www.rsd.tfbor.bg.ac.rs

Recycling and Sustainable Development

RSD

Online ISSN 2560-3132
Print ISSN 1820-7480

Municipal Solid Waste-to-Energy in EU-27 towards a Circular Economy

Georgios Tsekeris #, Georgios N. Anastassakis

[a] National Technical University of Athens, School of Mining and Metallurgical Engineering, Greece

A R T I C L E I N F O

Received 05 May 2022
Accepted 24 August 2022

Research article

Keywords:
Circular Economy
EU-27
Energy Recovery from Municipal Solid Waste
Municipal Solid Waste
WtE Technologies

A B S T R A C T

The current work deals with the energy recovery, through incineration (R1) and biological treatment (R3), from municipal solid waste (MSW), within EU-27 in a Circular Economy approach. The EU legislation is analyzed in reference to the production and management of MSW for energy recovery along with the Waste-to-Energy processes (Incineration, Anaerobic Digestion and Composting, Pyrolysis, Gasification, Plasma technology, and Landfill gas). As reference years, 2015 and 2019 have been considered, which are the corresponding years of the first European plan towards a Circular Economy (COM - (2015) - 614) and the year before COM-(2020)-98. Also, the following data have been collected and elaborated from each Member State for the years 2015 and 2019: the total MSW generated, the total MSW used for energy recovery through incineration and biological treatment, the primary energy production from renewable and non-renewable MSW, and the gross domestic energy consumption by MSW-generated energy. The main conclusion drawn from this work was the growing trend of the quantities of MSW used for energy recovery in EU-27 and the increasing trend of primary energy production from MSW that EU followed as aggregate. It was observed that for some Member States, energy followed increasing trend, of higher or lower rate, while for other showed descending trend. Despite the overall increasing trend of energy production from MSW, the rate is still relatively low, at least for some countries, and greater effort is required for their compliance with EU policy towards a Circular Economy approach.

1. Introduction

High levels of environmental pollution, overexploitation of resources, water and land pollution are subjects of main concern worldwide. The huge production of waste, combined with the inefficiency of their management, works negatively in reference to the improvement of living standards and achievement of sustainable development. It is therefore necessary to reduce waste production as much as possible and increase their management level. Given that the overconsumption of resources continues, waste production is expected to increase by 70 % until 2050 (COM-(2020)-98). As a result, the situation must be addressed immediately, in order to conserve resources and reduce the amount of waste generated. For this reason, the European Commission suggested the EU action plan for Circular Economy, on 2 December 2015. Circular Economy is characterized by an innovative economic system, which is totally different from the linear economy (produce - consume - reject), as the value of the products remains in the economy and resource utilization is maintained to a minimum (COM-(2015)-614). As it is referred in this action plan, the transition to the Circular Economy will

Corresponding autor: georgetsekeris@gmail.com

doi: 10.5937/ror2201085T

be an opportunity for the European Economy to transform and for Europe to gain new, sustainable competitive advantages (COM-(2015)-614). It is important to note that the relationship between the concepts of Circular Economy and Sustainability is not clear and efforts are being made through the existing literature to clearly define their similarities and differences (Geissdoerfer et al., 2017).

In 2018, four new Directives (2018/849, 2018/850, 2018/851, 2018/852) on solid waste were legislated by the European Union, in which the term "Circular Economy" appeared for first time. These new Directives have set higher targets in terms of recycling, separation at source and diversion of waste from landfilling (Komilis, 2020). No later than 31 December 2030 a minimum of 70 % by weight of all packaging waste must be recycled (Directive 2018/852/EU). By 2025, 2030, and 2035 the preparation for re-use and recycling of municipal waste should be increased to 55 %, 60 %, and 65 % by weight, respectively (Directive 2018/851/EU). By 2035, the amount of municipal waste ending up in landfills should be 10 % by weight or even less of the total amount of municipal waste generated (Directive 2018/850/EU). According to the European Commission (2021), "The EU aims to be climate-neutral by 2050 - an economy with net-zero greenhouse gas emissions". To achieve this target, the waste hierarchy must be respected. According to the Directive 2008/98/EC of the European Commission, the following waste hierarchy "shall apply as a priority order in waste prevention and management legislation and policy": i) prevention, ii) preparing for re-use, iii) recycling, iv) other recovery, e.g., energy recovery, and v) disposal (Directive 2008/98/EC). It is obvious that Waste-to-Energy (WtE) is the last option before landfilling of non-recyclable waste. This method of waste treatment has some serious benefits over landfilling such as the destruction of pathogens, the reduction of greenhouse gas emissions, the recovery of metals, etc. (Bourtsalas and Themelis, 2017). WtE technology has also a lot of benefits contributing to a Circular Economy. Energy production from waste can prevent the production of 50 million tons of carbon dioxide produced using fossil fuels (Levaggi et al., 2020). For example, in 2015, 90 million tons of waste in the EU was thermally treated at WtE facilities generating 90 TWh of heat and 40 TWh of electricity, saving 50 million tons of fossil fuels, and avoiding the production of 49 tons of carbon dioxide (CEWEP, 2021). With this method of waste treatment, energy can be produced either in the form of fuel or electricity and/or heat. WtE can also contribute to the reduction of the amount of waste, which is landfilled; hence, the production of methane is reduced too. In addition, recovery of metals from the bottom ash, left after incineration, is also possible. Effective source separation can prevent the entrance of recyclable waste (e.g., plastics) in WtE plants, reducing in this way the CO_2 emissions (CEWEP, 2021). This is sustained by Quina et al. (2011) whose research on the health impact of emissions from municipal solid waste incineration revealed that no health problems can be related to modern incinerators for MSW.

In 2017, the Document of European Commission COM-(2017)-34, about the role of waste to energy in a Circular Economy, was presented based on COM-(2015)-614. Communication (2017)-34 of the European Commission focuses on energy recovery from waste and its position in the Circular Economy. This document covers the following five WtE processes:

<u>Co-incineration of waste in incineration plants, as well as in the production of cement and lime (COM-(2017)-34).</u> According to a relevant study (Galvez-Martos et al., 2014), it was observed that with the use of waste-derived fuels, instead of fossil fuels, a large part of the emission becomes biogenic; simultaneously, the co-incineration of waste-derived fuels in cement plants may be linked with energy loss, which can neutralize the benefit of replacing carbon dioxide from fossil fuels with biogenic carbon dioxide from waste. Reducing the clinker factor can significantly help reduce carbon dioxide emissions and be more effective than substituting fossil fuels for waste-derived fuels. <u>Incineration of waste in special facilities (COM-(2017)-34).</u> In this case, special facilities are used for the incineration of municipal solid waste, where the plants have higher energy efficiency (R1) of 0.6 and 0.65, as will be discussed in more detail in the present work.

<u>Anaerobic digestion of biodegradable waste (COM-(2017)-34).</u> Organic waste (proteins, carbohydrates, fats) is converted by hydrolysis to soluble organic molecules (amino acids, sugars, and fatty acids, respectively); then, through the generation of acids (acidogenesis) a part of the hydrolysis products is converted directly to acetic acid, hydrogen, and carbon dioxide. The part of the products from acid production that has not been properly converted, i.e., the intermediate products (butyric acid, propionic acid, etc.), are subjected to the production of acetic acid (acetogenesis), in which only acetic acid, hydrogen, and carbon dioxide are produced in this process. The last process is the generation of methane (methanogenesis), through which acetic acid, hydrogen, and carbon dioxide are converted to methane and carbon dioxide (Abdelgadir et al., 2014; Tsekeris, 2021;). Pre-treatment of biomass before anaerobic digestion is mandatory to improve the biodegradability of the raw material and produce enhanced biogas. According to a recent research (Varjani et al., 2022), the physicochemical pretreatment method has benefits in enhancing hydrolysis throughout the digestion of waste biomass.

