Energy recovery from waste as an essential part of a sustainable economy

Marta Malec

Abstract: The article presents an analysis of benefits of the energy recovery from waste. Presented a look at energy recovery from waste as part of a modern and diversified national energy policy. Energy recovery from waste is an essential link in closing the model of a sustainable closed-cycle economy. The paper presents the basic legal regulations on energy recovery from waste in Poland and the European Union and discusses the waste hierarchy model, according to which energy recovery from waste is placed behind material recycling. The technical basis of the energy recovery process in waste incineration plants is presented, as well as the possibility of classifying part of the energy recovered from waste as energy from a renewable source. The importance of cogeneration, regarded as the most efficient way of producing energy from waste, is emphasised.

Key words: waste management, recycling, energy recovery, renewable energy sources, sustainability

Introduction

Waste is any substance or object which the holder discards, intends or undertakes to discard (OJ EU.L.2008.312.3, as amended: Article 3(1)). The generation of waste is inevitable, as it is inherent in the processes of production and consumerism (Famielec 2016: 175). Waste management is a significant environmental problem. With the economic development of countries and the improving quality of life of their inhabitants, the amount of waste is increasing. Waste management is usually associated with disposal. However, waste can be an important source of secondary raw materials and fuels. Considering the total amount of waste generated and its increase over the years, it can be concluded that waste incineration is a potential source of energy. Energy recovery from waste substances is referred to as WtE *(Waste to Energy)* processes. Energy from waste has been successfully recovered in cement plants for many years. In recent years, thermal waste treatment plants have become increasingly popular. Thermal waste treatment is replacing landfill, which is at the bottom of the waste hierarchy as the least desirable waste management method.

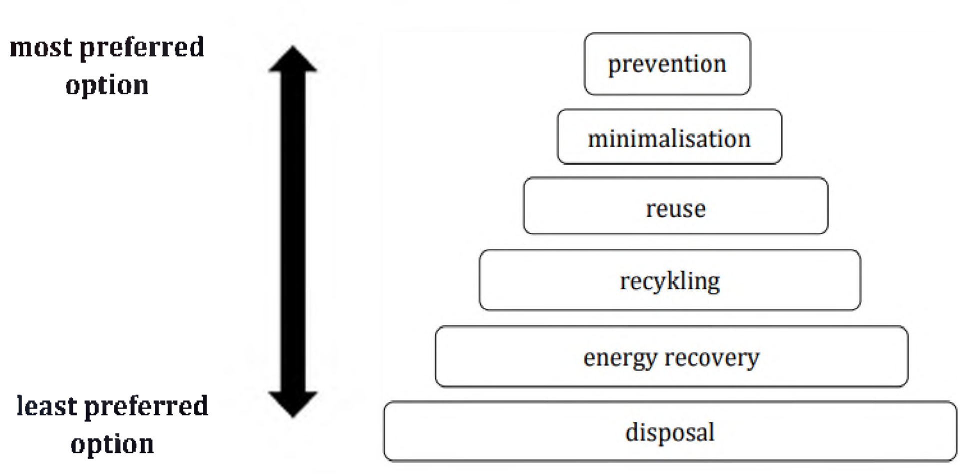
Some of the waste groups with favourable energy parameters contain a biodegradable fraction within them. The energetic use of such waste brings the additional benefit of being able to classify the energy generated, in part from the biodegradable fraction contained in the waste, as coming from renewable sources (Wasilewski, Bałazińska 2018: 130).

The process of thermal waste conversion with energy recovery is economically justifiable and technically feasible, regulated in EU and Polish law (Famielec 2016: 174).

Legislation on thermal waste treatment with energy recovery in Poland and the European Union

Under Article 194(1) of the Treaty on the Functioning of the European Union (OJ EU.L.2012.326.47, as amended), the promotion of renewable energy sources is one of the main objectives of EU energy policy. This objective is implemented by Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (OJ EU.L.2018.328.82, as amended). In this act, European Union Member States were obliged to develop support schemes for renewable energy sources, taking into account the available sustainable supply of biomass, the application of the closed-loop economy principle and the waste hierarchy so as to avoid distortions in the raw material markets. It was emphasised that waste prevention and material recycling are priorities and thus take precedence over energy recovery from waste. It follows from the above that, in the light of the legislation, energy recovery from waste is a less desirable activity than recycling of waste. Therefore, groups of waste that have already been recycled, or for which - for economic or technical reasons - the recycling process is not justified, should be subject to the energy recovery process (Wasilewski, Bałazińska 2018: 130). Fig. 1. shows the waste hierarchy model promoted by the EU.

