Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe

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Abstract

This paper provides an overview of waste generation and treatment operations in the European Union (EU) and other European countries and an analysis of the possibilities for the use of municipal solid waste (MSW) for energy production. A geographic information system based methodology was developed to investigate the spatial distribution of MSW and to identify the optimal location for new potential waste-to-energy in Europe. In 2016, there were 512 plants in Europe, with 251 combined heat and power plants, 161 electricity-only and 94 heat-only plants, which provide a total incineration capacity of 93 million tonnes. The suitability analysis showed that there is a potential to implement around 248 new waste to energy plants in the EU and 330 in all Europe, with a total capacity of 37 and 50 million tonnes, respectively. This represents an additional primary energy production of 260 PJ (6.2 Mtoe) in the EU, in comparison to 406 PJ (9.7 Mtoe) already produced in 2015, and about 352 PJ (8.4 Mtoe) in all European countries considered in this analysis.

Keywords Municipal solid waste · Energy from waste · Bioenergy · Renewable energy · GIS

Abbreviations

CHP	Combined heat and power
EEA	European Economic Area
EU	European Union
GIS	Geographic information system
GHG	Greenhouse gas
IED	Industrial Emissions Directive
JRC	Joint Research Centre
MSW	Municipal solid waste
Mtoe	Million tonnes of oil equivalent
OECD	Organisation for Economic Co-operation and Development
RED	Renewable Energy Directive
WFD	Waste Framework Directive
WID	Waste Incineration Directive
WtE	Waste-to-energy

Introduction

According to the RED 2009/28/EC [1] on the promotion of renewable energy sources, the use of renewable energy is projected to further increase in the European Union (EU) to reach a share of 20% in final energy consumption and 10% renewable energy in transport by 2020. The renewable energy contribution is further expected to increase to at least 27% by 2030 according to the 2030 Climate and Energy Policy Framework (COM(2014) 15 final) as proposed by the European Commission [2] and included in the proposal for a revised RED (COM(2016) 767 final/2) [3].

The use of municipal solid waste (MSW) can contribute to the increase of renewable energy share in the final energy production [4–9]. There are several advantages of recovering energy from MSW, such as providing local source of renewable energy and decreasing the volume of solid waste dumped in landfills, which in turn may have positive effects on carbon emissions since this process avoids methane emissions from landfills and carbon dioxide from fossil fuels [10]. Waste-to-energy (WtE) conversion processes, as a source of renewable energy, are expected to play an increasingly important role in sustainable management of MSW at global level. It is estimated that a reduction of about 10–15% in the global GHG emissions could be achieved through improved

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solid waste management (recycling, waste diversion from landfill and energy recovery from waste) [11].

A comprehensive legislation has been built in the EU with objectives and targets to improve waste management, as well as to reduce GHG emissions and adverse health and environmental impacts. The waste management has been developed in the EU on the concept of a hierarchy of waste management options, which includes a legally binding prioritisation of waste management activities. In essence, waste prevention is the most desirable option, followed by material recovery and recycling (metal, glass, paper recycling or organic waste composting), energy recovery from waste (through incineration, or digestion of biodegradable wastes) and finally disposal (landfilling) with no recovery of either materials and/or energy as the least desirable option [12–14].

Within this framework, the EU Member States have increasingly changed focus from disposal of MSW to prevention and recycling. The amount of waste recycled almost tripled and landfilled reduced by half in a 10 years period. The landfilling rates compared to MSW generation dropped significantly in the same period. However, a large share (> 30%) of the EU's municipal waste is still being landfilled, with significant variations between Member States [15].

The use of energy potential of MSW as waste management strategy has brought additional value for reaching renewable energy targets. The recovery of energy from MSW has a potential to become an important player in the renewable energy sector in Europa. Currently, this potential is still far from being fully exploited as only a minor fraction of the MSW resources is actually sent for incineration with energy recovery.

This paper explores the situation of waste management options currently employed and investigates how MSW can contribute to increase the renewable energy supply in Europe. For this purpose, a geographic information system (GIS) based methodology was developed to analyse the spatial distribution of MSW resources at European level and to identify the optimal location of potential new WtE plants.

Sustainability Constraints and Circular Economy

Biomass availability, competition between the alternative uses of biomass, as well as the sustainability issues are major concerns for bioenergy deployment. Various feedstocks could contribute to meet the demand, including energy crops and wooden biomass, residues from agriculture and forestry, MSW, as well as algae and aquatic biomass.

Sustainability constraints for the use of biomass for energy purposes can reduce biomass availability for energy production. In this context, the use of waste or residual streams of biological materials could have a significant contribution to bioenergy production and, at the same time, minimize impacts associated with landfilling [16]. Moreover, the

valorisation of waste streams for energy recovery is essential and provides additional environmental benefits.

