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Energy efficiency of waste gasification plants in the national municipal waste management system

Arkadiusz Primus[1]*, Dagmara Buntner[1], Czesława Rosik-Dulewska[2], Tadeusz Chmielniak[3]

[1]INVESTEKO S.A., Świętochłowice, Poland
[2]Institute of Environmental Engineering of the Polish Academy of Sciences in Zabrze, Poland
[3]Silesian University of Technology, Gliwice, Poland

* Corresponding author's e-mail: arkadiusz.primus@investeko.pl

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Abstract: To achieve high levels of municipal waste recovery through a system employing mechanical-biological waste processing technologies, effective management of the over-sieve fraction of mixed municipal waste (preRDF) is crucial. This preRDF cannot be landfilled due to its combustion heat exceeding 6 MJ/kg. Therefore, thermal treatment of waste and subsequent energy recovery become pivotal in the national waste management system, particularly amidst energy crises and fluctuating energy prices. Waste-derived energy can serve as a valuable renewable energy source. To ascertain the true efficiency of the plant in terms of energy, environmental impact, and economics, it is vital to organize the concepts of energy efficiency for thermal waste treatment plants. The energy efficiency of a waste gasification plant should be comprehensively assessed from three standpoints: energy efficiency of thermal waste treatment (i.e., energy efficiency index), energy efficiency of recovering chemical energy contained in waste (actual energy efficiency of the plant), and the efficiency of renewable energy production. A thermal waste processing plant qualifies as a renewable energy source, when it generates electricity and heat from the biodegradable fraction of waste. This article endeavours to determine the potential contribution of chemical energy from the biodegradable waste fraction, relying on preRDF fraction test results.

Introduction

The national municipal waste management system has been operational for over a decade, based on systemic solutions centered around Municipal Plants (formerly Regional Municipal Waste Treatment Plants). These plants include waste sorting facilities where valuable waste fractions are separated for further processing, as stipulated in(Article 35(6) of the Act of December 14, 2012, on Waste (hereinafter referred to as 'the Waste Act'). The primary aim of this system is to minimize the volume of designated for disposal through landfilling, the least environmentally favorable method of waste treatment.

The development of selective collection of secondary raw materials, supported by additional legal and economic mechanisms, is becoming a significant aspect of the municipal waste management system. This is particularly evident when combined with the processing of mixed municipal waste in Municipal Waste Treatment Plants (MWTP) (Ciechelska 2016). Such an approach also represents a step toward achieving a circular economy (Smol et al. 2019).

Achieving a high level of municipal waste recovery within the implemented system, which relies on mechanical-biological waste processing technologies, still depends significantly on the effective management of the over-sieve fraction of mixed municipal waste (preRDF). This fraction, generated after separating materials intended for recovery (recycling), has a combustion heat value exceeding 6 MJ/kg. As a result, preRDF does not qualify for landfilling under the regulation of the Minister of Economy dated July 16, 2015, concerning the acceptance of waste for landfilling. Consequently, the thermal transformation of waste and its energy recovery have become essential and indisputable components of the national waste management system.

In Poland, around 30-40% of RDF is combusted in existing thermal waste treatment plants, while approximately 1 million tones are used as a co-fuel in the cement industry. However, the capacity of these facilities is limited, and in the case of cement industry, RDF must meet specific quality criteria, such as calorific value and restricted limited chlorine content (Rajca et al. 2022).

Recently, energy recovery from waste has gained prominence due to its potential to produce economically viable electrical and thermal energy, particularly in the context of energy crises and price instability. Furthermore, energy from waste serves as an effective source of renewable energy, providing a compelling argument for its broader adoption (Wasielewski et al. 2018). According to EU source materials, energy from waste is or has the potential to become the third-largest energy carrier.

The construction of thermal waste processing plants involves significant investment costs, and any decision to undertake such a task must be preceded by thorough technical analyses, including the selection of optimal technology tailored to the prevailing economic conditions.

In this context, the financial efficiency of the project becomes a key factor, heavily influenced by the generation and sale of energy from waste. As a result, the choice of technology and the efficiency of energy recovery from waste are critical to the success of such investments (Famielec et al. 2016).

Gasification technology, as an alternative to traditional incineration, stands out for its potential to enhance electricity generation efficiency compared to combustion methods using grate furnaces and turbines for power production (Primus et al. 2021).

Given its ability to enhance electricity generation efficiency and its favorable cost dynamics in the market, waste gasification technology emerges as an economically advantageous alternative to conventional methods.

The aim of the research presented in this article is to determine the achievable share of renewable energy in the production of usable energy from gasification of municipal waste preRDF.

Materials and Methods

Determination of biodegradable fraction content

This article attempts to determine the potential share of chemical energy derived from the biodegradable fraction of waste. The analysis is based on the tests conducted on 18 samples of over-sieve waste fraction (preRDF) from mixed municipal waste. These tests were conducted in selected waste sorting plants during two campaigns: 12 samples in 2014 and 6 samples in 2023.

Methodology based on the Minister of Environment's Regulation of June 8, 2016 from waste thermal conversion

The biodegradable fraction content was determined using a selective dissolution method with sulfuric acid. This procedure follows the methodology outlined in Norm EN 15440:2011 and Annex 1 of the Minister of Environment's Regulation of June 8, 2016, which specifies the technical criteria for qualifying a portion of the energy recovered from waste thermal conversion.

