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Review

Review of Selected Determinants Affecting Use of Municipal Waste for Energy Purposes

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Abstract: The aim of the article is to analyse the impact of selected conditions on the use of municipal solid waste in energy production processes. The authors in this publication indicated that the factors determining the effective use of solid municipal waste may be, in particular, formal and legal conditions, methods used in the processes of thermal waste transformation, recovery logistics or emergency situations such as pandemics or armed conflicts. Their knowledge can be very useful in the processes of the effective use of municipal waste for the production of thermal energy, especially in the current period of the energy crisis faced by most EU countries. This paper also emphasizes the importance of RDF (refuse-derived fuel) for the thermal energy sector, which can be used both in large combustion plants and in less powerful facilities, including local heating and combined heat and power plants as an alternative to traditional fossil fuels. The article was prepared by means of the systematic literature review (SLR) method, utilising the Scopus database and secondary sources.

Keywords: municipal solid waste; RDF; waste management; thermal processing

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1. Introduction

The current situation in the energy sector raises public concerns and at the same time encourages not only a reduction in the consumption of fossil resources but also energy saving. One of the concerns, among others, of heating plants in Poland is problems with the availability and prices of coal for the heating sector expected in 2022–2023, which may be a result of the disruption of the supply chain from the east and the reduced level of extraction of this raw material. It was also important to increase the prices of the future contracts for coal, in connection with, among others, the expected sanctions on its imports from Russia. All of this will translate into an increased interest in investments aimed at improving energy efficiency. The rising prices of raw materials may also generate doubts as to the validity of the decision to gasify the heating industry. Above all, this may lead to a suspension of decisions related to the use of natural gas in the short term.

According to the latest press reports, the current situation may have a significant impact on the course of energy transformation aimed at accelerating the departure from fossil fuels not only in Poland but also in the world. There is already a growing interest observed in investments in heat pumps, as well as RDF (refuse-derived fuel) and biogas sources, at the expense of investments in maintaining gas boiler plants. The growing interest in the use of gas in heating has so far been linked to the EU's climate policy and the hopes placed in natural gas, which was to play the role of temporary fuel in the energy transition.

Therefore, it is also possible to accelerate the transition of the heating sector to renewable energy sources (RES). Nevertheless, such a change will involve long-term investments and a change in the strategic view of the heating sector, which in turn should be motivated by many factors, not only rising gas prices. The EU policy, the approach of the state as well as the shape of Polish regulations will play an important role in the transition to RES. An important element of the EC's strategy is an increase in biomethane production. This is a direction towards which the heating industry is looking with interest, also owing to the changes to be introduced by the draft act amending the Act on Renewable Energy Sources and some other acts of 24 February 2022. The suggested act includes a definition of waste heat. In addition to biogas, the use of heat pumps and RDF will become more important in the heating sector.

A change in the legal environment for waste heat is an enormous development opportunity for RDF. At the moment, there is a significant increase in interest in this fuel in the thermal and professional energy sector, including small systems, so-called PECs. Currently, RDF is used in Poland only by the cement sector and only one CHP plant. The utilisation of waste for energy purposes may not only solve the problem of rising prices for municipal waste collection, but above all may contribute to independence from the import of fossil fuels.

2. Theoretical Background

The State of Waste Management with the Example of Poland

Around 2.01 billion tonnes of solid municipal waste are produced annually in the world, of which 33% is not properly managed. The data indicate an urgent need to develop a strategy to address the growing rate of global waste generation [1]. Municipal waste generation is expected to increase further to 2.2 billion tonnes by 2025 and even to 4.2 billion tonnes by 2050 [2]. The dynamic pace of the development of civilization translates into increased quantities of waste generated also in Poland, which is a member of the European Union. According to the data of the Central Statistical Office, in the first years after Poland's accession to the EU, there was an increase in the quantity of waste collected to the level of approximately 10 million tonnes, which lasted until 2009. In the following years, there was a decrease in the quantity of collected waste, whereas since the Act on Cleanliness and Order in Municipalities (2012) was introduced in Poland, there has been an increase in the quantity of municipal waste collected from the level of less than 9.5 million tonnes in 2013 to over 13 million tonnes in 2020. This means an increase in the quantity of waste generated per capita from 246 kg in 2013 to 342 kg in 2020. Figure 1 presents the share of forms of municipal waste management in Poland in recent years.

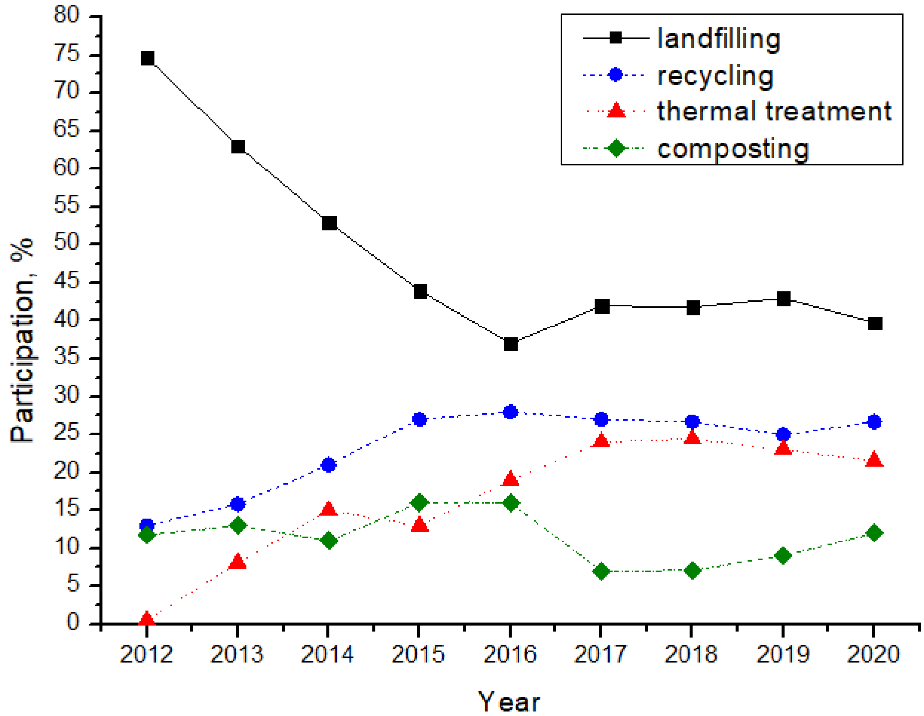

Figure 1. Share of forms of municipal waste management 2012–2020 [3].