Waste can play an important role in a circular economy provided that prevention, reuse, and recycling are prioritized in the waste management cycle. Energy from waste can also be a part of this process; however, waste is still regarded as 'nuisance' rather than a resource in most of the European countries, and this vision must change in order to move towards a circular economy [17]. The European Commission states that "it is only by respecting the waste hierarchy that WtE can maximise the circular economy's contribution to decarbonisation, in line with the Energy Union Strategy and the Paris agreement" [18].

Indeed, the rules on separate collection and ambitious recycling rates covering wood, paper, plastic and biodegradable waste are expected to reduce the amount of waste potentially available for WtE processes such as incineration and co-incineration.

Main Producers of Energy from MSW

Energy recovery from waste has started long time ago with the first waste incinerator being built in 1885 in the United States. In 2016, the number of WtE facilities for MSW reached 1618 plants worldwide, including 512 plants in Europe, 822 plants in Japan, 88 in the United States and 166 in China [9, 12, 15, 19–23].

The United States generated 258 million tonnes of MSW in 2014, of which 136 million tonnes were landfilled, 89 million tonnes were recycled and composted, and 33 million were burned with energy recovery. The installed WtE capacity in that year reached the total of 2.5 GW and resulted in a production of 14,310.2 GWh of electricity [24].

Landfilling in the United States is a more viable option due to the lowest economic cost compared to a MSW facility. On the other hand, incineration is predominant in Japan due to the land (e.g. availability of land areas) and environmental constraints (e.g. pressure for decreasing landfilling waste volume) as well as for energy production.

Waste incineration technology was introduced in China in the late 1980s and the number of incineration plants has increased significantly since then. Between 2013 and 2014, the WtE total capacity reached 46 million tonnes a year [8] and the power generation 18.7 billion kWh, accounting for 1.2% of total RE production. However, the majority of household waste is still deposited in landfills (105 million tonnes annually) or incinerated (46 million tonnes annually) without energy recovery.

In Europa, Germany, France and UK are the leading countries on energy recovery from MSW resources. Nevertheless, 18 countries have an incineration capacity of less than a quarter of their generated MSW, of which 10 countries have no incineration capacities at all.

Review of the Waste Legislation in the EU

Waste Framework

The EU waste policies and targets include minimum requirements for managing certain waste types. The most relevant targets for MSW are the landfill diversion targets for biodegradable municipal waste (Landfill Directive from 1999); recycling targets (the Packaging and Packaging Waste Directive from 1994); and the target on recycling and preparing for reuse (Waste Framework Directive from 2008).

The WFD 2008/98/EC has established legal requirements for the waste treatment within the EU, aiming to protect the environment and human health from the harmful effects of waste generation [25]. The WFD has set a 50% target for preparing for reuse and recycling of household and similar waste and a 70% target for preparing for reuse, recycling and other material recovery of non-hazardous construction and demolition waste by 2020. The Directive requires competent authorities to establish waste management plans including the type, quantity and source of waste, and existing collection systems. Prevention programmes must also be drawn up to break the link between economic growth and waste generation.

The aim of the WID 2000/76/EC [25] is to prevent or to reduce the possible negative environmental effects caused by the incineration and co-incineration of waste, setting strict operational conditions, technical requirements and emission limits for waste incineration plants and waste co-incineration plants. Emission limit values and monitoring requirements apply to atmospheric pollutants such as dust, nitrogen oxides (NO_x), sulphur dioxide (SO₂), hydrogen chloride (HCl), hydrogen fluoride (HF), heavy metals, dioxins and furans.

The WID addresses several types of waste incineration plants except biomass only plants using vegetable waste and residues from agriculture and forestry. The WID makes a distinction between: (a) incineration plants, which are dedicated to the thermal treatment of waste and may or may not recover generated heat; and (b) co-incineration plants, such as cement or lime kilns, steel plants or power plants whose main purpose is energy generation or the production of material products and in which waste is used as a fuel or is thermally treated for the purpose of disposal.

An energy efficiency criterion has been laid down in the WFD (R1, often referred to as the “R1 criterion” or the “R1 formula”) to promote the efficient use of energy generated from waste in WtE plants. This allows a distinction between waste incineration with energy recovery (R1) and without energy recovery or incineration on land for the purposes of disposal (D10). The R1 criterion takes into

account the energy recovered from waste and its effective uses as electricity or as heat for heating and cooling or as processing steam in industry. In most instances, electricity can be easily distributed through the national power grid. Whenever possible, it is valuable to export heat or process steam for local use in industry or in buildings, as it improves the overall energy efficiency and economic performances of the plant as well.