<u>Production of solid, liquid, and gaseous fuels from waste (COM-(2017)-34).</u> Since prevention, reuse, and recycling are preferable to WtE, more emphasis should be placed on the above-mentioned waste management processes and more research should be carried out on

other types of raw materials that can be converted into fuels. Lignin, for example, is a key raw material of high interest where efficient methods have been developed for its conversion into various forms of biofuels (solid, liquid, and gaseous). Although methods of converting lignin to biofuels have evolved, more research is needed in order to meet energy needs in the future (Suresh et al., 2021).

Other processes involving indirect incineration after the pyrolysis or gasification stage (COM-(2017)-34). Pyrolysis is a well-known waste management process and is characterized as the process of thermal decomposition of solid fuels, which takes place in environment with absence of oxygen or under conditions of limited oxygen; the final products are gases (carbon dioxide, methane, hydrogen, etc.), liquids (a mixture of oily form of high viscosity and density consisting of oxygenated hydrocarbons, methanol, acetone, and acetic acid) and solids (residue consisting of almost solid carbon) (Tchobanoglous and Kreith, 2002). Relevant research conducted (Reza et al., 2022) shows that the pyrolysis of fish waste (bluespotted stingray) can be an important source of biofuels, which makes this category of waste as a good alternative energy source. Regarding gasification, it is one of the thermal conversion processes available for the thermal treatment of solid waste. Gasification of biomass is a process of incomplete combustion (partial presence of oxygen) of biomass, resulting in the production of fuel gases consisting of hydrogen, carbon monoxide and methane (Rajvanshi, 1986; Belgiorno et al., 2003; Tsekeris, 2021). It seems that co-gasification using two raw materials is more beneficial than simple gasification in terms of better process efficiency as well as tar formation (Yang et al., 2021). Recently, the production of hydrogen-enriched syngas through a combined gasification pressurized system, which is being investigated in a novel integration with geothermal energy, has aroused interest (Gungor and Dincer, 2022).

These processes have different environmental impacts; therefore, they have a different rank in waste hierarchy. For example, incineration and co-incineration with limited energy recovery are considered as disposal (D10). On the contrary, incineration and co-incineration with high energy recovery are considered as recovery (R1). Regarding anaerobic digestion of organic waste, it is considered as recycling (R3) (Directive 2008/98/EC; COM-(2017)-34). According to the Document COM-(2017)-34 of the European Union, the most efficient methods of energy recovery from waste are listed below (Komilis, 2020):

i. upgrading of biogas into bio-methane for further distribution and use,
ii. gasification of solid recovered fuel (SRF) and combustion of the produced gaseous fuel to replace fossil fuels in thermal and electric power plants,
iii. co-existence of waste incineration plants with neighboring industries with the former targeting to waste management of the latter while they will provide heat and electricity to the industry that produces waste,
iv. co-incineration of waste together with fossil fuels for the production of lime and cement and preference for the operation, and
v. construction of combined heat and power (CHP) waste incineration plants because they achieve higher energy efficiencies than the types of municipal solid waste incinerators that recover only electricity or only heat.

The European Commission anticipates by applying these processes, it is possible for the amount of energy recovered from waste to rise by 29 % using the same amount of waste (COM-(2017)-34). It seems that the energy recovery from waste can contribute to the promotion of the Circular Economy, through reducing the volume of waste generated, while, at the same time, generating energy and reducing greenhouse gas emissions. It is important to note that energy recovery from waste is preferred from landfill only, according to waste hierarchy, as prevention, reuse, and recycling are of major priority. Waste-to-energy is a widespread method of waste treatment, and it is widely applied both in Europe and other countries. Although WtE has some benefits in establishing a Circular Economy, as described above, there are two main negative factors that need to be considered. The first major negative factor in municipal solid waste incineration is the production of negative carbon dioxide because part of carbon in waste is biogenic (Wienchol, 2020). As for the second dangerous feature, it is the hazardous fly ash and the residues left after incineration (Quina et al., 2011).

The current study deals with the subject of energy recovery from municipal solid waste (MSW) in a Circular Economy and the corresponding activity of EU Member States in this regard. To clarify, the term waste-to-energy denotes the processes of thermal treatment (Incineration with energy recovery, Pyrolysis, Gasification, and Plasma technology), biological treatment (Composting and Anaerobic Digestion), and landfilling (Landfill gas) (Kumar and Sammader, 2017; Komilis, 2020). As the most of Waste-to-Energy processes have been analyzed above, it is important to explain the plasma technology for a complete picture of the WtE operations. During the plasma technology, municipal solid waste is converted to gases and to an inert solid residue; it is reported that this method of waste treatment is still in the experimental stage for MSW (Komilis, 2020). Regarding composting, it is discussed in more detail further in this work. WtE is one of the most common methods used for MSW (Psomopoulos et al., 2009). Therefore, in this study, an attempt has been made to approach the issue, based on statistics, in order to determine the changes brought about by the Circular Economy, in terms of MSW quantities used for energy recovery through incineration with energy recovery (R1) and biological treatment (R3) by the Member States, for the years before and after the implementation of the Circular Economy, namely 2015 and 2019; it must be pointed out that the data for each one of EU-27 Member States have been collected and elaborated by the authors of the current work.

2. Materials and Methods

2.1. Municipal Solid Waste

In this study, data was collected for each one Member State regarding the production of the total municipal solid waste, the portion of generated MSW used for energy recovery (incineration (R1) and biological treatment (R3)), the amount of primary energy produced and the gross inland energy consumption by MSW-generated energy for the years 2015 and 2019.

In the category of municipal waste, mixed waste, separately collected waste from households (e.g., textiles, packaging, glass, waste electrical and electronic equipment, bulky waste, metals, plastics, bio-waste, wood, paper, and cardboard) and separately collected waste from other sources of similar nature and composition to the waste from households were included. Waste from forestry, agriculture, fishing, production, septic tanks and sewage network, and treatment was not included in the category of municipal waste. Also, waste such as end-of-life vehicles, wastes from construction and demolition, sewage sludge were not included (Directive 2018/851/EU).

2.2. Municipal Solid Waste generation in EU-27 in 2015 and 2019

Municipal waste accounts for approximately between 7 and 10 % of total waste generated in the EU (Directive 2018/851/EU). For example, the total waste production in 2018 was 2336.7 million tons (Mt), out of which the total municipal waste produced for the same year was 221.61 Mt (Eurostat, 2021). Therefore, the percentage of municipal waste was about 9.48 % of the total. This category of waste is too difficult to be managed due to its complex and mixed composition. Consequently, it requires effort from citizens and enterprises to achieve higher management level (Directive 2018/851/EU). Table 1 shows the quantity of municipal solid waste generated in 2015 and 2019 and the percentage of change between these years in the EU-27 (Eurostat, 2021).