Fig. 1. Hierarchy of waste management



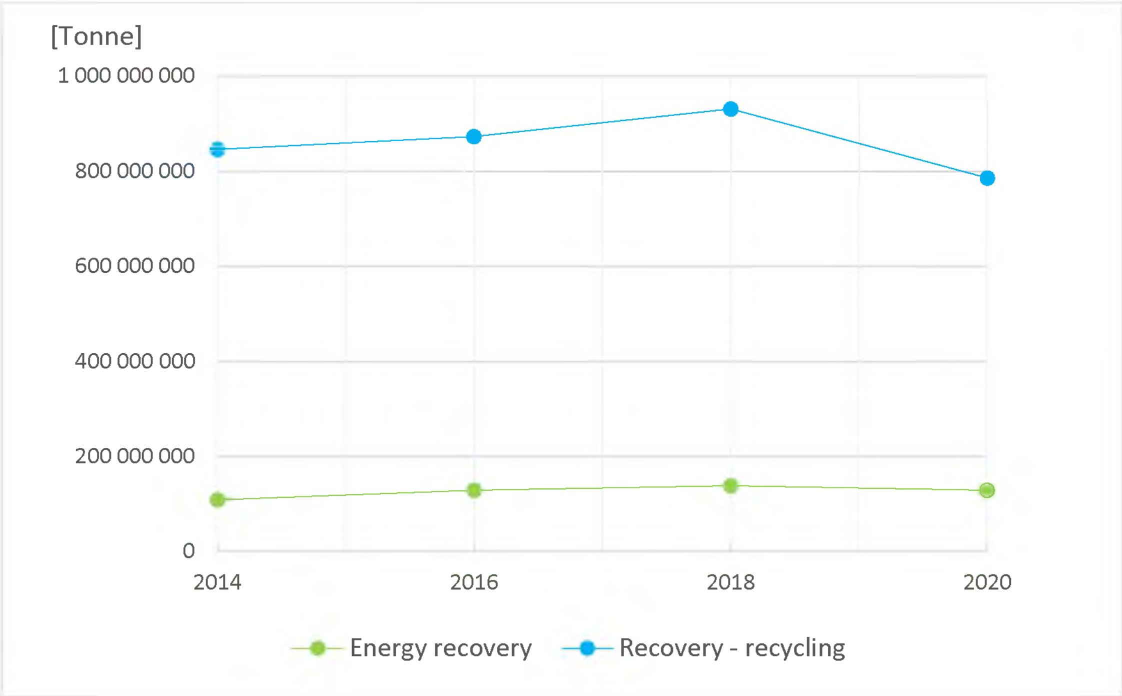
Source: Own elaboration

According to the waste hierarchy model, the most desirable action mechanisms are waste prevention, reduction and reuse. If these actions are not possible, the waste should be recycled. Energy recovery from waste, as a less desirable method than recycling, is ranked just behind it in the waste hierarchy. At the bottom of the presented model is waste disposal, which, as already mentioned, is the least desirable waste treatment method.

According to Eurostat (online data code: ENV_WASTRT), in 2020 in the countries of the European Union, about 60% of the total treated waste was recovered, of which 40% was recycled, 13% was used to fill pits and 7% of the total treated waste was incinerated with energy recovery. The remaining 40% of the treated waste was landfilled and 0,5% was incinerated without energy recovery.

Fig. 2. shows the levels of recycling and energy recovery from waste according to Eurostat data in European Union countries for the years: 2014, 2016, 2018 and 2020.