The above figure shows that until 2016 there was a significant decrease in the share of landfilling in favour of other forms of waste management, mainly recycling and thermal transformation (combustion, gasification and pyrolysis). In 2017, there was a slight increase in the share of landfilling, as well as a decrease in the share of recycling and composting. In the following years, there was a slight decrease in the share of thermal transformation and an increase in the share of composting, while the levels of storage and recycling remained unchanged. It is worth noting that the recycling rate of 26.7% achieved in 2020 deviates significantly from the 50% target set by European legislation, which shows how much still needs to be improved in this regard. Nevertheless, in recent years, there has been an increase in the amount of waste separately collected from approximately 2.5 thousand tonnes in 2015 to almost 5000 thousand tonnes in 2020 [3].

Western European countries such as Germany, the Netherlands, Belgium, Switzerland, Denmark or Scandinavian countries such as Sweden, Finland and Norway place great emphasis on ensuring a high level of waste recycling, combined with energy recovery in thermal waste-to-energy treatment systems (WTE) [4]. Combustion is widely used in Western European countries (35–80% of the total waste generated) and plays a significant role in other European countries [2]. In terms of the mass combustion of municipal waste, the only reliable, proven technology at the moment is grid combustion. This technology was created in the first half of the 20th century and since then it has been systematically developed and modernised [5].

The Polish municipal waste management system is based on mechanical–biological waste treatment (MBT) installations. According to the data for 2018, there were about 179 such facilities in Poland with a total capacity of over 11.5 million tonnes in the mechanical part, and it was planned to increase their number by another 47 facilities with a total capacity of almost 3.3 million tonnes in the mechanical part and 1.6 million tonnes in the biological part by 2021. This means that in 2021–2022, the total capacity of the MBT systems should amount to approximately 13 million tonnes. At the same time, it is assumed that by 2025, Poland will reach the level of about 14.5–15.0 million tonnes of waste generated per year.

The operation of MBT systems consists in separating specific fractions of municipal waste. However, regardless of the technical variant used, three streams are obtained at the output of the said installation: the oversize fraction (caloric), biological fraction and ballast fraction (non-combustible). The operational data of the MBT facilities functioning in Poland show that the oversize fraction, often referred to as waste fuel (pre-RDF or RDF) (code 19 12 12 or 19 12 10), constitutes about 30–40% of the initial weight of the waste entering the system and has a calorific value of 10–18 MJ/kg, depending on humidity. Annually, approximately 3.5–4 million tonnes of that fraction is generated.

In addition, approximately 30–40% of RDF is combusted in existing municipal waste combustion plants, while a maximum of approximately 1 million tonnes is used to prepare alternative fuel for cement plants. The cement industry sets high requirements in terms of fuel calorific value; therefore, in order to meet them, it is necessary to enrich the RDF with a fraction of plastics or rubber, to ensure appropriate temperature conditions for burning clinker. Currently, there is a lack of processing capacity to burn approximately 2 million tonnes of RDF per year [4,6].

3. Selected Determinants of Using Municipal Waste for Energy Purposes

The reasonable management of natural resources requires treating waste as a valuable source of raw materials that can be reused, recovered in materials or in energy [7,8]. On the other hand, energy recovery from waste is part of the concept of a circular economy as it contributes to reducing the consumption of fossil fuels. One of the possibilities for utilizing the energy potential [9] of waste is the use of its combustible fraction to prepare alternative fuel for the purposes of the cement industry [10]. The specific temperature conditions in a rotary kiln contribute to limiting the harmful effects on the environment. Currently, the share of alternative fuels in the national cement industry is approximately

75%, while the highest replacement rate of coal with alternative fuels was recorded in a cement plant located in the eastern part of Poland (95%) [11,12].

The high calorific value of the oversize fraction of municipal waste allows a wider range of available solutions to be considered in the area of thermal transformation technology. When selecting the optimum variant, the specificity of Polish waste management based on MBT and the operating regional municipal waste treatment installations (RIPOK), which play an important role in the development of a circular economy, should be taken into account. Thanks to the new regulations of the Industrial Emissions Directive and their implementation into national legislation, the development of gasification/pyrolysis technologies for waste has become possible. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (Industrial Emissions Directive—IED) introduced a separate consideration of gasification and pyrolysis technologies in thermal waste treatment processes. The above regulations provide a conditional exemption from the technical requirements for thermal conversion for waste gasification or pyrolysis technologies, which are mandatory for waste combustion processes. The special provisions on the thermal treatment of waste do not apply to gasification or pyrolysis systems if the gases generated in this thermal treatment of waste are cleaned to such an extent that they are no longer considered to be waste before their combustion and cannot cause emissions greater than as a result of natural gas combustion. Table 1 summarises the quality requirements for natural gas in accordance with the applicable standards and methods of syngas purification [13].

Table 1. Quality requirements for natural gas in accordance with applicable standards and methods of syngas purification [13].