Table 1
EU-27: Municipal Solid Waste generated, 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	213.409	224.447	5.17
Belgium	4.643	4.779	2.9
Bulgaria	3.011	2.862 (2018)	-4.94 (2015-2018)
Czech Republic	3.337	5.338	59.96
Denmark	4.671	4.907	5.05
Germany	51.625	50.612	-1.96
Estonia	0.473	0.49	3.59
Ireland	2.763 (2016)	2.912 (2018)	5.39 (2016-2018)
Greece	5.277	5.613	6.36
Spain	21.158	22.438	6.04
France	34.344	36.74	6.97
Croatia	1.654	1.812	9.55
Italy	29.524	30.023	1.69
Cyprus	0.525	0.566	7.8
Latvia	0.798	0.84	5.26
Lithuania	1.3	1.319	1.46
Luxembourg	0.346	0.491	41.9
Hungary	3.712	3.78	1.83
Malta	0.285	0.35	22.8
Netherlands	8.866	8.806	-0.67
Austria	4.836	5.22	7.9
Poland	10.863	12.753	17.39
Portugal	4.769	5.281	10.73
Romania	4.904	5.43	10.72
Slovenia	0.926	1.052	13.6
Slovakia	1.784	2.299	28.86
Finland	2.738	3.123	14.06
Sweden	4.422	4.611	4.27

As it can be observed from Table 1, there are huge differences in municipal solid waste generation between the Member States. According to the analysis made by the authors, this is due to the huge variations observed in the production of municipal solid waste (in kg per inhabitant). Combining the results of the analysis with a recent survey (Minelgaitė and Liobikienė, 2019), it seems that the level of municipal solid waste production depends significantly on the economic development of each Member State. Therefore, in the most economically prosperous countries there is production of more municipal solid waste per inhabitant, thus contributing to the production of large quantities of MSW in these countries (e.g., Denmark, Germany, etc.).

2.3. Municipal Solid Waste management in EU-27 in 2015 and 2019

Figure 1 shows the quantity of MSW that was managed in the EU-27 for the years 2015 and 2019. The generated MSW was subjected to either disposal (D) or recovery (R) operations. The 1st pair of bars in Figure 1 refers to the amount of MSW which was treated. The 2nd and 3rd pairs of bars refer to the amount of MSW that was subjected to disposal operations. In the 2nd pair of bars the following operations were included: the disposal operations D1 (deposit into or on to land), D2 (land treatment), D3 (deep injection), D4 (surface impoundment), D5 (specially engineered landfill), D6 (release into a water body), D7 (release to seas/oceans), and D12 (permanent storage) (Directive 2008/98/EC). The 4th, 5th and 6th pairs of bars refer to the amount of MSW that was subjected to recovery operations. In the last pair of bars, the amount of MSW that was generated but not managed (uncontrollable rejection) is presented (Eurostat, 2021). Figure 1 presents the municipal solid waste management in the European Union. It is interesting to refer to the conclusions of a study (Minelgaitė and Liobikienė, 2019), according which, despite the increasing level of prevention and reuse of MSW, no significant impact on their generation was observed.

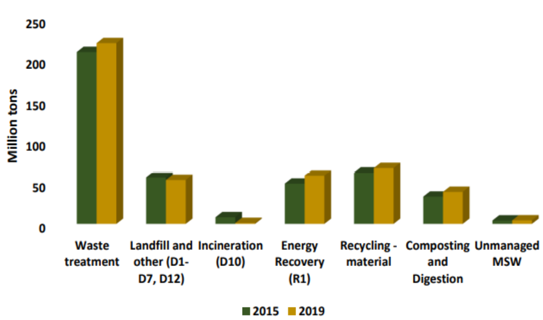

Figure 1. EU-27: Municipal Solid Waste management in 2015 and 2019

By considering 2010 (Eurostat, 2021) as reference year (instead of 2015), huge improvement over a period of nine years (2010-2019) is observed, in terms of the quantity of waste incinerated without energy recovery (D10) in the EU-27 (Eurostat, 2021). This quantity was about 13.105 million tons (Mt) and 1.121 Mt in 2010 and 2019, respectively (decrease by -91.44 %). For example, a great reduction of the quantity of MSW incinerated without energy recovery was observed in Germany (from 10.534 Mt in 2010 to 0.484 Mt in 2019). The rate of this reduction was about -95.4 %. The Netherlands reduced this amount from 1.833 Mt (2010) to 0.095 (2019) (- 94.81 % reduction). Also, in France the amount reduced from 0.42 Mt (2010) to 0.069 Mt (2019) or by -83.57 % (Eurostat, 2021). This study deals with the energy recovery from MSW through incineration (R1) and biological treatment (R3) in the EU-27 in 2015 and 2019. Tables 2 and 3, in the following sections 2.4 and 2.5, show the amount of MSW incinerated with energy recovery (R1) and the amount of MSW biologically treated (R3, Composting and digestion).

2.4. Incineration (R1) of Municipal Solid Waste with energy recovery, in EU-27, in 2015 and 2019

The recovery operation R1, which is defined as the "use of waste mainly as a fuel or as another means of generating energy", includes the incineration facilities dedicated to the processing of MSW only if their energy efficiency is equal to or higher than:

i. 0.60 for installations licensed before 1 January 2008 and
ii. 0.65 if licensed after 31 December 2008 (Directive 2008/98/EC).

According to a survey conducted in 2010 (Grosso et al., 2010), the distribution of plants dedicated to the processing of MSW in Europe was:

i. 43.5 % of MSW plants have energy efficiency higher than 0.65,
ii. 13.5 % of MSW plants between 0.60 and 0.65, and
iii. the remaining 43 % lower than 0.6, namely without energy recovery.

According to data obtained from CEWEP (2021) and Scarlat et al. (2019), the number of WtE plants differs significantly between the Member States. There are 121 WtE plants in France, followed by Germany (96), Italy (38), Sweden (37), Denmark (26), Belgium (17), The Netherlands (12), Spain (12), Austria (11), Finland (9), Poland (7), Czech Republic (4), Portugal (4), Slovakia (2), Ireland (2), Estonia (1), Lithuania (1), Hungary (1), Luxemburg (1), and Malta (1).

Before referring to the quantities of MSW incinerated with energy recovery, it is important to mention a characteristic of waste that plays a vital role in their incineration, known as heating value. Heating value is defined as the amount of energy generated from the complete combustion of a fuel; it can be expressed either as higher heating value (or higher calorific value), in which the latent heat of evaporation of water is included, or lower heating value (or net calorific value), in which the latent heat of evaporation of water is not included (Anastassakis, 2001). A recent survey carried out by Taki and Rohani (2022) concluded that the machine learning method, known as Radial Bias Function Artificial Neural Network, could predict the higher heating value of municipal solid waste more accurately in comparison with other models. The heating value of MSW ranges between 8 MJ/kg (Megajoule/kilogram) and 14 MJ/kg (Themelis et al., 2013). The average heating value of MSW is about 10 MJ/kg. For this reason, municipal solid waste is used for energy production (Malinauskaite et al., 2017). One ton of MSW, with heating value of 10 MJ/kg, produces thermal energy of approximately 2.78 MWh (Themelis et al., 2013). According to the International Energy Agency (IEA), 1 ton of oil equivalent (toe) or 1.429 ton of coal equivalent equals to the production of 11.63 MWh (IEA, 2021), which means that about four tons of municipal solid waste with heating value of 10 MJ/Kg equals to 1 ton of oil or 1.429 tons of coal. Generally, if a waste possesses heating value lower than 2.32 MJ/kg (e.g., stones, concrete blocks, etc.), it is considered unsuitable for incineration. Waste to be incinerated are wood, paper, rubber scraps, cartons, plastic scraps, rags, garbage and rubbish, vegetal and animal waste, etc. (Tchobanoglous and Kreith, 2002) In order to determine the capacity for the incineration of waste, the following five factors are taken into account:

i. the heating value,
ii. the moisture content of waste,
iii. the inorganic salts,
iv. the radioactive wastes, and
v. the high content of halogens or sulfur (Tchobanoglous and Kreith, 2002).