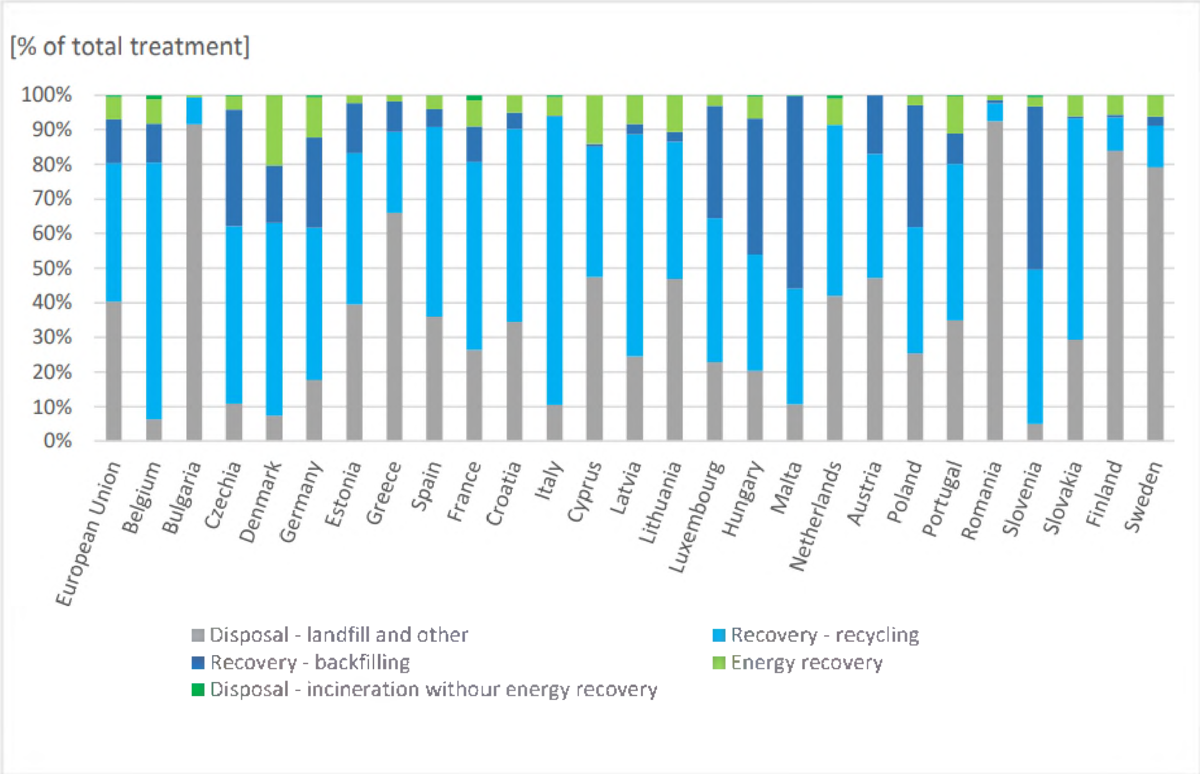
Fig. 2. Levels of achieved recycling and energy recovery from waste in the EU for the years: 2014, 2016, 2018, 2020



*For 2014,2016 and 2018, data are presented for the 28 EU members, for 2020 for the 27 EU members (excluding the UK)
Source: Compiled by the author based on Eurostat.

For both recycling and energy recovery from waste, we can see for 2020 a downward trend in the levels achieved. It is important to remember that in 2020, the Covid-19 pandemic broke out, reducing production and consumption, slowing the development of the world economies. The share of the various waste treatment options in EU countries in 2020 is shown in Fig. 3.