Methodology based on the National Waste Management Plan 2022

Norm PN-EN 15440:2011 (*Solid recovered fuels - Method of the determination of biomass content),* concerning the determination of biodegradable fraction content, allows for a manual sorting method (Regulation of the Minister of Development of 21 January 2016). This approach involves manually extracting fractions with biomass characteristics and calculating their mass fraction relative to the entire waste sample.

In accordance with this standard and the guidelines of the National Waste Management Plan 2022 (Resolution 2016), the biodegradable fraction of municipal waste includes:

1. Paper and cardboard;
2. Clothing and textiles made from natural materials (50%);
3. Waste from green areas;
4. Kitchen and garden waste;
5. Wood (50%);
6. Mixed-material waste (40%);
7. Fine fraction < 10 mm (30%).

The biodegradable fraction content in the examined pre-RDF samples was calculated based on the mass and percentage share of the above-mentioned material fractions.

Results

This section may be divided into subheadings to ensure clarity. It should present a concise and precise description of the experimental results, their interpretation, as well as the conclusions that can be drawn from the experiments.

Energy efficiency of waste gasification plant

In the context of the national waste management system, the energy efficiency of a model waste gasification plant designed for preRDF fraction of municipal waste has been analyzed. The model plant consists of fuel preparation, gasification, and syngas purification units, integrated with a power generation unit utilizing a piston engine. The plant's dedicated fuel includes the over-sieve fraction obtained from the MWTP facility (preRDF classified under code 19 12 12 – other wastes, including mixtures of materials, from mechanical treatment of wastes other than those mentioned in 19 12 11) and municipal sewage sludge (Primus and Rosik-Dulewska 2018). The gasification plant has a processing capacity of 15,000 tons per year, with the calorific value of the waste stream (over-sieve fraction + sewage sludge) estimated at 14 MJ/kg.

The energy efficiency of waste gasification plants should be evaluated comprehensively in three dimensions:

1. Energy efficiency of thermal waste treatment,
2. Energy efficiency of recovering the chemical energy contained in waste, and
3. Efficiency of renewable energy production.

Each of these aspects reflects distinct definitions and legal regulations, allowing for proper legal classification and valuation of thermal waste treatment plants in terms of energy recovery.

Systematizing these energy efficiency concepts is essential for accurately assessing a plant's performance from energy, environmental, and economic perspectives.

Energy efficiency of thermal waste treatment

A significant parameter characterizing a thermal waste treatment plant that produces electricity and heat in cogeneration is the energy efficiency calculated according to the guidelines in Appendix 1 of the Waste Act, using the following formula:

$$Energy\ efficiency = \frac{E_p - (E_f + E_i)}{0{,}97 \times (E_w + E_f)} \tag{1}$$

where:

E_p – is the annual energy produced as thermal or electrical energy, expressed as the sum of 2.6 x the quantity of electrical energy and 1.1 x the quantity of heat energy generated for commercial use (GJ/a),

E_f – is the annual energy input from fuels used in steam generation (GJ/a),

E_w – is the annual energy content of the processed waste, calculated based on the waste's calorific value (GJ/a),

E_i – is the annual energy introduced from external sources, excluding E_w and E_f (GJ/a),

0.97 – is a coefficient accounting for energy losses due to bottom ash and radiation.

It should be noted that the parameter defined in this manner is often mistakenly interpreted as the energy efficiency value of a thermal waste treatment plant. In reality, it serves as informative and indicative purpose, given the assumptions made regarding specific rewards for energy transformations into heat and electricity production (Wielgosiński 2020). Therefore, adopting appropriate nomenclature is crucial. This parameter should be referred to as an indicator of energy efficiency in thermal waste treatment. Its primary objective is to classify thermal waste treatment plants according to waste treatment methods as either recovery processes (R-method catalogue) or disposal processes (D-method catalogue). Based on this classification, thermal waste treatment plants can be designated as either waste recovery method R1 or disposal method D10.

The criterion for classifying and qualifying thermal waste treatment methods is based on an indicator value set at 0.65. Plants with an indicator value equal to or greater than 0.65 are classified under the recovery process (R-method), while values lower than that are designated under the disposal process (D-method).

For the analyzed model waste gasification plant, integrated with a power generation unit utilizing a piston engine, the energy efficiency indicator value has been determined and is presented in the Table 1. The parameters used for the gasification process model were derived from experience gained during the construction and testing of a gasification installation for municipal waste under the project Lifecogeneration.pl (Primus and Rosik-Dulewska 2018).

The high energy efficiency indicator determined for the model waste gasification plant clearly qualifies it for the recovery process under the R1 method. Compared to the criterion value of 0.65, the gasification plant performs significantly better than waste incineration plants using steam

Table 1. Energy efficiency Indicator of the waste gasification plant (for the calorific value of the over-sieve fraction at 14 MJ/kg)

No.	**Parameter name**	**Symbol**	**Unit**	**Value**
	Assumptions for calculations			
1	Operating time per year	T	h/a	7 500
2	Annual burner operating time	T_{gas}	h/a	288
3	Mass efficiency of the plant	Q_n	Mg/a	15 000
4	Calorific value of the over-sieve fraction	W	MJ/kg	14
5	Maximum gas consumption	Q_{gas}	Nm3/h	200
6	Calorific value of the gas	W_{gas}	MJ/Nm3	40
7	Installed capacity/power	$E_{el\ inst.}$	kW	1000
8	Maximum electricity consumption	-	MWh/a	4500
		-	GJ/a	16 200
	Calculation parameters			
10	Produced electrical energy	E_{el}	MWh/a	13 500
			GJ/a	48 600
11	Produced thermal energy	E_{term}	GJ/a	56 700
12	Amount of energy produced annually as thermal or electrical energy. It is calculated by multiplying the quantity of electrical energy by 2.6 and the quantity of heat energy produced for commercial purposes by 1.1	E_p	GJ/a	18 8730
13	Amount of energy introduced annually into the system, derived from the combustion of fuels involved in steam generation	E_f	GJ/a	2 304
14	Amount of energy contained within the processed waste, calculated using the calorific value of the waste	E_w	GJ/a	21 0000
15	Amount of energy introduced from external sources, excluding E_w and E_f	E_i	GJ/a	16 200
The energy efficiency indicator of the thermal waste processing plant				0,83