No.	Size	Unit	Permissible Value	Available Syngas Purification Methods
1.	Hydrogen sulphide content	mg/Nm^3	7.0	methods: wet alkaline absorption
2.	Mercaptan sulphur content	mg/Nm^3	16.0	
3.	Total sulphur content	mg/Nm^3	40.0	
4.	Mercury vapour content	µg/Nm^3	30.0	adsorption on activated carbon
5.	Oxygen content not greater than	% (mol/mol)	0.2	control of the gasification process, technological requirements
6.	Dust content greater than 5 µm in diameter	mg/Nm^3	1	combined methods—centrifugal separation, fabric filtration, granular filters, absorption in wet methods
7.	Content of hydrocarbons that can be condensed at −5 °C at pressure prevailing in gas pipeline [1]	mg/Nm^3	30	combined methods—catalytic and thermal destruction, condensation in shock cooling methods, filtration through oil and granular filters and adsorption by activated carbon

[1] Reference conditions: T = 273.15 K (0 °C); p = 101.325 kPa.

The oversize fraction generated in the current waste management model, due to its fuel properties, allows real consideration of gasification/pyrolysis technology with a local scope using the existing RIPOK systems. Pyrolysis/gasification systems equipped with gas cleaning systems meeting the quality and emission requirements will allow the combustion of syngas in high-efficiency cogeneration systems based on piston engines producing electricity and heat. These solutions ensure high efficiency of electricity production even for small-scale cogeneration systems up to 5 MWe. At the same time, it is worth noting that low-power turbine systems based on combustion and steam production technology require significantly higher investment costs than in the case of cogeneration systems based on piston engines. In addition, the proposed gasification/pyrolysis technology for energy production on a local scale will solve the growing problem related to the development of the oversize fraction and the RDF produced from it [4,14].

At the same time, both European and Polish legal conditions emphasise limiting the storage of waste, especially calorific waste above 6 MJ/kg. This group includes both sewage sludge, mixed municipal waste and residues from the processes of mechanical and biological treatment of municipal waste (pre-RDF), or properly prepared RDF. The use of waste for energy purposes must first of all be economically viable, which is influenced by factors such as distance, shaping the costs of waste transport, as well as the costs of waste storage and processing and the preparation of alternative fuel. Additionally, energy recovery from waste closes the life cycle of calorific waste that has not been managed by other methods, making it a perfect complement to the circular economy.

In addition, the ongoing energy-related crisis caused by the war in Ukraine prompts European countries in particular to look for an alternative to the increasingly more expensive fossil fuels. One of them is the use of waste for energy purposes, which brings both economic and environmental benefits in terms of reducing waste storage and related harmful emissions to the environment. Taking into account the current situation of the market of alternative fuels in Poland, the determinants shaping the use of municipal waste for energy purposes were specified (Figure 2).

Quality is an important factor influencing the use of waste for energy purposes is its quality, which determines its classification as fuel. As regards the quality requirements for waste fuels, they mainly relate to parameters such as the moisture and ash content, calorific value, as well as the chlorine and sulphur content. They ensure proper temperature conditions during thermal waste conversion, limiting the negative impact on the structural elements of the system. Considering the calorific fractions of municipal waste, the following can be listed: paper and cardboard, plastics [15], rubber, textiles and wood. The calorific value of mixed municipal waste is 8–9 MJ/kg, while the oversize fraction of municipal waste (pre-RDF), covering the above-mentioned calorific fractions, depending on the season, has a calorific value of 11–14 MJ/kg [14]. If the plastic fraction dominates in a given area, it also translates into an increased calorific value of the oversize fraction and the produced RDF [16]. Table 2 summarises the selected properties of municipal waste and the RDF fraction.

Table 2. Selected properties of municipal waste and RDF.

	Municipal Waste			**RDF**	
	Hognert et al. [17]	**Edo et al. [18]**	**Grove et al. [19]**	**Chan et al. [20]**	**Edo et al. [18]**
Coal [%]	48.00	49.00	53.00	56.30	52.00
Hydrogen [%]	6.00	6.30	6.80	8.40	6.60
Nitrogen [%]	0.20	0.90	2.20	1.10	0.18
Sulphur [%]	0.10	0.08	0.30	0.30	<0.02
Chlorine [%]	0.9	0.47	-	1.10	0.10
Oxygen [%]	38.00	35.00	37.80	25.40	38.00
Moisture content [%]	34.00	0.00	38.40	0.00	0.00
Ash content [%]	8.00	8.20	33.50	8.50	3.40
Calorific value [MJ/kg]	11.30	18.60	4.50	23.00	19.80