Table 2 shows the quantity of MSW incinerated in 2015 and 2019 in the EU-27 and the percentage change between these years (Eurostat, 2021).

2.5. Biological treatment (R3) of Municipal Solid Waste (Composting and Anaerobic Digestion) in 2015 and 2019, in EU-27

Table 3 shows the quantity of MSW that was biologically treated (R3) in the EU-27 in 2015 and 2019, through composting and digestion (Eurostat, 2021). Composting is a biological process of degradation and stabilization of organic materials. This procedure consists of three basic processes regarding the MSW:

Table 2
EU-27: Municipal Solid Waste incinerated with energy recovery, 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	48.972	58.62	19.7
Belgium	2.014	2.021	0.34
Bulgaria	0.082	0.208 (2018)	153.6 (2015-2018)
Czech Republic	0.586	0.868	48.12
Denmark	2.396	2.333	-2.62
Germany	12.068	15.98	32.41
Estonia	0.243	0.221	-9.05
Ireland	0.811 (2016)	1.243 (2018)	53.26 (2016-2018)
Greece	0.018	0.074	311.11
Spain	2.685	2.533	-5.6
France	11.957	12.461	4.21
Croatia	0	0.001	-
Italy	2.969	5.711	92.35
Cyprus	0	0.005	-
Latvia	0.015	0.028	86.66
Lithuania	0.15	0.194	29.33
Luxembourg	0.156	0.229	46.79
Hungary	0.525	0.515	-1.9
Malta	0.004	0	-
Netherlands	4.057	3.577	-11.83
Austria	1.833	2.004	9.32
Poland	1.318	2.742	108.04
Portugal	0.941	0.996	5.84
Romania	0.116	0.251	116.37
Slovenia	0.158	0.136	-13.92
Slovakia	0.191	0.125	-34.55
Finland	1.312	1.735	32.24
Sweden	2.284	2.427	6.26

Table 3
EU-27: Municipal Solid Waste biologically treated (composting and digestion), 2015-2019 (Million tons)

	2015	2019	% Change 2019/2015
EU-27	33.122	38.946	17.58
Belgium	0.9	0.982	9.11
Bulgaria	0.311	0.052 (2018)	-83.27 (2015-2018)
Czech Republic	0.141	0.602	326.95
Denmark	0.858	0.882	2.8
Germany	9.298	9.442	1.54
Estonia	0.017	0.012	-29.41
Ireland	0.19 (2016)	0.245 (2018)	28.94 (2016-2018)
Greece	0.135	0.283	109.62
Spain	2.452	3.751	52.97
France	6.186	7.394	19.52
Croatia	0.028	0.063	125
Italy	5.203	6.387	22.75
Cyprus	0.018	0.008	-55.55
Latvia	0.047	0.042	-10.63
Lithuania	0.132	0.293	121.96
Luxembourg	0.063	0.094	49.2
Hungary	0.231	0.353	52.81
Malta	0	0	0
Netherlands	2.414	2.569	6.42
Austria	1.511	1.677	10.98
Poland	0.611	1.153	88.7
Portugal	0.745	0.883	18.52
Romania	0.365	0.239	-34.52
Slovenia	0.071	0.176	147.88
Slovakia	0.13	0.269	106.92
Finland	0.341	0.442	29.61
Sweden	0.684	0.653	-4.53

i. processing of the MSW,
ii. decomposition of the organic MSW, and
iii. preparation of the final compost (Hamoda et al., 1998).

This final product can be used as soil fertilizer. Regarding anaerobic digestion, it is also a biological waste process, which provides with biogas and a final solid residue (digestate) with potential fertilizer characteristics (Komilis, 2020). The most common biomass used for biogas production is:

i. the organic fraction of municipal waste,
ii. the agricultural residues and by products,
iii. the animal manure and slurry,
iv. the digestible organic wastes from food, and
v. the sewage sludge, etc. (Adekunle and Okolie, 2015).

Of particular interest is the production strategy of soil amendment products and biogas through anaerobic digestion of biodegradable MSW at first and then composting of the solid residue, according to relevant research (Preble et al., 2020).

2.6. Primary energy production from municipal solid waste, in EU-27, in 2015 and 2019

In this work, the data regarding the production of primary energy from renewable and non-renewable municipal solid waste for the years 2015 and 2019 were collected for each Member State. Primary energy production from municipal solid waste (MSW) represents the heat produced after combustion (corresponding to the net heating value). As for anaerobic digestion of wet wastes, primary energy production corresponded to the net heating value (heat content) of the biogases generated, including the gases consumed in the installation for the fermentation processes but not of flare (European Commission - Eurostat, 2015). It must be pointed out that renewable was characterized the portion of the municipal waste that was of biological origin (e.g., newspaper, textiles, leather, food wastes, mixed paper, containers and packaging, wood, etc.), while non-renewable the portion of non-biological origin (e.g., plastics, rubber, etc.). These types of wastes were produced by hospitals, the tertiary sector, and households, and incinerated at dedicated installations (EIA, 2007; Commission Regulation 844/2010/EU). Table 4 shows the primary energy production from renewable and non-renewable municipal waste in the EU-27 in 2015 and 2019 and the percentage of change between these years (Eurostat, 2021).

2.7. Gross inland energy consumption by MSW-generated energy

Figure 2 shows the percentages of the gross energy generated from all MSW sources and consumed within each Member State of EU-27 for the years 2015 and 2019 (Eurostat, 2021). According to Eurostat (2021), the gross inland energy consumption is defined as the total energy demand of a country or region, representing the quantity of energy necessary to satisfy inland consumption of the geographical entity under consideration. To obtain the per cent change, the data regarding the gross energy generation from all MSW sources and the percentage of its recovery and consumption were collected and processed by the authors.

Table 4
EU-27: Primary energy production from Renewable and Non-Renewable Municipal Solid Waste, 2015-2019 (Million tons of oil-equivalent)

	2015	2019	% Change 2019/2015
EU-27	16.831	17.987	6.86
Belgium	0.728	0.727	-0.13
Bulgaria	0.015	0.057 (2018)	280 (2015 - 2018)
Czech Republic	0.132	0.151	14.39
Denmark	0.836	0.809	-3.22
Germany	5.988	6.182	3.23
Estonia	0.045	0.042	-6.66
Ireland	0.129 (2016)	0.285 (2018)	120.93 (2016 - 2018)
Greece	0	0	0
Spain	0.504	0.51	1.19
France	2.444	2.51	2.7
Croatia	0	0	0
Italy	1.69	1.746	3.31
Cyprus	0.0005	0.002	300
Latvia	0.006	0.015	150
Lithuania	0.031	0.034	9.67
Luxembourg	0.032	0.037	15.62
Hungary	0.112	0.105	-6.25
Malta	0	0	0
Netherlands	1.436	1.448	0.83
Austria	0.462	0.472	2,16
Poland	0.156	0.487	212.17
Portugal	0.194	0.206	6,18
Romania	0.003	0.004	33.33
Slovenia	0	0	0
Slovakia	0.038	0.056	47.36
Finland	0.471	0.601	27.6
Sweden	1.365	1.485	8.79