Table 2. The energy balance for gasification of the over-sieve fraction with a calorific value of 14 MJ/kg

No.	Type of stream	Power MW		Stream characteristic
		Input Energy	Output Energy	
1	Feed (waste stream for gasification)	7,7		Chemical Energy
2	Air for gasification	- 0,4		Own Needs
3	Syngas cooling/purification/drying	- 0,8		Own Needs
4	Slag and ash	- 0,15		Loss
5	Losses to the environment	- 0,6		Loss
6	Syngas		4,8	Usable Energy
7	Thermal Oil (Stage II Cooler)		0,95	Usable Energy
Overall balance sum		5,75	5,75	

turbines for electricity production, which typically have relatively low energy conversion efficiency, especially in low-capacity systems. This favorable outcome is attributed to the emphasis on electricity production in these waste treatment plants. The gasification process, combined with the production of thermal and electrical energy in cogeneration, achieves a high cogeneration factor when using a piston engine. This efficiency surpasses that of steam turbines, resulting in notably high energy efficiency indicators.

It is important to highlight that the definition of the energy efficiency indicator was originally developed based on a model waste incineration plant, which assumed energy production in cogeneration primarily through steam turbines. Therefore, this definition incorporates a high conversion factor for produced electrical energy. In this context, this definition does not fully account for technologically distinct cogeneration systems, such as those based on piston engines. Nonetheless, the energy efficiency indicator value determined under the current legal regulations of the Waste Act underscores the attractiveness of the waste gasification plant. When compared to conventional waste incineration processes involving steam production and electricity generation in small steam turbines, the gasification plant demonstrates clear advantages.

Energy efficiency of chemical energy recovery

A thermal waste treatment plant should primarily be regarded as a source of useful energy production, with the chemical energy contained in waste serving as the primary fuel. In this context, such a facility should be defined as a cogeneration plant operating within a cogeneration system. Therefore, the energy efficiency of the plant should be defined as the efficiency of converting the chemical energy of the waste into useful forms of energy, specifically electrical and thermal energy. Hence, evaluating the energy efficiency of thermal waste processing requires an analysis through the lens of thermodynamic transformations and the system's final energy performance, evaluated in terms of its utility properties.

Energy efficiency, understood as the effectiveness of recovering chemical energy from the waste stream, is a key parameter in the economic assessment of a thermal waste treatment plant as an energy system. It plays a crucial role in investment decision-making, particularly for plants where waste, as a fuel, has a relatively high calorific value.

To assess the energy efficiency of cogeneration systems, multiple definitions of this parameter are used, each describing and characterizing specific aspects of these systems' operation. In case of a thermal waste treatment plant functioning as a cogeneration power plant, the following definitions are commonly applied to evaluate the efficiency of converting the chemical energy of the fuel:

- Overall efficiency,
- Efficiency of electrical energy generation,
- Efficiency of usable thermal energy production.

Additionally, a qualitative assessment of the cogeneration system's performance in producing electrical and thermal energy can be provided using the cogeneration indicator. This indicator is defined as the ratio of the electricity generated (E_{el}) in the cogeneration system (based on the heat carrier stream used for heat production) to the thermal power of the system Q (Skorek and Kalina 2005):

$$q = \frac{E_{el}}{Q} \quad (2)$$

The fundamental definitions characterizing the energy efficiency of a thermal waste treatment plant, when treated as a cogeneration plant, provide a general assessment of the conversion quality of the fuel's chemical energy into usable forms. Additionally, the cogeneration factor describes the relationship between electrical and thermal energy production in the cogeneration system, defining its utility characteristics for a waste gasification plant employing a piston engine as the cogeneration unit.

To evaluate the energy efficiency of a model waste gasification plant with a capacity of 15,000 Mg/year, operating in collaboration with a piston-engine-based cogeneration unit, energy streams were balanced. These streams account for the chemical energy produced into the gasification plant and the chemical energy extracted after syngas purification, which serves as the gas fuel for the cogeneration unit. The energy balance calculation results, based on an average lower heating value of the oversize fraction at 14 MJ/kg, are presented below in the diagram (Figure 1) and table (Table 2).