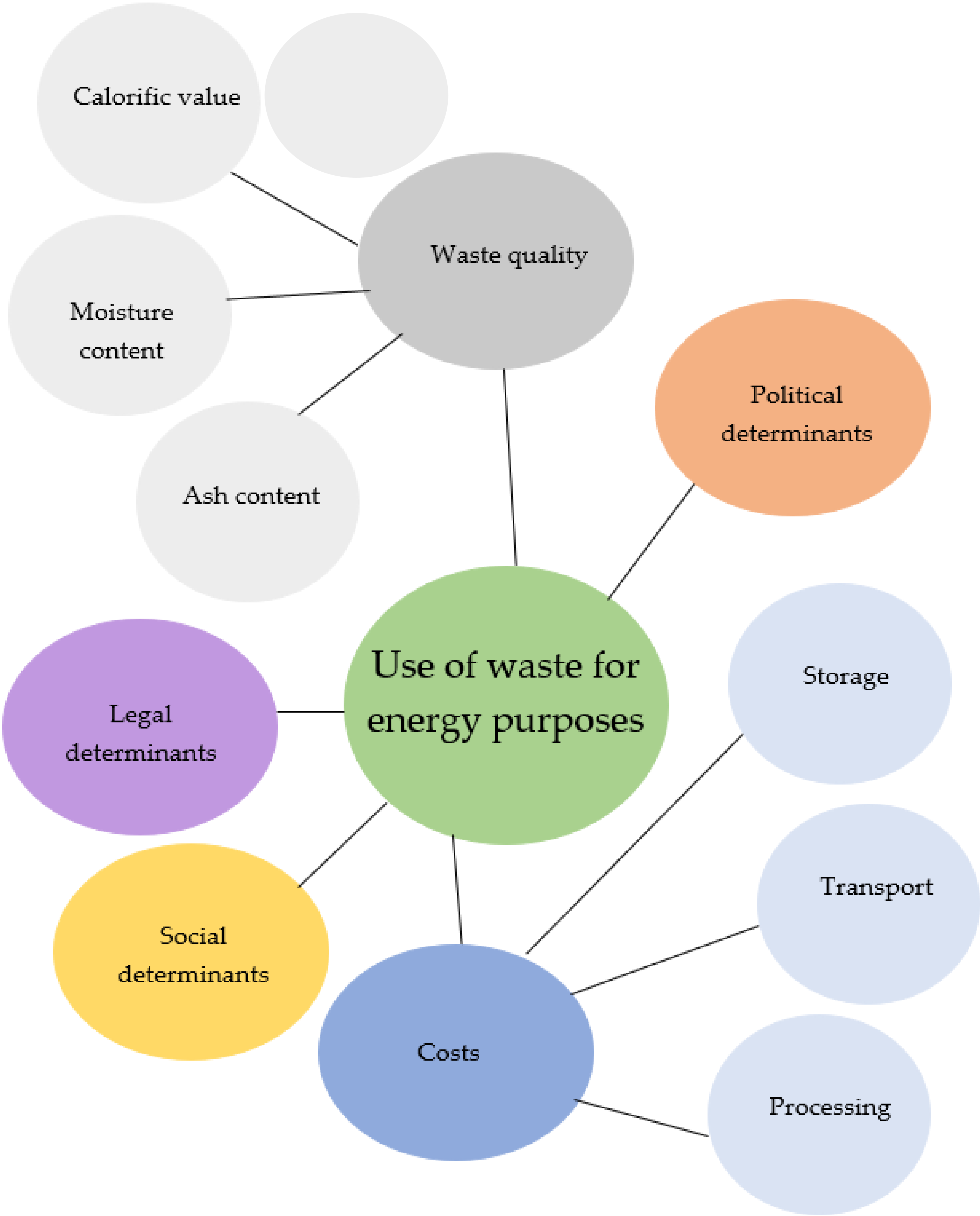

Figure 2. Determinants shaping the use of waste for energy purposes.

3.1. Formal and Legal Possibilities of Energy Recovery from Waste with the Example of Poland

The first document on the circular economy published by the European Commission was the vision of a zero-waste programme for Europe. This announcement is a key document in the implementation of the circular economy model in the EU as it clearly sets out the steps to be taken to move from a linear economy to a circular economy. The EC's vision was to eliminate the storage of municipal waste. In addition, it has been shown that positive changes in municipal waste management can increase the economic, environmental and social benefits in EU member states. In 2015, a second document was published regarding the circular economy, the so-called Circular Economy Action Plan or Circular Economy Package. The plan proposed long-term measures to reduce waste storage (including illegal landfills) and increase the preparation for re-use and recycling. It indicates that municipal waste and packaging waste are the key waste streams.

As a member state of the European Union, Poland is obliged to implement and transpose all legal solutions established by EU institutions into its national laws. The formal state body responsible for carrying out activities and preparing Poland for the transformation of the economy to the requirements of the circular economy is the Ministry of Development, which, in accordance with national legislation, established the Task Force for Circular Economy, consisting of representatives of ministries involved in the economic transformation. The result of the Task Force's work was the publication of the draft Road Map of the Polish Circular Economy already in December 2016 [21,22].

The preparation of this document was necessary because the depletion of raw materials, their rising prices and increasing dependence on suppliers from third countries constitute a serious threat to the further economic development of Poland and a challenge in the context of environmental protection. This document contains a set of legislative and non-legislative tools that, when implemented by the Polish administration, should contribute to the introduction of the circular economy model in Poland. It should be emphasised that the Polish Road Map indicates activities that primarily contribute to a reduction in the production of waste [22].

The Waste Act of 14 December 2012 entered into force on 23 January 2013 and is an implementation of Community law—the 2008 Waste Directive. The above approach results from the European waste hierarchy, in which the most desirable forms are waste prevention and its preparation for re-use, then recycling (including composting) and other recovery methods (including combustion with energy recovery). The last link in the hierarchy of waste management is a disposal by means of waste storage that is safe for human health and life [23].

Energy recovery from waste is the process of thermal transformation. The functioning of systems used for the thermal conversion of waste, because of potential environmental hazards, is subject to detailed legal regulations. The key guidelines for conducting the thermal processing of waste have been specified in the Act of 14 December 2012 on waste [24]. Figure 3 presents the formal and legal possibilities of energy recovery from waste, while Figure 4 presents the basic technical requirements for energy recovery from waste.