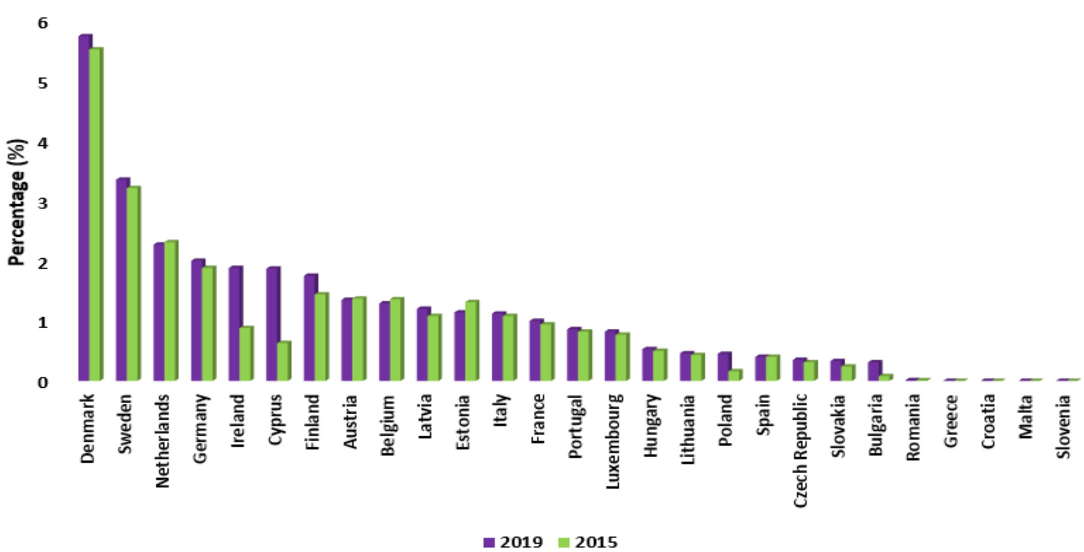

Figure 2. Percentage (%) of energy generated from MSW (renewable and non-renewable) used to cover the gross inland energy consumption in EU-27, in 2019 and 2015

3. Results and Discussion

Table 1 shows that the amount of MSW generated in EU-27 in 2019 was 5.17 % higher than that of 2015. Only in three European countries, the amount of MSW was reduced. These countries were Bulgaria (-4.94 %, comparison period 2015-2018), Germany (-1.96 %), and the Netherlands (-0.67 %). In all other Member States, the increase of this rate was observed. The highest MSW generation in 2019 was observed in Germany (50.62 million tons), followed by France (36.74 Mt), Italy (30.023 Mt), Spain (22.438 Mt), Poland (12.753 Mt), and the other Member States. The highest change, between the generated MSW in 2015 and 2019, was observed in Czech Republic (59.96 %), followed by Luxemburg (41.9 %), Slovakia (28.86 %), Malta (22.8 %), Poland (17.39 %), Finland (14.06 %), Slovenia (13.6 %) and other countries.

Figure 1 shows that the highest change regarding the recovery operations of MSW in EU-27 between 2015 and 2019 was observed in energy recovery (R1) operation (19.7 %), followed by composting and digestion (17.58 %), and recycling (8.62 %). Regarding the percentage of incineration of MSW without energy recovery, it decreased by -86.03 % and the percentage of landfill and other disposal operations decreased by -5.56 %. Based on the aforementioned, it is concluded that the amount of waste subjected to recovery operations increased while the amount of waste subjected to disposal operations decreased. Therefore, it seems that the management of MSW in the European Union is getting improved.

The largest amount of MSW incinerated for energy recovery in 2019 was observed in Germany (15.98 million tons), followed by France (12.461 Mt), Italy (5.711 Mt), the Netherlands (3.577 Mt), Poland (2.742 Mt), Spain (2.533 Mt), Sweden (2.427 Mt), Denmark (2.333 Mt), Belgium (2.021 Mt) and the other countries (Table 2). The highest change between the amount of MSW incinerated for energy recovery in 2019 compared to 2015 was observed in Greece (311.11 %) but with low incinerated quantity, followed by Bulgaria (153.6 %, comparison period 2015-2018), Romania (116.37 %), Poland (108.94 %), Italy (92.35 %), Latvia (86.66 %) and other countries. In some Member States less MSW was incinerated for energy recovery in 2019 compared to 2015. These countries were Slovakia (-34.55 %), Slovenia (-13.92 %), the Netherlands (-11.83 %), Estonia (-9.05 %), Spain (-5.6 %), Denmark (-2.62 %) and Hungary (-1.9 %), as observed in Table 2.

The largest amount of MSW biologically treated (composting and digestion) in 2019 was observed in Germany (9.442 million tons), followed by France (7.394 Mt), Italy (6.387 Mt), Spain (3.751 Mt), the Netherlands (2.569 Mt), Austria (1.677 Mt), Belgium (2.021 Mt) and the other Member States (Table 3). The highest change for the MSW biologically treated in 2019 compared to 2015 was observed in Czech Republic (326.95 %), followed by Slovenia (147.88 %), Croatia (125 %), Lithuania (121.96 %), Greece (109.62 %), Slovakia (106.92 %) and other countries. There were some countries where less municipal solid waste was biologically treated in 2019 compared to 2015. These countries were Bulgaria (-83.27 %), Cyprus (-55.55 %), Romania (-36.52 %), Estonia (-29.41 %), Latvia (-10.63 %), and Sweden (-4.53 %), as observed from Table 3.

In case of Member States with negative incineration (R1) and biological treatment (R3) rates, data were collected and analyzed to investigate whether there was a reduction in quantities leading to disposal operations (D1-D7, D12) and an increase in regards to recycling. As it was observed, there was an increase in recycling rates, between 2015 and 2019, in Slovakia (352.9 %), Latvia (65.9 %), Bulgaria (48.1 %, 2015-2018), Romania (35.2 %), Cyprus (23.1 %), Denmark (21.4 %), Estonia (18.8 %), Spain (12.5 %), the Netherlands (12.1 %), Sweden (5.5 %), Hungary (4.4 %), and Slovenia (3.9 %) and a decrease in disposal operations rates, in Slovakia (-2.9 %), Latvia (-2.4 %), Bulgaria (-12.1 %, 2015-2018), Cyprus (-7.5 %), Denmark (-24.6 %), Spain (-1.73 %), the Netherlands (-0.8 %), Sweden (0 %), Hungary (-3.7 %), and Slovenia (-48.5 %), except Romania (17.1 %) and Estonia (142.8 %) (Eurostat, 2021). According to the aforementioned, the Member States with negative incineration and biological treatment rates increased the amount of waste recycled in 2019 compared to 2015. The same applied to the quantities of waste subjected to disposal operations (D1-D7, D12), except for Estonia and Romania, where the quantity of wastes directed to disposal operations increased by 142.8 % and 17.1 %, respectively. As for Sweden, in case of waste disposal (D1-D7, D12) it seems that the percentage did not change. The purpose of this analysis was to investigate whether the situation improved in other municipal solid waste management processes as there was a reduction in incineration energy recovery rates (Slovakia, Slovenia, the Netherlands, Estonia, Spain, Denmark and Hungary) and in biological treatment rates (Bulgaria, Cyprus, Romania, Estonia, Latvia and Sweden).