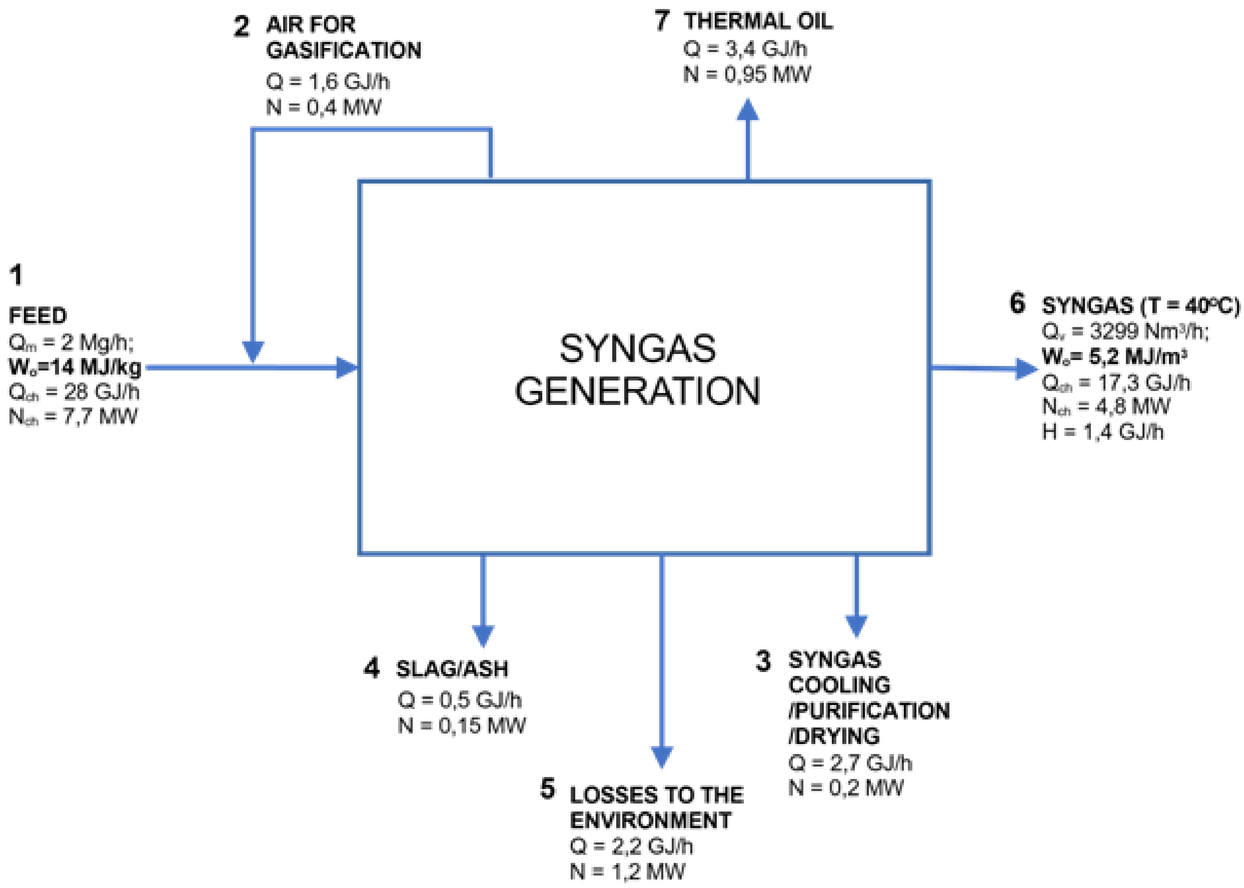

Figure 1. The energy balance of the waste gasification plant with a capacity of 15,000 tons/year for the calorific value of the over-sieve fraction at 14 MJ/kg

The basic operational parameters for energy production in the waste gasification plant and the cogeneration system, utilizing the Jenbacher JMS620GS-S.L piston engine, are presented in Table 3.

The energy efficiency and cogeneration factor, expressed through the efficiencies of useful energy generation in the model waste gasification plant and the cogeneration system based on the (Jenbacher JMS620GS-S.L) piston engine, are presented in Table 4. For the energy balance of the gasification plant integrated with the cogeneration system, an internal electrical energy demand of 0.6 MW was assumed. This value has been included in the calculations of energy efficiency and the cogeneration factor.

In the analyzed model plant, a notable feature of this waste-to-energy technology is its relatively high efficiency in generating electrical power, even with a relatively low waste processing capacity. This is a favorable outcome, especially when compared to thermal waste treatment plants based on combustion technology and steam production, which typically achieve efficiencies of 15-18% (Piecuch and Dąbrowski 2014).

However, there is an observable decrease in the overall efficiency of the system due to thermochemical transformation losses in the gasification process and additional thermal energy losses during syngas purification. Despite this, the cogeneration indicator highlights a high proportion of electricity production as a key energy product from waste processing. The energy efficiency values determined for the

Table 3. The energy generated from syngas - derived from gasification of the over-sieve fraction with a calorific value of 14 MJ/kg in the Jenbacher JMS620GS-S.L piston engine

No.	Parameter	Unit	Value
1	Chemical energy flux in syngas	MW	4,8
2	Electricity generation efficiency	%	37,4
3	Thermal power generation efficiency	%	44,1
4	Electrical power at generator terminals	MW	1,8
5	Thermal power available for utilization	MW	2,1

Table 4. The efficiency of useful energy generation and the cogeneration factor for the model waste gasification plant

No.	Parameter		Unit	Value
1	Efficiency of usable syngas generation		%	74,7
2	Efficiency of usable thermal energy generation		%	39,6
3	Electricity generation efficiency		%	23,4
4	Overall operational efficiency		%	55,2
5	The cogeneration factor	The gasification system with the engine	%	39,3
6		Engine	%	85,7

integrated gasification system with a small-scale piston engine could be suitable for locations where technical conditions limit the use of thermal energy. Therefore, a gasification plant could serve as a viable alternative to combustion-based thermal waste treatment plants.

Efficiency of renewable energy production

Biomass refers to organic plant or animal matter that can undergo biodegradation and is recognized as a renewable energy source. It is considered carbon neutral as it emits an equivalent amount of carbon dioxide during combustion as is absorbed during photosynthesis. The biodegradable fraction of waste is classified as 'biomass' under specific conditions.