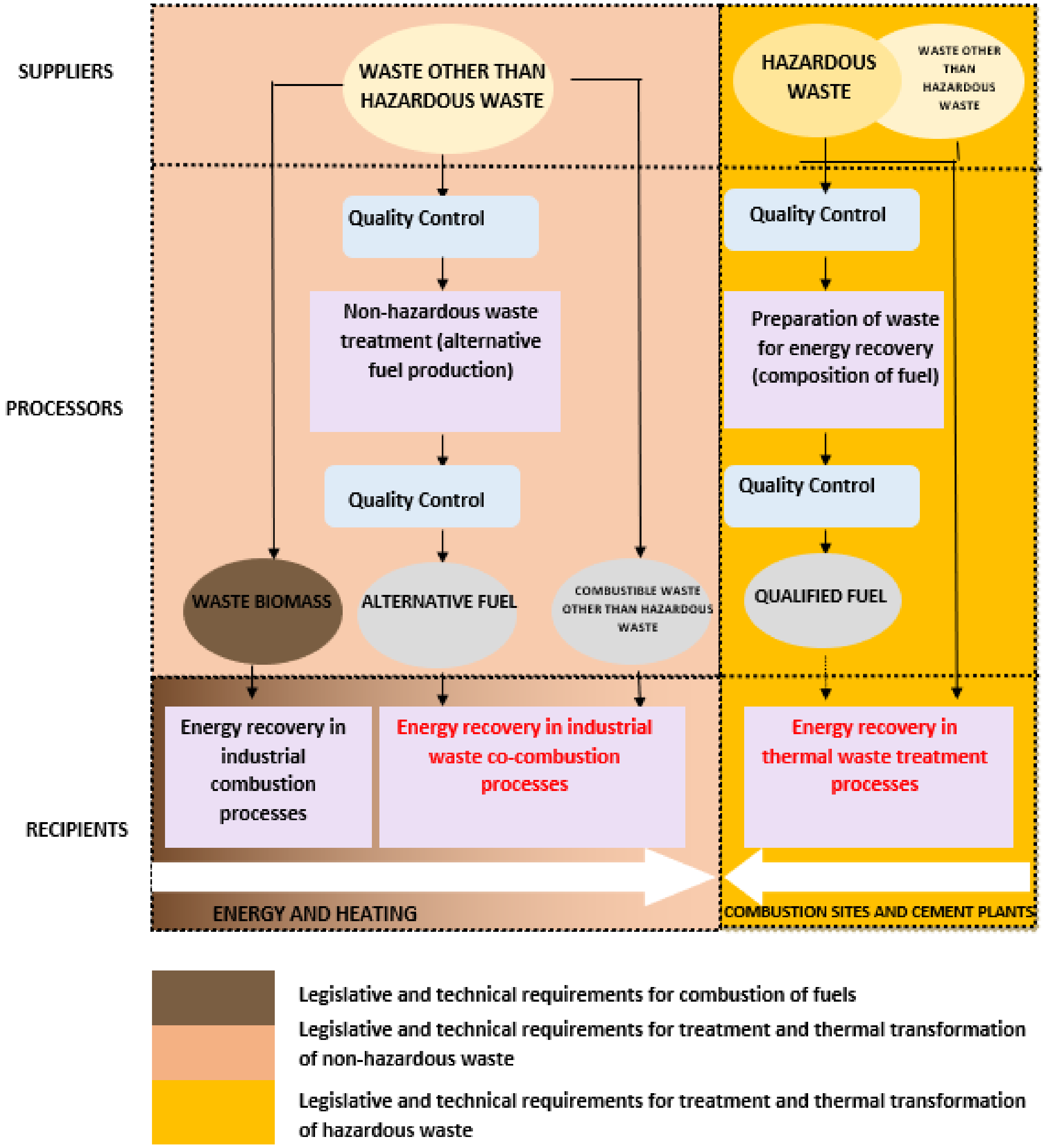

Figure 3. Formal and legal possibilities of energy recovery from waste [25].

Figure 4. Qualification of recovery operations related to energy recovery of waste [25].

3.2. Energy Recovery from Waste—Evaluation and Review of Selected Methods Used in Thermal Transformation Processes of Municipal Waste

A modern waste management system should take into account energy recovery [26], without which it is impossible to close the energy balance of many groups of waste. Chemical energy contained in the waste can be used for energy purposes, including electricity and heat production by means of thermochemical conversion, which seems important from an economic point of view [24]. The world leader in energy recovery from waste is Japan, which has achieved a WTE (waste-to-energy [27]) conversion rate of 78%. Nevertheless, there are 455 systems in 18 countries in Europe, of which Denmark, Sweden, Switzerland and Norway are considered the most developed countries in terms of energy recovery [28]. It is worth noting that according to the existing waste hierarchy, energy recovery is treated as a less desirable activity than recycling [29] or composting [30]; therefore, it should be used for groups of waste that have been previously recycled or for which recycling is technically or economically unjustified [24].

The qualification of recovery processes related to energy recovery from waste includes the following processes:

R12—the exchange of waste to be subjected to any of the R1–R11 processes

Refers to pre-treatment processes such as disassembly, sorting, crushing, compaction, granulation, drying, grinding, conditioning, repackaging, separation, blending or mixing prior to submission to any of the R1–R11 processes.

R1—used principally as a fuel or other means to generate energy.

Figure 4 presents a scheme for the qualification of energy recovery processes for use of municipal waste for energy purposes.

European legislation, with the natural environment in mind, imposes on the member states increasingly more stringent requirements regarding waste management and the reduction in pollutant emissions [31]. It aims to minimise the storage of waste for material and energy recovery purposes by employing thermal waste conversion methods. Thermochemical conversion by means of pyrolysis and gasification ensures lower emissions of pollutants into the atmosphere compared to the combustion, and is also perceived as an economically viable approach to the management of municipal or industrial waste. In recent years, pyrolysis and gasification have become increasingly important in reducing the environmental impact of combustion and electricity production from waste. The use of the above methods allows great flexibility of the raw material, obtaining chemical energy in the form of hydrocarbon products, as well as the production of electricity. Large-scale utilisation of plants for the recovery of energy from waste may allow countries to become independent from fossil fuels. Each tonne of recovered municipal waste replaces 0.4 tonnes of coal used to produce electricity in the US. Large-scale utilisation of these technologies in the United States is expected to replace coal extraction by 100 tonnes per year [32].