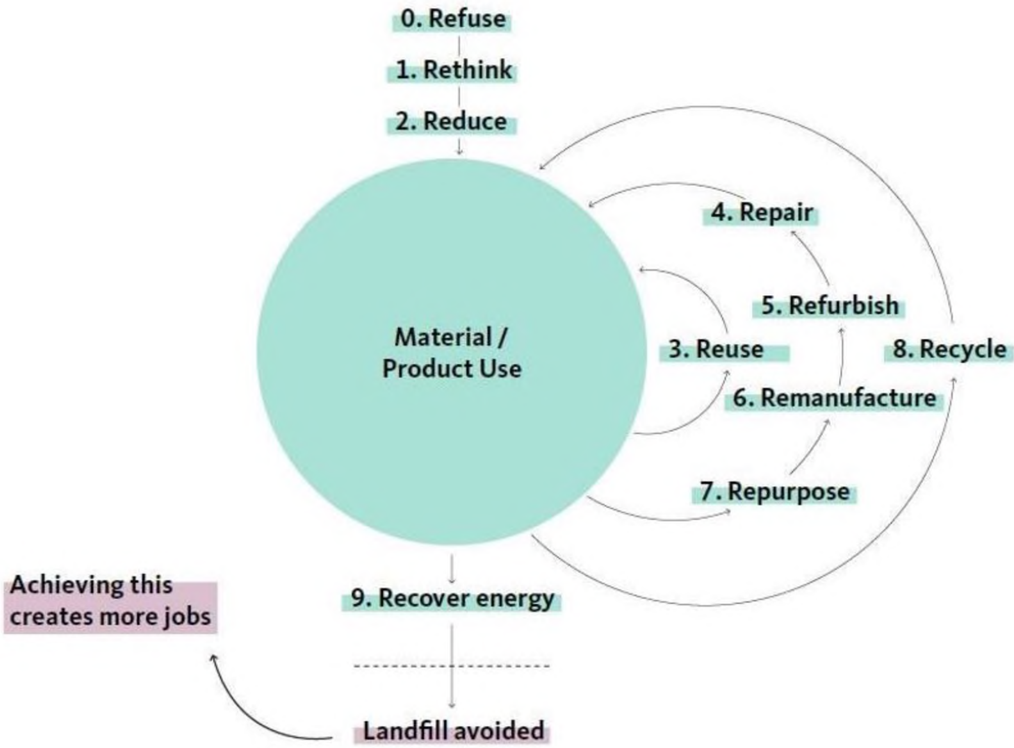
Fig. 3. Waste treatment by type of recovery and disposal in 2020 in EU



*data for Ireland - not available
Source: Compiled by the author based on Eurostat.

The European Union is taking action to protect human health and the environment by setting out a framework for proper waste management, including recycling and recovery. Measures taken to promote a circular economy are intended to reduce demand for resources, use them prudently and efficiently, expand the use of renewable energy, increase energy efficiency, reduce the Union's dependence on imported raw materials or create new economic opportunities.

Fig. 4. Schematic of a closed-loop economy



Source: www.gensler.com/blog/circular-economy-reusing-materials-to-save-cost-lower-carbon

The enacted Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (OJ.EU.L.2008.312.3, as amended) reaffirmed the waste hierarchy, according to which the re-use and recycling of waste takes precedence over energy recovery from waste, if and only to the extent that these are the most environmentally sound methods available. Article 23 of the Directive requires establishments and undertakings that intend to treat waste to obtain a permit from the competent authority to carry out the activity. One of the conditions for carrying out the activity of incineration or co-incineration of waste with energy recovery is a high level of energy efficiency of the process carried out. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (OJ.EU.L.2018.150.109) also placed emphasis on, inter alia, increasing synergies between the closed-loop economy and energy and climate policies, among others.

The waste management system in Poland is regulated by the Waste Act of 14 December 2012 (Journal of Laws 2022 item 699, as amended). According to the definition contained in this Act, thermal waste conversion should be understood as the incineration of waste by oxidation or thermal waste conversion processes other than oxidation, including pyrolysis, gasification and plasma process, as long as the substances generated during these processes are subsequently incinerated. In addition, the Act defines a waste incineration plant as a plant or part thereof intended for the thermal treatment of waste with or without recovery of the thermal energy generated, and waste co-incineration plants as a plant or part thereof whose main activity is the generation of energy or products in which waste is thermally transformed together with fuels for the purpose of recovering the energy contained therein or for the purpose of disposal.

Under the Waste Act, the thermal conversion of hazardous waste and municipal solid waste constitutes a disposal process. In contrast, the thermal treatment, for the purpose of energy recovery, of packaging waste, non-hazardous waste and municipal solid waste constitutes energy recovery.

According to EU law, which has also been implemented into Polish law, it is prohibited to landfill waste whose heat of combustion exceeds 6 MJ/kg. Such waste that cannot be recycled can be diverted to an energy recovery process (Pikoń, Bogacka 2016: 123).