According to the Renewable Energy Sources Act, a thermal waste treatment plant is considered a renewable energy source facility, where a portion of the generated electricity and heat comes from the conversion of the biodegradable fraction of waste. This portion of energy can be classified as energy from

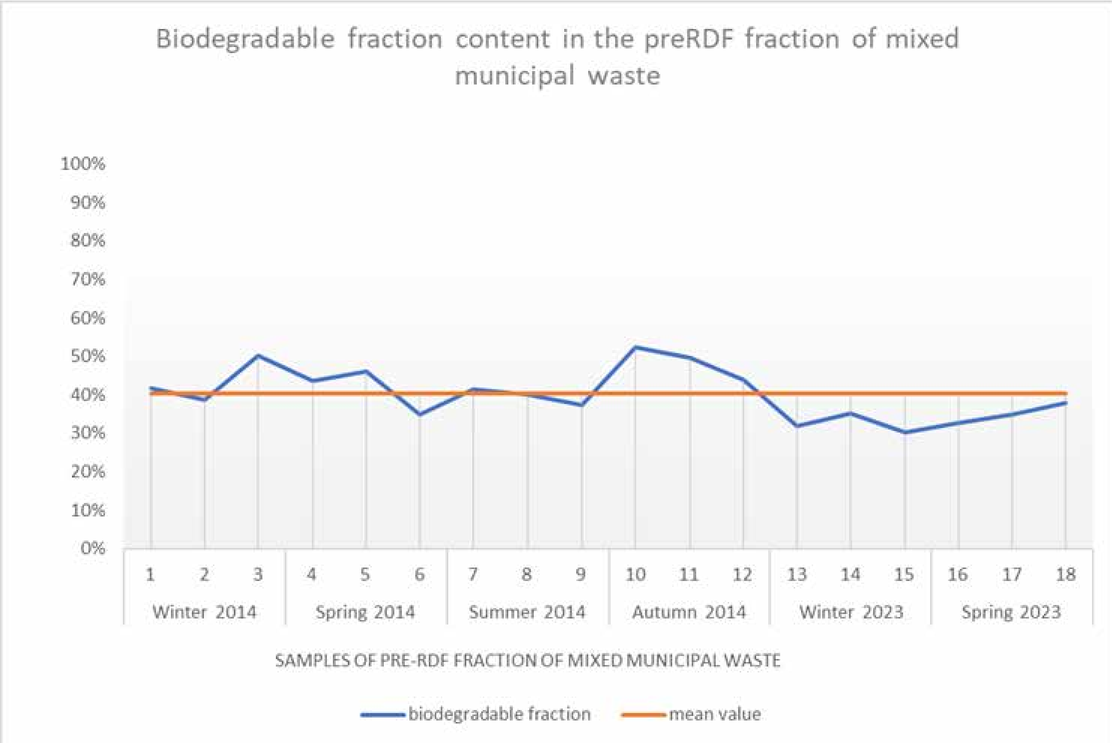

Figure 2. Biodegradable fraction content in the pre-RDF fraction of mixed municipal waste

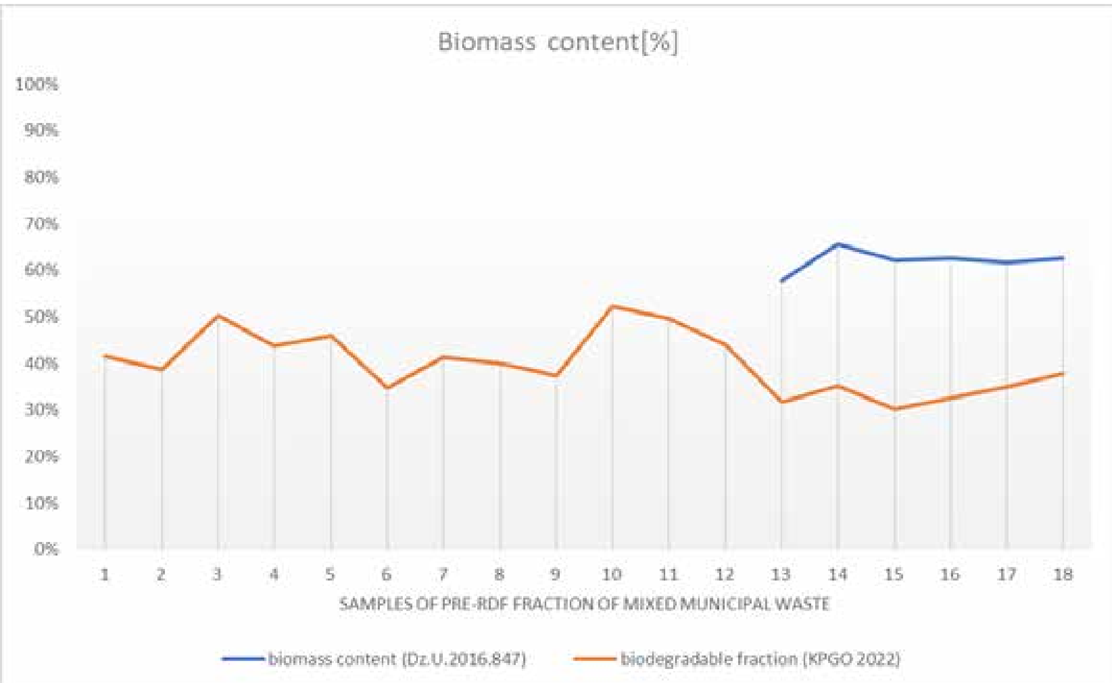

Figure 3. Biomass content calculated according to the Regulation Journal of Laws 2016, item 847 (blue) and based on the guidelines of the National Waste Management Plan 2022 (orange)

a renewable energy source, provided that technical conditions outlined in the Minister of Environment's Regulation of June 8, 2016, regarding the technical criteria for qualifying energy recovered from waste thermal conversion, are met.