All thermal conversion processes (Figure 5) are employed to produce electricity and heat in various types of combined heat and power plants around the world [2,33]. Nonetheless, each of these processes differs in parameters such as atmospheric conditions (the presence of oxygen), operating temperature, reactor systems, etc. They determine the quality of the end products and usable intermediate products [34]. The operating temperature of thermal processes depends to a large extent on the proper design of the process and on the input materials [35,36]. In the case of incineration, waste pre-treatment is generally not practised in developing countries since untreated municipal waste is used as raw material. The factors determining the use of thermal conversion methods for municipal waste are presented in Table 3.

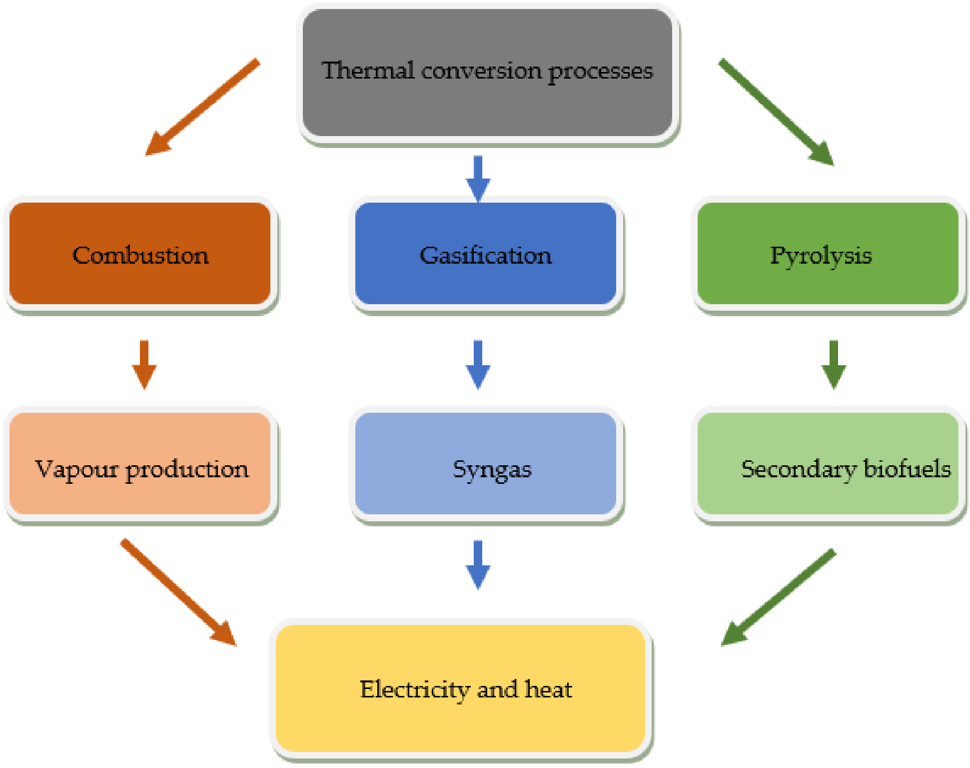

Figure 5. Thermal conversion technologies for municipal waste [2].

Table 3. Factors determining use of thermal conversion methods of municipal waste [13,37–39].

Rotating/Oscillating Combustion Kiln (ROCK)	Pyrolysis	Gasification
✓ High environmental performance => −50% CO compared to grate = low level of dioxins and furans => very low TOC content in slag (<2.5%). ✓ Enables combustion of fuels of various sizes and densities. In small combustion plants, it allows a greater variety of input material compared to traditional grate. ✓ Calorific value of waste may change over time. ✓ Low maintenance costs. ✓ Optimum cost–performance ratio for installations <30 MW/80,000 Mg/yr.	✓ The only thermochemical process in which liquid, solid and gaseous fractions can be obtained for direct use in different energy production plants. ✓ More environmentally friendly compared to conventional waste combustion systems as smaller amounts of NOx and SOx can be released due to inert atmosphere used in the process. ✓ High calorific value of processed waste (significant share of plastics) determines the quality of obtained secondary fuels that can successfully replace conventional energy carriers.	✓ Possibility of achieving high energy efficiency and reduction in pollutant emissions. ✓ Ease of purification of syngas obtained compared to treatment of exhaust gases after combustion of solid fuels. ✓ Waste gasification technologies using cogeneration systems based on piston engines enable higher efficiency of electricity production to be achieved, which is of considerable importance in terms of the possibility of their application in existing waste management systems based on mechanical and biological treatment of municipal waste.

Thermal conversion includes the heat treatment of the organic matter contained in municipal waste to produce heat energy, oil or gas [40]. This technology is generally useful for waste with a low moisture content and a high content of non-biodegradable organic substances. Thermal conversion is often applied [41,42] to the RDF generated from selected and processed municipal waste. Combustion or controlled reduction of waste to ash is the most common method of thermal conversion [43]. The technology of combustion on a grate is one of the best-known and most widespread throughout the world [43–47].

On the other hand, other thermal conversion methods (pyrolysis, gasification) are still in the research phase and it is not possible to introduce them for commercial use on a large scale. The reasons for the above phenomenon can be seen in the lack of sufficient data characterising municipal waste, the poor quality of the raw material or an inadequate structure of facilities. Nevertheless, pyrolysis and gasification technologies are preferable to combustion in terms of energy recovery as well as their environmental impact. Pyrolysis [48] and gasification can reduce the waste volume by 95% and require less intensive flue gas treatment compared to combustion [2,43,49].