The basis for qualifying energy generated from waste as coming from a renewable source is the content of the biodegradable fraction. This issue is regulated in Polish law by the Regulation of the Minister of the Environment of 8 June 2018 on the technical conditions for qualifying the portion of energy recovered from thermal waste conversion (Journal of Laws 2016 item 847). There are two ways of determining the share of renewable energy, i.e. on the basis of direct measurements of the content of biodegradable fractions in the tested waste or taking into account the relevant lump sum value of the share of chemical energy of biodegradable fractions (for certain types of waste listed in Annex 3 to the Regulation).

Technical basis of energy recovery from waste. Energy efficiency of thermal waste treatment plants

Energy is extracted from waste through thermal conversion, mainly by incineration. However, some fractions can be subjected to methane fermentation - this process results in high-energy biogas (Pikoń, Bogacka 2016: 120).

Methods of recovering energy from waste include:

- the thermal treatment of waste, i.e:
    - combustion,
    - pyrolysis,
    - gasification, and
- biogas production by methane fermentation from biodegradable fractions.

Waste incineration takes place in specially designed thermal waste conversion plants, commonly referred to as waste incineration plants (Cyranka, Jurczyk 2015: 33). The financial outlay needed to build a thermal waste conversion plant can be a major problem when starting to build a new facility. Profit from operating a plant may only emerge after several years or even several decades of operation. Sources of revenue include fees charged for waste disposal, the sale of electricity and heat, and the sale of iron or scrap non-ferrous metals recovered from the slag and fly ash (Pikoń, Bogacka 2016: 121). The construction of new facilities also creates new jobs.

Thermal waste treatment plants operating in the EU are subject to stringent standards, which means that modern installations, covered by a system of constant monitoring of pollutant emissions, can confidently be regarded as completely safe for people and the environment.

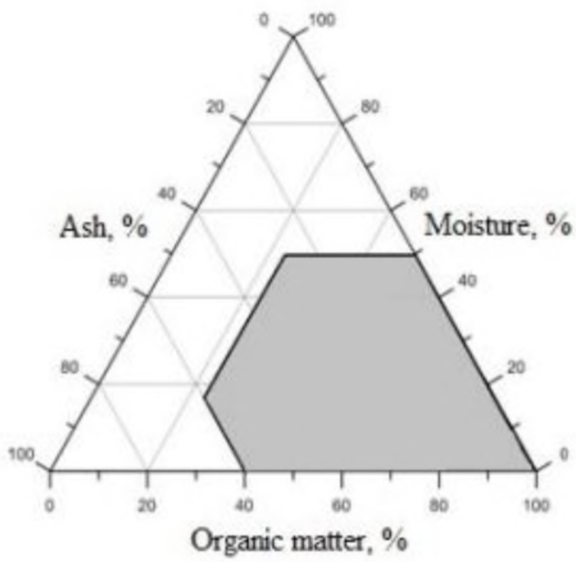
The recovery of energy from waste depends on the use of a number of installations and facilities to ensure that the combustion and energy conversion processes can take place properly. In addition to the energy recovery segment, which includes, among others, the boiler, turbine, condensers and heat exchangers, the design of such a plant should also include other installations and equipment designed, in particular, to receive and collect delivered waste, treat flue gases or manage solid residues (Cyranka, Jurczyk 2015: 35).

The physical and chemical properties of the waste delivered to the plant determine the selection of appropriate technologies, as well as the degree of efficiency of the waste incineration process. The most important parameter that determines the amount of energy that can be produced from 1 Mg of waste is its calorific value. It defines the suitability of matter for use in the energy sector (Jędrzejowski, Latosińska et al. 2018: 358) and denotes the amount of energy (heat) released during the combustion of a unit of mass, or a unit volume of fuel, expressed in [MJ/kg]. The calorific value depends on the proportion of combustible parts, mineral matter and moisture. The calorific value of a fuel decreases with increasing moisture, which is often a result of the storage and transport conditions of that fuel, as well as its pretreatment (Wasielewski, Stelmach et al. 2015: 116).