Figure 3 shows the percentage of MSW incinerated for energy recovery and the percentage of MSW biologically treated in relation to the total MSW generated in each Member State for the year 2019. In the Nordic countries a great share of the generated MSW was incinerated for energy recovery (R1). In Finland, for example, the share was 55.55 %, in Sweden 52.63 %, and in Denmark 47.54 %. Luxembourg (46.63 %), Estonia (45.1 %), Ireland (42.68 %, 2018), Belgium (42.28 %), the Netherlands (40.62 %), Austria (38.39 %), France (33.91 %), and Germany (31.57 %) also showed high percentages. In most Member States, the share of MSW incinerated with energy recovery (R1) was greater that the corresponding biologically treated (R3). For example, in Poland, a smaller amount of MSW was biologically treated (9.04

%) than incinerated for energy recovery (21.5 %). In nine Member States only, the amount of MSW biologically treated was higher than the incinerated for energy recovery. These countries were Italy, Lithuania, Slovenia, Spain, Slovakia, Latvia, Greece, Cyprus, and Croatia.

An innovative method (Chen et al., 2022), according which anaerobic digestion of organic waste and incineration of municipal solid waste are combined for energy production is interesting. As biogas is recovered through anaerobic digestion, it is collected and used by a gas turbine in order to enhance the steam cycle of the incineration unit with significant financial benefits.

According to Table 4, the largest production of primary energy from renewable and non-renewable municipal waste in 2019 was observed in Germany (6.182 million tons of oil-equivalent). The other countries following were France (2.51 Mtoe), Italy (1.746 Mtoe), Sweden (1.485 Mtoe), the Netherlands (1.448 Mtoe), Denmark (0.809 Mtoe), Belgium (0.727 Mtoe), Finland (0.601 Mtoe), Spain (0.51 Mtoe), etc. Increase in primary energy production from renewable and non-renewable municipal waste between 2015 and 2019 was observed in most Member States except the following four: Estonia (-6.66 %), Hungary (-6.25 %), Denmark (-3.22 %), and Belgium (-0.13 %). It seems that Cyprus (300 %) had the largest increase in primary energy production from renewable and non-renewable municipal waste between 2015 and 2019, being followed by Bulgaria (280 %, comparison period 2015-2018), Poland (212.17 %), Latvia (150 %), Ireland (126.61 %, comparison period 2016-2018), etc. (Table 4).

Table 5 presents the total production of primary energy from all sources and the percentage of primary energy produced from renewable and non-renewable municipal solid waste in the EU-27 in 2015 and 2019 (Eurostat, 2021).

In most Member States, the percentage of primary energy production from renewable and non-renewable municipal solid waste increased in 2019 compared to 2015. Only in six Member States this percentage decreased. These countries were Belgium, Spain, Lithuania, Luxembourg, Hungary, and Portugal. The percentage presented by Luxembourg is impressive, as, according to the data in Table 5, 21.05 % of the total primary energy production in 2015 originated from MSW. Regarding 2019, this percentage was 15.94 %. A large increase of this percentage was observed in Bulgaria (from 0.12 % in 2015 to 0.49 % in 2018), Ireland (from 3.04 % in 2016 to 5.65 % in 2019), Cyprus (from 0.38 in 2015 to 0.96 in 2019), Latvia (from 0.25 % in 2015 to 0.53 % in 2019), The Netherlands (from 2.98 % in 2015 to 4.37 % in 2019), and Poland (from 0.23 % in 2015 to 0.82 % in 2019), as shown in Table 5.

According to the data in Figure 3, it seems that most of the Member States, especially the central and the northern ones (i.e., Germany, France, Nordic countries, etc.), covered between 0.9 and 5.7 % of their gross inland energy consumption by MSW-generated energy.

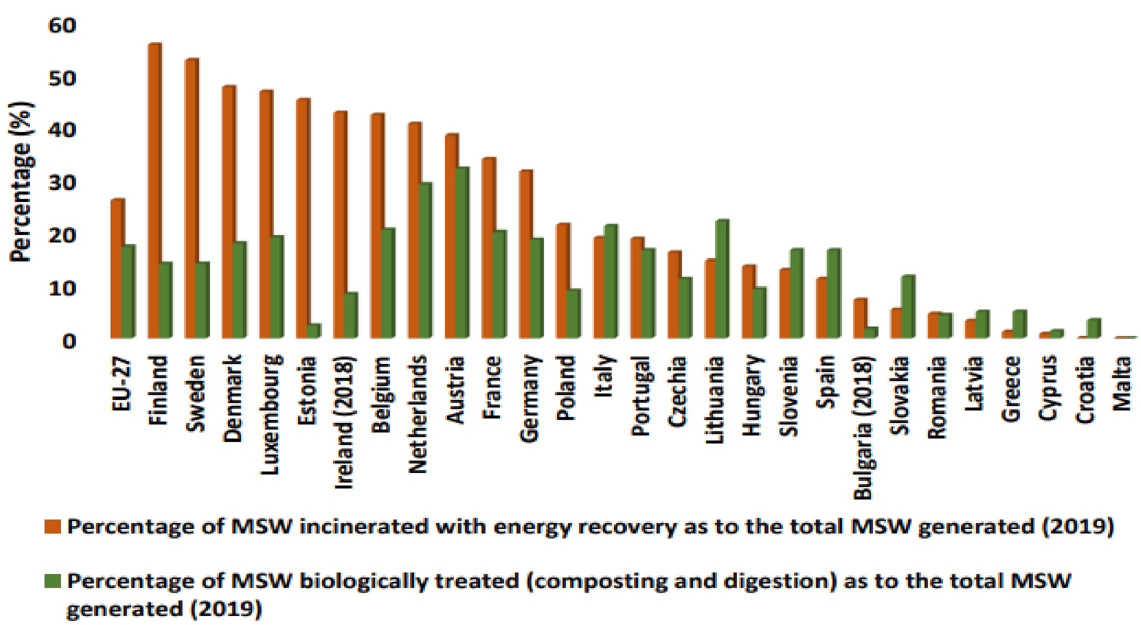

Figure 3. Percentage of MSW incinerated with energy recovery and biologically treated (composting and digestion) in reference to the total MSW generated in EU-27 in 2019

Table 5
Primary energy production from all sources and percentage of primary energy produced from renewable and non-renewable Municipal Solid Waste, EU-27, 2015-2019

	2015*	2015**	2019*	2019**
EU-27	658.334	2.55	615.946	2.92
Belgium	10.818	6.72	15.946 (2018)	4.55
Bulgaria	12.032	0.12	11.957	0.49
Czech Republic	28.553	0.46	26.597	0.56
Denmark	16.239	5.14	12.509	6.46
Germany	120.545	4.96	105.426	5.86
Estonia	5.591	0.8	4.909	0.85
Ireland	4.237 (2016)	3.04 (2016)	5.037 (2018)	5.65 (2018)
Greece	8.529	0	6.367	0
Spain	34.013	1.48	34.981	1.45
France	140.81	1.73	133.92	1.87
Croatia	4.414	0	3.9	0
Italy	36.098	4.68	36.909	4.73
Cyprus	0.13	0.38	0.208	0.96
Latvia	2.338	0.25	2.826	0.53
Lithuania	1.859	1.71	2.039	1.66
Luxembourg	0.152	21.05	0.232	15.94
Hungary	11.104	1	10.785	0.97
Malta	0.0156	0	0.38	0
Netherlands	48.107	2.98	33.116	4.37
Austria	12.228	3.77	12.359	3.81
Poland	67.759	0.23	59.345	0.82
Portugal	5.907	3.28	6.561	3.13
Romania	26.374	0.011	24.529	0.016
Slovenia	3.317	0	3.378	0
Slovakia	6.394	0.59	6.939	0.8
Finland	17.213	2.73	19.268	3.11
Sweden	35.821	3.81	37.019	4.01