3.3. The Importance of Reverse Logistics for the Use of Municipal Waste for Energy Purposes

Currently, there is a deterioration in the ecological situation in the world, which is associated with, among others, deforestation, burning fossil fuels or improper waste management, affecting climate change on Earth. Addressing the growing amount of solid municipal waste is one of the key challenges for the future. According to data from the World Bank, the annual production of solid municipal waste amounts to 2.01 billion tonnes. Nonetheless, at least 33% of this waste is not disposed of by any environmentally friendly method. Despite the fact that only 16% of the world's population lives in higher-income countries, they produce about 34% of the world's solid municipal waste (683 million tonnes). Global waste generation is expected to increase to 3.4 billion tonnes by 2050 [50]. Logistics management for solid waste worldwide varies depending on the region. This is due to the country's legislation, geographical conditions, its environmental culture, as well as the incentives and sanctions applied in different economies.

Today's severe environmental problems have led all international institutions to change their environmental laws and regulations to a new alternative—the circular economy. Some Asian countries, notably Japan and China, have completely transformed their economic systems into circular economy models. The shift towards a circular economy model is due to the unavailability of raw materials and the increase in the quantity of waste as a consequence of the large population of these countries.

In turn, the EU is a precursor in the implementation of circular economy rules, and most European countries have limited the use of sanitary landfills owing to environmental issues and policy. Although the quality of the infrastructure of EU member states is uneven, these states understand that an efficient transport system depends on a solid waste management system that functions properly. This is reflected in the road network, which offers options for effective mobility, not only in trade and for people, but also for a waste management system that allows the implementation of collection programmes on different schedules [51].

Reverse logistics is a part of sustainable management that ensures the correct treatment or elimination of waste in a socially responsible manner in order to recover its economic and ecological value, and thus reduce the mass of the generated waste. According to the definition of reverse logistics, it involves certain aspects of environmental protection, in particular regarding the proper management of waste. The relationship between reverse logistics and waste management occurs in reverse distribution operations such as reuse, recycling and proper waste treatment.

When looking at the general aspects of environmental and economic activity in reverse logistics, it can be stated that it covers all processes related to the flow of waste materials and information in the system, in particular the processes of collecting, processing and reusing waste, provided that they are carried out in an efficient manner, economically and ecologically and that they lead to closed material flow systems. This means that the key objective of reverse logistics is to shape the flows of all kinds of products in the reverse direction (compared to the classical flow) in order to minimise the amount of waste affecting the environment and to exploit the full potential of waste suitable for recovery and reuse [52].

The use of waste for energy purposes is a perfect complement to reverse logistics and allows the product life cycle to be closed. The main benefits of this include:

➢ substitute for decreasing fossil fuel deposits;
➢ reduction in waste storage problems, and thereby reducing greenhouse gas emissions;
➢ increased level of waste recovery;
➢ increased amount of electricity produced from renewable sources (from the biodegradable fraction contained in waste);
➢ economic benefits.

At the same time, it is worth emphasising that the use of waste for energy purposes in thermal conversion systems generates a number of problems:

- heterogeneity of the physicochemical properties of waste;
- formal and legal approach to waste fuels as waste;
- higher requirements in terms of emission standards;
- compliance of boiler systems with the parameters required for the thermal processing of waste;
- technical and operational problems in the existing power systems (increased corrosion, increased amount of ash and difficulties with its management, a necessity for structural changes within the boiler system as well as in the flue gas purification unit;
- resistance of local communities to obtain permits for energy recovery from waste [25].

3.4. The Impact of the Pandemic and Armed Conflicts on the Possibilities of Using Municipal Waste for Energy Purposes

It is worth emphasising the significant impact of the Coronavirus (COVID-19) pandemic on global waste management. Contaminated textile masks, used gloves and tissues were placed in the stream of municipal solid waste [53,54]. Additionally, the SARS-CoV-2 virus may persist for a long time on various waste fractions produced by infected individuals [55]. In connection with the above, it was important to ensure the safety of people involved in the collection of waste, by means of appropriate separation and marking of the above-mentioned waste, as well as the frequent cleaning of work clothes, the replacement of gloves, and disinfection of used vehicles. Moreover, in order to reduce the exposure of workers in recycling plants, it was necessary to introduce the automation of waste-sorting processes, as well as to quarantine the received waste for a minimum of 72 h [55–58].

The economic paralysis and closure of restaurants caused [59] by the pandemic resulted in a rise in the demand for delivering food to homes. As a consequence, it contributed to an increase in the amount of plastic packaging waste (PP polypropylene, LDPE low-density polyethylene, PET polyethylene terephthalate, PS polystyrene) [60]. At the same time, the amount of plastics in medical waste (the packaging of sanitisers, syringes, bowls, containers, medical bags, face shields, overalls, gloves) grew significantly, which resulted from the high demand for the health service. There was an estimated sixfold increase in plastic waste compared to the pre-pandemic period [61]. A record increase of 370% was noted in Hubei Province, China. In addition, the amount of biomedical waste generated in medical facilities and research laboratories during testing and vaccination increased. They consisted of 85% non-hazardous waste and 15% hazardous waste (including 10% biological waste and 5% chemical and radioactive waste) [62].

Due to the pandemic, some countries, e.g., the USA and Brazil partially halted recycling programmes for fear of the spread of the virus. Because of public health-related concerns in the United States, the widespread use of single-use plastic bags was reinstated. On the other hand, despite the low activity and lack of demand for secondary raw materials, Canada and most European countries such as the United Kingdom, France, Spain and

Italy allowed recycling units to operate throughout the epidemic, considering them an indispensable sector [55]. Table 4 presents changes in the management of plastic waste caused by the pandemic.