The share of the biodegradable fraction (biomass content) in all examined waste samples (in blue) and the average value (in orange) are presented in Figure 2.

Based on the results from waste morphology, the average content of the biodegradable fraction, calculated using the method specified in the National Waste Management Plan 2022, was approximately 40%.

For the samples collected during the 2023 campaign, the biomass content was also determined using the methodology outlined in the aforementioned regulation. In all 6 examined samples, the biomass content measured by the dissolution method was significantly higher than that determined by the method involving manually extracting biomass fractions. The biomass content calculated using the dissolution method (represented in blue) and based on the guidelines of the National Waste Management Plan 2022 (represented in orange) is depicted in the chart below (Figure 3). The average biomass content in the examined samples, calculated using the dissolution method, was 62%.

According to the description in the EN 15440:2011 standard, the selective dissolution method may yield false results due to the presence of the following components in the preRDF sample:

- solid fossil fuels such as hard coal, coke, brown coal, lignite and peat;
- charcoal;
- biodegradable plastics of fossil origin;
- non-biodegradable plastics of biogenic origin;
- oil or fat present as a constituent of biomass;
- natural and/or synthetic rubber residues;
- wool;
- viscose;
- nylon, polyurethane, or other polymers containing molecular amino groups;
- silicon rubber.

If those components are present in amounts less than 10 % by weight (for natural and/or synthetic rubber residues) or 5 % by weight (for the other components), no assessment is necessary. However, if the aforementioned components are present in higher amounts, the selective dissolution method is not applicable, or an assessment must be made regarding the estimated influence of these components. These components are commonly found in the preRDF fraction of mixed municipal waste, which explains the differences between the results obtained using the KPGO 2022 method and the selective dissolution method (Figure 3).

According to the regulation, the average share of electricity or heat generated from RES is calculated based on the physicochemical properties of waste provided for thermal conversion. This assessment is conducted using the reference testing methods specified in Annex 1 of the regulation and depends on the types of fuels used in thermal waste treatment plant. The calculation follows the formula:

$$E_{RES} = \frac{\sum_{i=1}^{n} M_{fBOi} \times q_{fBOi} + \sum_{j=1}^{m} R_{Oj} \times M_{ORj} \times q_{ORj}}{\sum_{k=1}^{o} M_{Kk} \times q_{Kk} + \sum_{i=1}^{n} M_{Oi} \times q_{Oi} + \sum_{j=1}^{m} M_{ORj} \times q_{ORj}} \times E \tag{3}$$

E_{RES} - the amount of electricity or heat produced from renewable energy sources, in [MWh or GJ];

E - the total amount of electricity or heat generated in the thermal waste treatment plant, in [MWh or GJ];

M_{fBOi} - biomass content in thermally treated waste, for which the determination of biodegradable fractions by the aforementioned method has been adopted (calculated using biomass content determination according to the norm EN 15440:2011), in [Mg];

q_{fBOi} – calorific value (in operational condition) of thermally treated biomass fractions, for which the determination of biomass content was adopted (calculated using the biomass content determination according to the norm EN 15440:2011), in [MJ/Mg].

n - number of types of thermally treated waste for which the determination of the biomass content has been adopted;

R_{Oj} - flat-rate share (0-1) for thermally treated waste, for which a flat-rate share of chemical energy of biomass content has been adopted;

M_{ORj} - total mass of thermally treated waste, for which a flat-rate share of chemical energy of biomass content was assumed, in [Mg];

q_{ORj} - calorific value (in working condition) of thermally treated waste, for which a flat-rate share of chemical energy of biomass content was assumed, in [MJ/Mg];

m - number of types of thermally treated waste for which a flat-rate share of chemical energy of biomass content has been adopted;

(M_{Kk} - mass of fuels other than waste containing biodegradable fractions thermally converted in thermal waste processing plant, into [Mg];

q_{Kk} - calorific value (in working condition) of fuels other than waste containing biodegradable fractions thermally converted in the thermal waste treatment plant, in [MJ/Mg];

o - number of types of fuels other than waste containing biodegradable fractions thermally converted in the thermal waste processing plant);

M_{Oi} - total mass of waste for which the proportion of biodegradable fractions has been determined by the test method, in [Mg];

q_{Oj} - calorific value (in working condition) of wastes for which the share of biodegradable fractions has been determined by the test method, in [MJ/Mg].

Mass of biodegradable fractions:

$$M_{fBOi} = M_{Oi} \times Y_{BOi} \tag{4}$$

where:

Y_{BOi} - share of the biodegradable fraction determined on the basis of tests.

In a model waste gasification plant, the feedstock mass (M_N, [Mg]) consists of a mixture of the preRDF fraction (M_{Oi}, [Mg]) and sewage sludge (M_{ORj}, [Mg]) in a 80:20 ratio, with an average calorific value of 14 MJ/kg. For the calculations, the same proportion of preRDF and sewage sludge was used, but with the following assumptions: the average calorific value of the preRDF was taken as 17 MJ/kg, based on the earlier physicochemical tests, and the total moisture content of the sewage sludge was assumed to be approximately 72%, resulting in a calorific value of about 2 MJ/kg. These values were used to simulate the operational calorific value of the feedstock (Wielgosiński 2020).