* Total Primary energy produced from all sources (Million tons of oil- equivalent)
** Primary energy produced from renewable and non-renewable MSW (%)

4. Conclusions

In order to determine the importance of municipal solid waste used in energy production through incineration (R1) and biological treatment (R3), out of total solid waste utilized for energy recovery, data on the total solid waste used for energy recovery in 2016 and 2018 were collected to be used with the findings of the present work. These years have been selected as reference years, because of lack of statistics on the total solid waste used for energy recovery in 2015 and 2019 from Eurostat database. According to this database, 120.85 million tons of solid waste was used for energy recovery in 2016 (Eurostat, 2021). As for 2018, the quantity was 129.72 Mt (increase by 7.3 %). According to the findings of the present analysis, the aggregate of municipal solid waste subjected to incineration (R1) and biological treatment (R3), in 2015 and 2019, were 82.094 and 97.566 million tons, respectively (increase by 18.8 %). Based on data between 2015 (MSW incinerated R1 and biologically treated R3) and 2016 (total solid waste for energy recovery), as well as the corresponding between 2018 and 2019, it was concluded that the percentage of MSW for energy recovery increased from 67.9% in 2016 to 75.21 in 2018. As the data from different years were used (2015/2016 and 2018/2019), it must be pointed out that the percentage was approximate. The specific purpose of that reference is to point out the important role of municipal solid wastes and their contribution to the energy recovery from waste in the EU-27 in reference to the total solid waste.

Also, in the case of primary energy production from municipal solid waste, it was necessary to cite data from previous years (2010 and 2018) in combination with the findings of the present work in order to justify the increasing trend of primary energy production from MSW. Primary energy supply from municipal solid waste (renewable and non-renewable) followed an ascending trend. Primary energy production from MSW in 2010 was 14.496 million tons of oil-equivalent (Mtoe) (Eurostat, 2021), 16.831 Mtoe in 2015 (Table 4), 17.742 Mtoe in 2018 (Eurostat, 2021), and 17.987 Mtoe in 2019 (Table 4). The percentage of primary energy production from MSW in relation to the total primary energy production from all sources for the years 2010, 2015, 2018, and 2019 was 2.08 %, 2.55 % (Table 4), 2.79 %, and 2.92 % (Table 4), respectively. According to these specific percentages, it seems that the production of primary energy from renewable and non-renewable municipal solid waste in the EU-27 increased over the years.

Combining the f indings of this study, it is concluded that Germany and France were highly active in Waste-to-Energy, as the number of existing plants in these two countries exceeded the sum of the rest. Therefore, a large amount of MSW was utilized for energy recovery. There was also an important activity in the sector of waste-to-energy in the Nordic countries (Sweden, Denmark, and Finland), as well as in Italy, Belgium, Austria, the Netherlands, Poland, and Spain. In countries such as Slovakia, Slovenia, Greece, Latvia, Cyprus, Croatia, and Malta, more effort was required to achieve higher level of Waste-to-Energy, without affecting the increase in quantities leading to other more environmental-friendly waste management operations (prevention, reuse and recycle) which were of major priority.

In general, there were no significant differences in the rate of gross inland energy consumption by MSW-generated energy in the four-year period (2015-2019) in the Member States. A relatively small increase in this percentage was observed in Ireland, Cyprus, and Poland, as observed in Figure 2.

Although in some Member States (i.e., Hungary, Spain, Bulgaria, The Netherlands, etc.) there was a decrease in the quantities of waste incinerated for energy recovery (R1) and subjected to biological treatment (R3), increasing rates in recycling and decreasing rates in disposal operations were observed, which denoted improvement of waste management in these countries, despite the declining rates of energy recovery operations.

In terms of the overall municipal solid waste management, and especially incineration (R1) and biological treatment (R3) with which the current paper deals, it seems that the situation improved, despite the significant differences between the Member States. Circular Economy can play an essential role to meet the goals towards climate neutrality in Europe, as all Member States will keep going on and increasing their efforts in this respect.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Abdelgadir A., Chen X., Liu J., Xie X., Zhang J., Zhang K., Wang H., Liu N., Characteristics, process parameters, and inner components of anaerobic bioreactors, BioMed Research International, 2014,

Adekunle K. F., Okolie J. A., A review of biochemical process of anaerobic digestion, Advances in Bioscience and Biotechnology, 6 (03), 2015, 205-212,

Anastassakis G. N., Solid Waste Management, NTUA, Athens, Notes, 2001, 58-65,

Belgiorno V., De Feo G., Della Rocca C., Napoli D. R., Energy from gasification of solid wastes, Waste Management, 23 (1), 2003, 1-15,

Bourtsalas A. C., Themelis N. J., The role of Waste-to-energy (WtE) in a circular economy society, UNECE Ministerial Conference, Astana, Kazakhstan, June 14, 2017, 8,

CEWEP, Confederation of European Waste-to-Energy Plants. Available at: https://www.cewep.eu/ (accessed on 13 July 2021),

Chen H., Li J., Liu J., Li T., Xu G., Liu W., Thermodynamic and economic evaluation of a novel waste-to-energy design incorporating anaerobic digestion andincineration, Energy Conversion and Management, 252, 2022, 115083,

Commission Regulation (EU), No 844/2010 of 20 September 2010, pp. 258/48,

Communication From The Commission, Brussels, 2.12.2015 COM(2015) 614 final, pp.2,

Communication From The Commission, Brussels 26.1.2017 COM(2017) 34 final, pp. 2-11,

Communication From The Commission, Brussels 11.3.2020 COM(2020) 98 final, pp. 2,

Directive 2008/98/EC of the European parliament and of the council of 19 November 2008, pp. 312/10, 312/24,

Directive (EU) 2018/850 of the European parliament and of the council of 30 May 2018, pp. 150/104,

Directive (EU) 2018/851 of the European parliament and of the council of 30 May 2018, pp. 150/110, 150.129,

Directive (EU) 2018/852 of the European parliament and of the council of 30 May 2018, pp. 150/47,

Energy Information Administration (EIA), Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy, May 2007, 18,

European Commission 2050 long-term strategy, Available at: https://ec.europa.eu/clima/policies/strategies/2050_en (accessed on 13 July 2021),

European Commission - Eurostat 2015, Energy Statistics of the European Union: Concepts and Definitions on All Flows (‘‘Aggregates”) and Products used in the Energy Statistics on Quantities, Luxembourg, 2015, 1-242,

Eurostat, Your key to energy statistics, 2021, Available at: https://ec.europa.eu/eurostat/web/main/home (accessed on 13 July 2021),

Galvez-Martos J. L., Schoenberger H., An analysis of the use of life cycle assessment for waste co-incineration in cement kilns, Resources, Conservation and Recycling, 86, 2014, 118-131,