Table 4. Impact of coronavirus pandemic on trends in plastic waste management.

Before the Pandemic	During the Pandemic	After the Pandemic
- waste from plastics based on fossil fuels - mechanical recycling rate 16% - share of waste combustion 25% - share of waste storage 40% - unmanaged waste 19%.	- Lower fuel prices and fear of virus transmission contribute to a reduction in the recycling rate of plastics. - Significant loading of combustion facilities with an increased amount of packaging waste and used personal protective equipment. - Increased amounts of plastic waste and recommendation of deep burial of infectious waste contribute to growth in a number of landfills. - Insufficient management of used personal protective equipment and packaging waste leads to an increase in plastic waste in the environment.	- Mechanical recycling and combustion with optimal efficiency to cope with the increase in the amount of plastic waste. - Raw material recycling may be promoted in order to complement other technologies to cope with a rise in plastic waste. - In absence of abnormal conditions, dependence on storage should be significantly reduced. - Release of plastic waste into the environment should be controlled as a result of improper management. - Transition from fossil fuel-based plastics to bio-based materials should be promoted.

Source: authors' own compilation based on [63].

Taking into account press reports relating to war refugees from Ukraine, a significant impact of the increased population in Poland on waste management can be noticed. A larger population translates into a rise in the amount of generated municipal waste. The growth in the amount of packaging waste, as well as plastic waste generated when serving meals in places of temporary residence of refugees, is particularly visible [64]. In turn, a greater amount of waste generated translates into higher costs for its management. Currently, the increased costs of waste management are transferred to the owners of real estate hosting citizens from Ukraine.

The war in Ukraine has created unrest in global markets, contributing to the rise in fuel and energy prices. Any attempts at becoming independent from Russian fossil fuels by means of imports from other directions may be costly; therefore, it is worth considering the use of energy contained in waste. It is not possible to supply the entire thermal energy industry this way, but 10% of energy could come from waste. The combustion process uses a calorific fraction of municipal waste (constituting approximately 30% of its weight), not recyclable, from which RDF is produced. This fuel is currently used in the cement industry as a substitute for part of fossil fuel, for combustion in power plants adapted to the use of alternative fuels having the status of waste combustion plants, and for co-combustion in power boilers.

Nevertheless, using the currently existing installations for the thermal processing of waste, there is no processing capacity for the combustion of approximately 2 million tonnes of RDF per year. At the same time, according to the Institute for Chemical Processing of Coal, approximately 30 million tonnes of fuel are stored in various places in the country [4]. In addition, the Central Statistical Office of Poland forecasts indicate an increase in the amount of municipal waste generated in Poland from 13.1 million tonnes in 2020 to 15.5 million tonnes in 2050; hence, Polish RDF resources will continue to increase. In connection with the above, a good solution to the problem of fuel surplus may be the creation of new systems for the thermal processing of waste at the local level, which will allow support for the Polish heating system as well as the entire municipal economy in Poland. In addition, this solution brings tangible benefits, such as [65]:

- lower costs of managing the combustible fraction of municipal waste, which ensures long-term stability of the cost of this service for local governments;
- stabilisation of residents' fees for waste removal and management collected by municipalities;
- improvement of air quality in Poland—a reduction in the pollutant emissions from local heating networks;
- stabilisation of heat prices by reducing their dependence on the purchase price of CO_2 emission allowances (a part of the energy from waste can be considered as renewable energy);
- significant reduction in dependence on the import of hard coal by means of the optimum use of the combustible fraction of municipal waste. RDF is a locally produced energy resource.

4. Summary and Conclusions

The growth in the environmental burden caused by the depletion of resources, as well as the rise in the amount of waste, leads to a change in the approach to the management of solid municipal waste. Both European and Asian countries, such as China and Japan are seeking to change the waste management model towards a circular economy.

Logistics processes play a special role in waste management. The relationship between reverse logistics and waste management occurs in reverse distribution operations such as reuse, recycling and proper waste treatment. Taking into account the environmental and economic aspects, it can be stated that reverse logistics covers all processes related to the flow of waste materials and information in the system, provided that they are carried out in an economically and ecologically effective manner and that they lead to the creation of closed material flow systems.

The use of waste for energy purposes is a perfect complement to reverse logistics and allows the product life cycle to be closed. The chemical energy contained in the waste can be used for energy purposes, including electricity and heat production by means of thermochemical conversion, which seems economically important. The primary determinants of using municipal waste for energy purposes include: the legal conditions, moisture content and the calorific value of the waste divided into fractions, the costs of waste storage, distance costs of waste transport, costs of RDF preparation, closure of the life cycle of calorific waste within the circular economy, as well as the energy crisis caused by the war in Ukraine.

The war in Ukraine has caused unrest in the world markets. The rise in fuel and energy prices is prompting countries to look for alternatives to Russian fossil fuels. The growing amount of municipal waste in Poland and the amount of RDF produced from its combustible fraction, with an insufficient processing capacity of the thermal waste treatment installations, has led to significant surpluses of the said fuel. It is a locally produced energy raw material that can significantly reduce dependence on the import of hard coal and support the Polish heating system as well as the entire municipal economy in Poland.

It is also worth noting the significant impact of the coronavirus pandemic on waste management. During the period of the pandemic, it was necessary to ensure the safety of persons involved in the collection and transport of waste by the issuing and marking of infected waste, frequent changes of personal protective equipment or the disinfection of clothing and means of transport. At the same time, greater automation of the sorting process and quarantine of the received waste were introduced in order to reduce the exposure of workers. During the pandemic, reverse logistics in waste management for storage and thermal transformation were severely limited, which was justified in order to limit the spread of the virus.

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