The lump sum value of 0.42 specified in the regulation applies to non-segregated (mixed) municipal waste classified under code 20 03 01. However, the preRDF fraction derived from the MWTP is classified under code 19 12 12, for which no lump sum value has been established. Therefore, for the preRDF fraction, the biomass content was determined using the method specified in the regulation (i.e. the dissolution method), resulting in an average value of 62%. Consequently, M_{fBOi} =0,62 x M_{Oi}.

For sewage sludge, the lump sum value R_{Oj}, is 0.9. The values for M_{ORj} and q_{ORj}, were assumed to be 0.2 x MN and 2 MJ/kg, respectively. Since only the preRDF fraction and sewage sludge are processed in the gasification plant, the values for M_{Kk} and q_{Kk} were omitted.

Given the circumstances, the equation 4 is simplified to:

$$E_{RES} = \frac{\sum_{i=1}^{n} M_{fBOi} \times q_{fBOi} + \sum_{j=1}^{m} R_{Oj} \times M_{ORj} \times q_{ORj}}{\sum_{i=1}^{n} M_{Oi} \times q_{Oi} + \sum_{j=1}^{m} M_{ORj} \times q_{ORj}} \times E \quad (5)$$

The goal of estimating the share of renewable energy (RES) in the thermal and electrical energy generated during the thermal waste treatment process of the preRDF fraction of municipal waste (combined with sewage sludge) was achieved by calculating the average calorific value of the biodegradable fraction in the examined samples (Table 5). This calculation was based on the calorific values of specific material fractions derived from available literature sources (Skorek et al. 2025) and the proportion of these material fractions in the biodegradable fraction, as outlined in KPGO 2022.

The calorific value of the biodegradable fraction of the tested samples was calculated using the formula:

$$W_U = \frac{\sum W_U^i \times x_i \times \sigma_i}{\sum x_i \times \sigma_i} \quad (6)$$

where:

W_U – calorific value of the biodegradable fraction [MJ/kg];

W_{Ui} – average calorific value of the material fraction [MJ/kg], as presented in Table 5;

x_i – mass fraction of fraction “i” in waste;

σ_i – the coefficient representing the share of fraction “i” in calculating the biodegradable fraction, as defined by KPGO 2022 (kitchen waste – 1.0, paper/cardboard – 1.0, wood – 0.5, textiles – 0.5, multi-material waste – 0.4, fraction <10 mm – 0.3).

The calculated average preliminary calorific value of the biodegradable fraction in the examined samples was approximately 12 MJ/kg, meeting the minimum requirements for waste to be used as fuel. According to the criteria for the classification of recovery or disposal processes set in (Szpadt et al. 2003), the minimum calorific value required for waste to qualify as a suitable substitute fuel, meeting the energy recovery requirements for process R1, exceeds 11 MJ/kg.

The calorific value of the examined preRDF fraction samples (in a dry state) was approximately 20 MJ/kg, significantly exceeding the minimum threshold. However, the average preliminary calorific value of the examined samples was around 17 MJ/kg. This measured calorific value is higher than the assumed value for the model waste gasification plant.

The calculated calorific value of the biodegradable fraction for each sample of waste, as well as the calorific value of the preRDF fraction (in a dry state), is shown in the graph below (Figure 4). The yellow color represents the calorific value of the preRDF fraction based on physicochemical test results, while the blue color represents the calorific value of the biodegradable fraction, expressed as a weighted average of the calorific values of individual material fractions. The green and orange colors indicate the average values for these parameters.

Considering the above values and using Equation 5, the share of renewable energy in the energy generated from the thermal processing of waste for the tested preRDF fraction, with a 20% share of sewage sludge, is calculated as E_{RES} = 0,45 x E.

Discussion

Energy recovery from waste has gained increasing importance due to its potential for producing economically beneficial electricity and heat, especially in light of the ongoing energy crisis and fluctuating energy prices. According to EU sources,

Table 5. Calorific value for selected material components of the over-sieve fraction of municipal waste (preRDF)

No.	Material fraction	Calorific value [MJ/kg]									
		Lorber et al. 1999	Lorber et al. 1999	Socotec 2008	Walendziewski et al. 2007	Kozera-Szałkowska 2013	Budzyń et al. 2014	Jaglarz et al. 2015	Klimek 2013	Szpadt et al. 2003	Average values
1.	Kitchen waste	-	-	-	-	-	-	-	-	3,5	3,5
2.	Paper/Cardboard	14,1	16,2	13,3	11,0	16,0	12,4	13,7	20,5	11,0	14,2
3.	Multi-material waste	-	-	-	-	-	16,2	-	-	-	16,2
4.	Textiles	14,7	-	14,9	-	-	12,8	18,3	16,0	14,0	15,1
5.	Wood	14,5	16,8	15,2	18,0	15,0	15,4	-	19,0	18,0	16,5
6.	Fraction <10 mm	-	-	5,3	-	-	-	4,6	-	-	4,9