Geissdoerfer M., Savaget P., Bocken N. M., Hultink E. J., The Circular Economy-A new sustainability paradigm?, Journal of cleaner production, 143, 2017, 757-768,

Grosso M., Motta A., Rigamonti L., Efficiency of energy recovery from waste incineration, in the light of the new Waste Framework Directive, Waste

Management, 30 (7), 2010, 1238-1243,

Gungor B., Dincer I., A renewable energy based waste-to-energy system with hydrogen options, International Journal of Hydrogen Energy, 47 (45), 2022, 19526-19537,

IEA: www.iea.org, (accessed by 27 January 2022),

Hamoda M. F., Qdais H. A., Newham J., Evaluation of municipal solid waste composting kinetics, Resources, conservation and recycling, 23 (4), 1998, 209-223,

Komilis D., Solid Waste Management and Engineering, Tziola Publications, Thessaloniki, Athens, 496, (in Greek), ISBN 978-960-418-622-8,

Kumar A., Samadder S. R., A review on technological options of waste to energy for effective management of municipal solid waste, Waste Management, 69, 2017, 407-422,

Levaggi L., Levaggi R., Marchiori C., Trecroci, C., Waste-to-Energy in the EU: The effects of plant ownership, waste mobility, and decentralization on environmental outcomes and welfare, Sustainability, 12 (14), 2020, 5743,

Malinauskaite J., Jouhara H., Czajczyńska D., Stanchev P., Katsou E., Rostkowski P., Thorne R. J., Colón J., Ponsá S., Al-Mansour F., Anguilano L., Krzyżyńska R., López I. C., Vlasopoulos A., Spencer N., Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe, Energy, 141, 2017, 2013-2044,

Minelgaitė A., Liobikienė G., Waste problem in European Union and its influence on waste management behaviours, Science of The Total Environment, 667, 2019, 86-93,

Preble C. V., Chen S. S., Hotchi T., Sohn M. D., Maddalena R. L., Russell M. L., Brown N. J., Scown C. D., Kirchstetter T. W., Air Pollutant Emission Rates for Dry Anaerobic Digestion and Composting of Organic Municipal Solid Waste, Environmental Science & Technology, 54 (24), 2020, 16097-16107,

Psomopoulos C. S., Bourka A., Themelis N. J., Waste-to-energy: A review of the status and benefits in USA, Waste Management, 29, 2009, 1718-1724,

Quina M. J., Bordado J. C., Quinta-Ferreira R. M., Air pollution control in municipal solid waste incinerators, The impact of air pollution on health, economy, environment and agricultural sources, 2011, 331-358,

Rajvanshi A. K., Biomass gasification, Alternative energy in agriculture, 2 (4), 1986, 82-102,

Reza M. S., Azad A. K., Abu Bakar M. S., Karim M. R., Sharifpur M., Taweekun J., Evaluation of Thermochemical Characteristics and Pyrolysis of Fish Processing Waste for Renewable Energy Feedstock, Sustainability, 14 (3), 2022, 1203,

Scarlat N., Fahl F., Dallemand J. F., Status and opportunities for energy recovery from municipal solid waste in Europe, Waste and Biomass Valorization, 10 (9), 2019, 2425-2444,

Suresh S., Viswanathan V., Angamuthu M., Dhakshinamoorthy G. P., Gopinath K. P., Bhatnagar A., Lignin waste processing into solid, liquid, and gaseous fuels: a comprehensive review, Biomass Conversion and Biorefinery, 2021, 1-39,

Taki M., Rohani A., Machine learning models for prediction the higher heating value (HHV) of municipal solid waste (MSW) for waste-to-energy evaluation, Case Studies in Thermal Engineering, 31, 2022, 101823,

Tchobanoglous G., Kreith, F., Handbook of Solid Waste Management, second edition, McGraw-Hill Handbooks, New York, 2002, 950, ISBN-10: 0071356231,

Themelis N. J., Barriga M. E. D., Estevez P., Velasco M. G., Guidebook for the application of waste to energy technologies in Latin America and the Caribbean (WTE Guidebook, EEC/IDB), Columbia University, Earth Engineering Center, July 2013, 228,

Tsekeris G., The role of waste-to-energy evaluation in Circular Economy - Comparison of the condition between Greece and EU, Diploma Thesis, NTUA, 2021, 148,

Varjani S., Sivashanmugam P., Tyagi V. K., Gunasekaran M., Breakthrough in hydrolysis of waste biomass by physico-chemical pretreatment processes for efficient anaerobic digestion, Chemosphere, 294, 2022, 133617,

Wienchol P., Szlęk A., Ditaranto M., Waste-to-energy technology integrated with carbon capture-Challenges and opportunities, Energy, 198, 2020, 117352,

Yang Y., Liew R. K., Tamothran A. M., Foong S. Y., Yek P. N. Y., Chia P. W., Lam S. S., Gasification of refuse-derived fuel from municipal solid waste for energy production: a review, Environmental Chemistry Letters, 19, 2021, 2127-2140.

Pretvaranje komunalnog čvrstog otpada u energiju u EU-27 kao korak ka kružnoj ekonomiji

Tsekeris Georgios #, Anastassakis N. Georgios

Nacionalni tehnički univerzitet u Atini, Fakultet rudarstva i metalurgije, Atina, Grčka

INFORMACIJE O RADU

Primljen 05 maj 2022
Prihvaćen 24 avgust 2022

Originalan rad

Ključne reči:
Kružna ekonomija
EU-27
Dobijanje energije iz čvrstog komunalnog otpada
Čvrsti komunalni otpad
WtE tehnologije

I Z V O D

Ovaj rad se bavi obnavljanjem energije iz čvrstog komunalnog otpada putem spaljivanja (R1) i biloškog tretmana (R3) u okviru EU-27 kao koraku ka kružnoj ekonomiji. Zakonodavstvo EU je analizirano u odnosu na proizvodnju i upravljanje komunalnim otpadom za dobijanje energije, zajedno sa procesima pretvaranja otpada u energiju (spaljivanje, anaerobna digestija i kompostiranje, piroliza, gasifikacija, plazma tehnologija i deponijski gas). Kao referentne godine uzete su 2015. i 2019. godina, koje predstavljaju prvu godinu predstavljanja evropskog plana za kružnu ekonomiju (COM-(2015)-614) i godinu pre predstavljanja COM-(2020)-98. Takođe su prikupljeni i obrađeni podaci svake države članice za 2015. i 2019. godinu, koji obuhvataju ukupno proizvedeni komunalni otpad, ukupan komunalni otpad koji se koristi za dobijanje energije spaljivanjem i biološkim tretmanom, proizvodnaj primarne energije iz obnovljivih i neobnovljivih komunalnih otpadnih voda, kao i bruto domaća potrošnja energije dobijene od komunalnog otpada. Glavni zaključak koji je donesen na osnovu ovog rada bio je trend porasta količine komunalnog otpada koji se koristi za dobijanje energije u EU-27, kao i trend povećanja proizvodnje primarne energije iz komunalnog otpada koji je EU posmatrala kao agregat. Uočeno je da je u nekim državama članicama energija pratila trend rasta sa većom ili nižom stopom, dok je kod drugih imala opadajući trend. Uprkos opštem trendu povećanja proizvodnje energije iz komunalnog otpada, stopa je još uvek relativno niska kod nekih zemalja i potrebno je uložiti veći napor kako bi se uskladila sa politikom EU na putu ka kružnoj ekonomiji.