A key issue is the autothermicity of the combustion process, meaning the ability to burn waste without introducing additional energy. Autothermic combustion of waste is assumed to have a calorific value of at least 6 MJ/kg. In addition to the calorific value, the autothermicity of combustion processes is also influenced by the proportion of: combustible parts, non-combustible parts and moisture in the waste. Using Tanner's triangle, the area of autothermic combustion can be determined for a given fuel. On its individual axes, the percentages of the parameters: combustible parts, non-combustible parts and moisture are plotted (Famielec 2016: 179). It can be seen from the Tanner diagram shown in Fig. 4 that the autothermic combustion area is taken to be the area (circled in grey) bounded by the proportion:

- combustible parts min. 25%,
- non-combustible parts max. 60%,
- moisture content max. 50%.

Fig. 5. The Tanner diagram



Source: Wilk M., Magdziarz A., An evaluation of rewenable fuels microstructure after the combustion process, Journal of Power Technologies 97(4) (2017) 265-271.

The energy efficiency (a.k.a. efficiency) of a waste incineration plant compares the value of the input chemical energy contained in the waste with the energy recovered from the waste, i.e. the electrical and thermal energy produced (which has not been dissipated, e.g. by flue gas, radiation, cooling system) (JRC Report: 259). The energy efficiency of the recovery process determines the environmental benefits that the process can provide. Adequate energy efficiency in the recovery process depends to a large extent on the construction of the thermal waste treatment facility and its operation in such a way as to guarantee optimum recovery, i.e. that the maximum amount of energy is obtained without endangering the environment. The plant in operation must meet BAT - *Best Available Techniques* - requirements, thus guaranteeing the highest environmental standards.

The most desirable way to do this is to operate the plant in a cogeneration process *(CHP – Combined Heat and Power)*, which produces electricity and heat simultaneously. Cogeneration is a highly efficient process - the overall efficiency exceeds 85%. A unit operating in cogeneration system is characterised by a lower fuel requirement than in the case of separate electricity and heat production processes (Cyranka, Jurczyk 2016: 103-104). In a traditional power plant, heat is converted into electricity. During the process, more than half of the power is lost. A modern combined heat and power plant operating in cogeneration units uses waste heat generated in the production of electricity. Thanks to the cogeneration operation, savings in the purchase of electricity can even exceed 40%. According to the estimates financial outlays for the investment can be returned after about 3 - 4 years (HNL). In addition, the use of cogeneration has a significant impact on the environment, such as the reduction of greenhouse gas emissions.

Energy generated in cogeneration can be considered as electricity generated in high-efficiency cogeneration, provided that the cogeneration unit PES *(Primary Energy Savings)* achieves:

- PES $\geq$ 10 % - for installations with a capacity above 1 MW;
- PES $\geq$ 0 - for installations with a capacity less than or equal to 1 MW.

Optimisation of recovery process techniques requires plants to be designed to meet the requirements of consumers. It is clear that plants that supply only electricity will be designed differently from those designed to supply only heat. Plants that are intended to supply both electricity and heat will also be designed differently (JRC Report: 327).

Only the right waste resource, as well as an optimal and stable source for the energy produced, is a guarantee for the stability, availability and energy efficiency of the operation of a thermal waste treatment plant. The importance of physical and chemical properties of waste should be emphasized, especially waste containing high-calorific combustible fractions (>6 MJ/kg), which ensure stable operation of installation, with the highest possible recovery efficiency. The most important factors determining the way and effectiveness of the integration of waste incineration plants into the local infrastructure are:

- availability of the power grid,
- demand for the energy produced,
- reliability of the energy source and adequate supply of waste,
- waste composition,
- the level of local prices for electricity and heat (Cyranka, Jurczyk, 2015: 40).