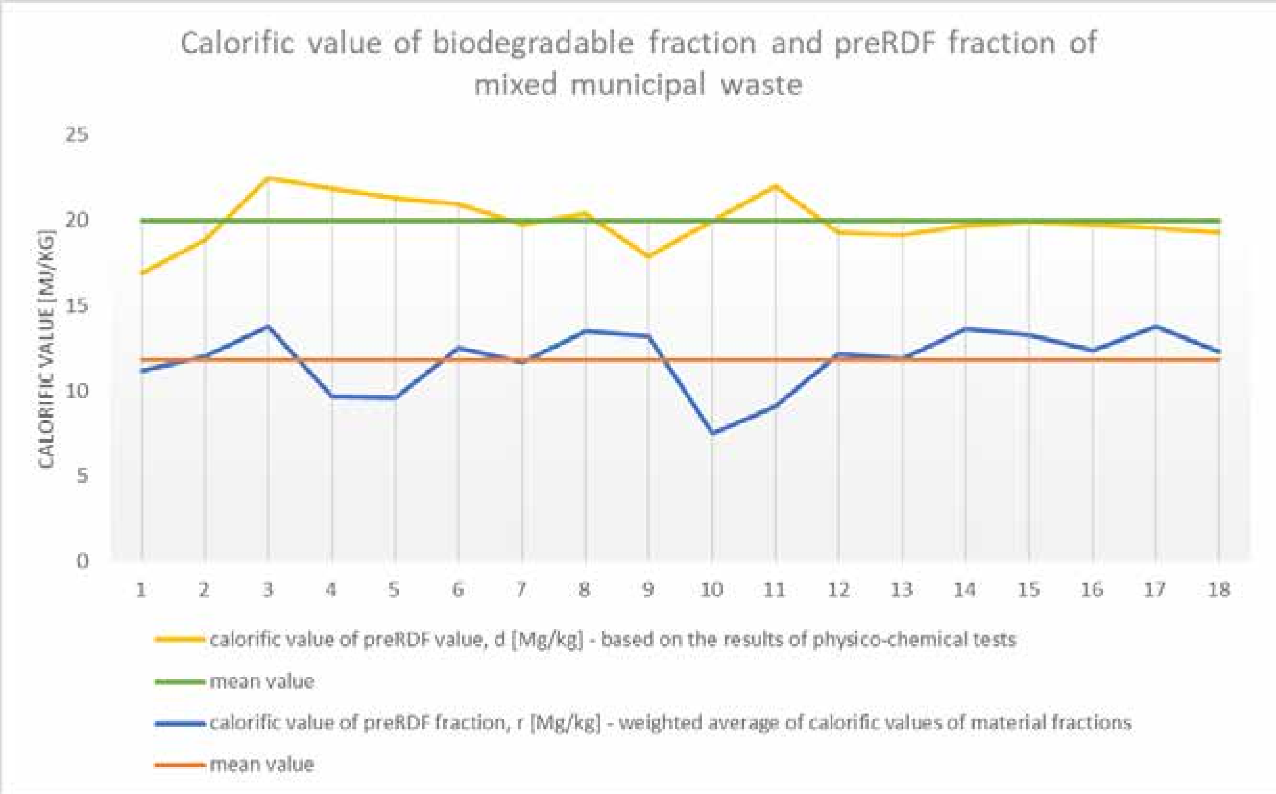

Figure 4. The calculated calorific value of the biodegradable fraction compared to the measured calorific value (d) of the preRDF fraction

energy from waste could become the third-largest energy carrier (Wielgosiński 2020). Moreover, energy recovered from waste can serve as an efficient source of renewable energy, making it an environmentally significant option (Primus, Chmielniak and Rosik-Dulewska 2021).

Systematizing the concepts of energy efficiency in thermal waste treatment plants is crucial for determining the actual efficiency of plant's performance, not only from an energy and environmental perspective but also from an economic standpoint. Therefore, the energy efficiency of waste gasification plants should be considered in three aspects: energy efficiency of thermal waste treatment (here referred to as the energy efficiency index), the energy efficiency of recovering the chemical energy contained in the waste (the plant's actual energy efficiency), and the efficiency of renewable energy production (Santos et al. 2023).

Conclusions

For the analyzed model waste gasification plant, the energy efficiency index, calculated according to the standard methodology, was 0.83. This value allows the plant to be classified under the R1 recovery process. It highlights the attractiveness of this technology when compared to conventional waste incineration processes, which involve steam production and electricity generation using small steam turbines. These conventional systems typically exhibit relatively low energy efficiency, especially in low-power setups.

The energy efficiency of recovering chemical energy (defined as the overall efficiency of the system) for the model waste gasification plant, operating at a capacity of 15,000 Mg/year and integrated with a cogeneration unit based on a piston engine, was 55.2%, with a feedstock calorific value of 14 MJ/kg. The efficiency of generating usable energy was 39.6% for thermal energy and 23.4% for electrical energy. The efficiency of syngas generation reached 74.7%. The model gasification plant also boasts a high cogeneration ratio for the piston engine, reaching nearly 86%.

The thermal waste treatment plant serves a renewable energy source facility, where part of the generated electrical and thermal energy is derived from biodegradable waste fractions. This article estimates the potential share of chemical energy from biodegradable waste fractions, based on the tests conducted on 18 samples of preRDF fractions. The biomass content, calculated using the methodology outlined in KPGO 2022, was approximately 40%, while the regulation-defined method indicated a biomass content of 62%. The calculated calorific value of the biodegradable fraction was 12 MJ/kg. Assuming an average calorific value of 17 MJ/kg for preRDF samples under operational conditions and a calorific value of 2 MJ/kg for sewage sludge (with a moisture content of about 72%), the share of renewable energy in the chemical energy generated from thermal waste treatment would be 45%.

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