marczak, 2022) and exergy inputs to produce 1 kg of primary polymers

Polymer	Primary energy input, MJ/kg	Exergy input, MJ/kg
Polyethylene (PE)	70.0	74.9
Polypropylene (PP)	73.0	78.1
Polystyrene (PS)	80.0	85.6
Polyethylene terephthalate (PET)	71.2	76.2

Table 8. Cumulative exergy demand in the expanded P1 waste management option

Specification	Unit exergy demand		Input		Exergy demand, MJ
	Value	Unit	Value	Unit	
Collection and transport of waste of which natural gas diesel fuel propane-butane gas	611.32 95.4 463.0 15.6	MJ/Mg	1.0	Mg	611.32
Mechanical treatment of waste (electricity)	1.728	MJ/MJ	54.0	MJ	93.31
Primary PE	74.9	MJ/kg	$15.8 \cdot \alpha_1$	kg	$1183.42 \cdot \alpha_1$
Primary PP	78.1		$1.8 \cdot \alpha_2$		$140.58 \cdot \alpha_2$
SP primary	85.6		$1.8 \cdot \alpha_3$		$154.08 \cdot \alpha_3$
PET primary	76.2		$18.8 \cdot \alpha_4$		$1432.56 \cdot \alpha_4$
Total					$704.63 + 2910.64 \cdot \alpha$

Table 9. Cumulative exergy demand for the expanded P2 waste management option

Specification	Unit exergy demand		Input		Exergy demand, MJ
	Value	Unit	Value	Unit	
Collection and transport of waste of which natural gas diesel fuel propane-butane gas	611.32 95.4 463.0 15.6	MJ/Mg	1.0	Mg	611.32
Sorting and shredding of mixed waste (electricity)	1.728	MJ/MJ electrical energy	54.0	MJ	93.31
Sorting and shredding of waste plastics (electricity)			29.86		51.60
Granulation (electricity)			62.2		107.48
Combustion (electricity added)			386.0		667.00
Combustion (heat added)			1115.0		1926.72
Total					3457.43

PET, respectively. The substitution factor is used to determine the mass of virgin polymer that can be substituted by one kilogram of polymer regranulate. A simplification has been introduced:

$$\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha \quad (5)$$

The exergy of heat was assumed to be equal to the exergy of electricity. After comparing the exergy demand for variants P1 and P2, a substitution factor value of 0.95 was obtained. The waste management options considered differ in the energy input and the effects achieved. In particular, waste management as in option one results in higher amounts of electricity and heat compared to option two. Only in variant two is the resultant product plastic regranulate.

The values of the substitution coefficient α are in the range from 0 to 1. When the value of the coefficient is 0, it means that regranulate cannot replace primary plastics, and equal to 1, it can. The value of the coefficient α depends significantly on the quality of the regranulate.

The substitution coefficient α calculated in this study is 0.95. This result indicates that variant two of plastics waste management will be more favorable in terms of exergy consumption if the produced regranulate from waste has a substitution coefficient $\alpha > 0.95$. If the produced regranulate has a substitution coefficient $\alpha < 0.95$, then variant one will be better in terms of exergy consumption.

Both waste management variants will be equally beneficial in terms of exergy when $\alpha = 0.95$. This value means that one kilogram of produced polymer regranulate will be able to replace 0.95 kg of virgin polymer. At the same time, this value indicates that the regranulate produced from the waste should be of high quality.

CONCLUSIONS

Two options for the management of municipal plastic waste, selectively collected, were analyzed. Variant one considered combustion of this waste together with mixed municipal waste to produce heat and electricity. Variant two considered the processing of plastic waste to produce regranulate for use as a substitute for virgin plastic granulate. The quality of the regranulate depends on the value of the substitution coefficient, which can take values from 0 to 1. The higher the value of this coefficient, the higher the quality of the regranulate. A substitution coefficient of 1 means that regranulate replaces virgin granulate in a 1:1 ratio in the production of a new product.

The analysis of both options, expanded according to the equal benefit basket approach, shows that significant amounts of exergy are needed in option one. The reason for this is the high exergy intensity of plastics production from virgin raw materials. Considering the results of the exergetic assessment of both variants, it can be concluded that for substitution coefficient above 0.95 the second variant involving material recycling of plastic waste is more favorable. For substitution coefficient below 0.95, option one would be a better choice. The results of the described study can be helpful in making an informed decision regarding the choice of the exergetically optimal waste management method.

Only mixed plastic waste collected separately was tested. It would be advisable to extend the scope of the study to include the plastic waste occurring in the mixed municipal waste stream. It should be borne in mind that sorting and cleaning this waste will be more difficult due to its high degree of contamination. Changes in the energy mix, upgrading of waste treatment machinery and technology, and changes in the quantity and purity of waste will affect the results of the study. It may be necessary to repeat the study taking into account the resulting changes. An important addition to the study would be a sensitivity analysis, which would give an idea of the impact of changing various factors on the results of the evaluation of waste management options in terms of exergy consumption.

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