Thermal waste conversion technology should be characterized by low energy consumption and high-efficiency energy conversion and production. In the case of facilities converting only municipal solid waste, the installation should maximize the use of recovered energy to such an extent that the energy efficiency of the installation reaches a level that allows it to obtain the legal status of an installation implementing recovery process R1 (use mainly as a fuel or other means of energy production), according to the criterion indicated in Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), where the average annual energy efficiency factor reaches a minimum value of 0,65 for installations permitted after 31 December 2008. The energy efficiency is then determined from the formula:

$$Energy\ efficiency = \left(E_p - \left(E_f + E_i\right)\right) / \left(0{,}97 \times \left(E_w + E_f\right)\right)$$

In which:
E_p - annual energy produced as heat or electricity. It is calculated with Energy in the form of electricity being multiplied by 2,6 and heat produced for commercial use multiplied by 1,1 (GJ/year)
E_f - annual energy input to the system from fuels contributing to the production of steam (GJ/year)
E_w - annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)
E_i - annual energy imported exluding E_w and E_f (GJ/year)
0,97 - a factor accounting for energy losses due to bottom ash and radiation.

This formula shall be applied in accordance with the reference dokument on Best Available Techniques for waste incineration (OJ EU.L.2008.312.3, as amended: Annex II, Recovery operations). However, it is important to remember that higher process energy efficiency also leads to higher investment and maintenance costs.

Recycling is much less capital-intensive than incineration and often does not need modern technological solutions. The principle of recycling is to maximise the use of waste materials while minimising the input into their manufacture. The energy consumed in the process of making the products in question from primary raw materials will generally be greater than if they were made from secondary raw materials. However, the preparation of the input itself, by which is meant the collection and sorting of waste, can also be costly and energy-intensive (Pikoń, Bogacka 2016: 122).

The gateway to energy security through energy recovery from waste

Energy security is a priority for modern states, both economically, politically, environmentally and socially. The promotion of renewable energy sources is without a doubt among measures conducive to enhancing energy security. Their use affects a country's greater independence from the supply of raw materials (Seroka 2022: 88).

The European Union aims to ensure that citizens and businesses have access to energy that is *'secure, affordable and environmentally friendly'*. Its actions relate to promoting energy efficiency, diversifying energy sources or strengthening the share of energy from renewable sources. The closed-loop (zero-waste) economy promoted by the EU is part of the principle of sustainable development, contributing among other things to reducing the extraction of fossil fuels. Ways of preventing landfill are recycling and energy recovery. Disposing of waste to landfill diminishes the raw material and energy potential of EU countries. The operation of thermal waste treatment facilities with energy recovery counteracts the proliferation of landfill sites and helps to increase Europe's independence from fossil fuel imports, thereby contributing to strengthening energy security, which is in line with the main objectives of EU energy policy (Ecogenerator).

Summary

One of the inevitable consequences of the development of civilisation is the increase in the amount of waste produced. The more developed a country is, the greater the problem becomes. However, economic development must be compatible with environmental protection requirements (Dziolak, 2010: 649). The perceived energy potential in waste has made it possible to look at the problem of waste management in a somewhat softer way. The benefits of waste-to-energy are many, both ecologically and economically. The environmental benefits of recovering energy from waste include reducing the need for fossil fuels, which are non-renewable fossil fuels. The energy use of waste also contributes to reducing the number of landfills, including preventing the dumping of waste with high calorific value. Disposal of waste using traditional methods is a source of significant emissions of harmful gases, especially methane and carbon dioxide. Obtaining energy from waste reduces greenhouse gas emissions and thus counteracts climate change. Some types of waste with favorable energy parameters also contain a biodegradable fraction. The energetic use of such types of waste provides the basis for qualifying the generated energy as coming from renewable sources and leads to an increase in the share of RES in the energy mix. From an economic point of view, it can be said that the energetic use of waste can contribute to lower energy prices and waste management fees. It also creates new jobs. Thermal waste conversion is a good solution, but on condition that the thermal waste conversion plants are operated sustainably, with energy recovery. Such projects in the most developed countries of Europe are already a permanent part of waste management and also a permanent part of the energy industry. The use of waste for energy recovery can certainly be considered a desirable element of any country's energy policy and as a necessary link to closing the model of a closed-loop economy. Technological progress makes it possible to convert waste, in modern installations, into high-quality energy carriers, with no burden on the environment. The most efficient energy recovery is considered to be the cogeneration process, which simultaneously produces electricity and heat. The amount of waste generated and the requirements imposed by the EU make the expansion of energy recovery infrastructure from waste necessary and desirable (Cyranka and Jurczyk, 2016: 99).

What is needed is to increase public awareness and environmental education about the operation of thermal waste conversion plants and to dispel public doubts about the safe and non-hazardous operation of this type of plant.

Bibliography

1. Cyranka M., Jurczyk M., *Skojarzone wytwarzanie energii elektrycznej i cieplnej w spalarniach odpadów komunalnych*, 2015, https://www.researchgate.net/publication/298409548_Skojarzone_wytwarzanie_energii_elektrycznej_i_cieplnej_w_spalarniach_odpadow_komunalnych_-_Combined_production_of_electricity_and_heat_in_municipal_waste_incineration_plants

2. Cyranka M., Jurczyk M., *Uwarunkowania energetyczne, ekonomiczne i prawne odzysku energii z odpadów komunalnych w ramach układów kogeneracji*, "Energy Policy Journal" 2016, Tom 19, Zeszyt 1, s. 99-115.
3. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance) (OJ EU.L.2018.328.82, as amended).
4. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste (Text with EEA relevance) (OJ.EU.L.2018.150.109).
5. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) (OJ EU.L.2008.312.3, as amended).
6. Działak P., *Procesy energetycznego przetwarzania odpadów w wybranych krajach europejskich*, CHEMIK 2010, 64, 10, 649-652.
7. Eurostat: online data code: ENV_WASTRT, (accessed: 18.04.2023), https://ec.europa.eu/eurostat/databrowser/view/ENV_WASTRT/default/table?lang=en
8. Fabielec S., Fabielec J., *Ekonomiczne i techniczne uwarunkowania procesów spalania odpadów komunalnych*, Prace naukowe Uniwersytetu Ekonomicznego we Wrocławiu: Ekonomika ochrony środowiska i ekoinnowacje, Wyd. Uniwersytetu Ekonomicznego we Wrocławiu, 2016, nr 454, s. 174-185.
9. HNL, https://hnl.pl/kogeneracja.html (accessed: 17.07.2023)
10. https://www.gensler.com/blog/circular-economy-reusing-materials-to-save-cost-lower-carbon
11. Jędrzejowski P., Latosiński J., *Comparison of energy efficiency of the municipal waste treatment plant in Krakow and Bialystok*, "Structure and Environment" 2018, Vol. 10 no 4, s. 357-366.
12. Neuwahl F., Cusano G., Sprawozdanie JRC „Nauka dla polityki" Dokument referencyjny dotyczący najlepszych dostępnych technik (BAT) w zakresie spalania odpadów, 2019.
13. Pikoń K., Bogacka M., *Gospodarowanie odpadami a odzysk energii*, "Napędy i Sterowanie" 2017, nr 4, s. 120-124.
14. Regulation of the Minister of the Environment of 8 June 2018 on the technical conditions for qualifying the portion of energy recovered from thermal waste conversion (Journal of Laws 2016 item 847).
15. Seroka A., *Odnawialne źródła energii jako element zarządzania bezpieczeństwem energetycznym państwa*, "Research Reviews of Czestochowa University of Technology. Man-agement" 2022, nr 46, s. 88-100.
16. Spalarnie w Europie, https://ecogenerator.eu/ecogenerator/spalarnie-w-europie.html, (accessed: 20.04.2023)
17. The Treaty on the Functioning of the European Union (OJ EU.L.2012.326.47, as amended)
18. Wasilewski R., Bałazińska M., *Odzysk energii z odpadów w aspekcie kwalifikacji wytworzonej energii elektrycznej i ciepła jako pochodzącej z odnawialnego źródła energii oraz uczestnictwa w systemie handlu uprawnieniami do emisji gazów cieplarnianych*, "Energy Policy Journal" 2018, Tom 21, zeszyt 1, s. 129-142.

19. Wasilewski R., Stelmach S. i in., *Analiza porównawcza węgla i odpadów dla produkcji ciepła i/lub energii elektrycznej*, "Archives of Waste Management and Environmental Pro-tec-tion" 2015, vol. 17, issue 3.
20. Waste Act of 14 December 2012 (Journal of Laws 2022 item 699, as amended).
21. Wilk M., Magdziarz A., *An evaluation of renewable fuels microstructure after the combustion process*, "Jurnal of Power Technologies" 2017, 97(4), s. 265-271.

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