The IED 2010/75/EU (Integrated Pollution Prevention and Control—IPPC) aims to “reduce emissions into air, soil, water and land and to prevent the generation of waste, in order to achieve a high level of protection of the environment” [14]. The IED established key requirements for the operation of an incineration plant: a minimum combustion temperature and residence time of the resulting combustion products (minimum requirement of 850 °C for 2 s for MSW); specific emission limits for: SO₂; nitrogen oxide and nitrogen dioxide (NO and NO₂); HCl; HF; gaseous and vaporous organic substances expressed as total organic carbon (TOC); carbon monoxide (CO); dust; heavy metals; and dioxins and furans; a limit of 3% for TOC content of the bottom ashes and slag produced.

The Landfill Directive 31/1999 EC called for a strategy on biodegradable waste that achieves the progressive diversion of biodegradable municipal waste from landfilling [26]. It defines the different categories of waste (municipal waste, hazardous waste, non-hazardous waste and inert waste) and applies to all landfills. The Directive is intended to prevent or reduce the adverse effects of landfilling on the environment as well as any resultant risk to human health. The Landfill Directive sets strict guidelines for landfill management and bans certain types of waste, such as used tyres, and sets targets for reducing quantities of biodegradable waste. The Landfill Directive requires Member States to reduce the amount of biodegradable municipal waste landfilled to 75% by 16 July 2006, to 50% by 16 July 2009 and to 35% by 16 July 2016 with reference to the total amount of biodegradable municipal waste produced in 1995. Different approaches have been followed for such waste, that is to say pre-treatment, such as mechanical–biological treatment, composting (including fermentation) and incineration.

The EU waste policy and legislation comes along with a number of wider EU policies and programmes including 7th Environment Action Programme, the Resource Efficiency Roadmap and the Raw Materials Initiative. The 7th Environment Action Programme sets the following priority objectives for waste policy in the EU: to reduce the amount of generated waste; to maximise recycling and reuse; to limit incineration to non-recyclable materials; to phase out landfilling to non-recyclable and non-recoverable waste; to ensure full implementation of the waste policy targets in all Member States.

The Resource-efficient Europe flagship initiative is part of the Europe 2020 Strategy (COM(2010) 2020 final), aiming to support the shift towards sustainable growth via a resource-efficient, low-carbon economy [27]. The Roadmap to a resource efficient Europe (COM(2011) 571) sets out a framework for the design and implementation of future actions and also outlines the structural and technological changes needed by 2050, including milestones to be reached by 2020 [28]. The Raw Materials Initiative (COM(2008) 699 final), adopted in 2008, set out a strategy for tackling the issue of access to raw materials used by European industry except materials from agricultural production and materials used as fuel [28]. This strategy aims to ensure access to these raw materials: (1) fair and sustainable supply of raw materials from global markets; (2) sustainable supply of raw materials within the EU; (3) resource efficiency and supply of “secondary raw materials” through recycling.

The use of waste and residues could play a significant role in reaching the renewable energy targets set by the RED 2009/28/EC [1] and by the 2030 Climate and Energy Policy Framework (COM(2014) 15 final) with no impact of land use/land use change, food security or with no or reduced competition for raw materials with other sectors [2].

Waste Legislation

The long-term vision for the waste sector is to establish a circular global economy in which the use of materials and generation of waste is minimised, waste is recycled and reused, and remaining waste is used for recovering energy. In 2015, the European Commission presented a Circular Economy Package which includes revised legislative proposals on waste to stimulate Europe’s transition towards a circular economy. The Communication “Towards a Circular Economy” (COM(2014) 398 final) promotes a fundamental transition from a linear economy where resources are extracted, used and thrown away, towards a concept of circular economy, involving multiple uses of materials in various sectors in the economy [29].

The overall vision is to establish a circular economy in which material use and waste generation are minimised, waste is recycled and reused in the production of new materials, the unavoidable waste treated in a least harmful way to the environment and human health or is used for energy recovered and the remaining waste is landfilled.

Turning waste into a resource is a key to a circular economy. This would bring benefits to both the environment and the economy. The EU Action Plan for the Circular Economy (COM(2015) 614 final) establishes a programme of action, with measures covering the cycle from production to consumption, to waste management and the market for secondary raw materials to support the transition towards a circular economy [30].

WtE, including various waste treatment processes generating energy, can play a role in the circular economy (COM(2017) 34), and in meeting the objectives set out in the EU Strategy (COM(2015) 80 final) [30]. Various WtE processes could contribute and create synergies with EU energy and climate policy: co-incineration of waste in combustion plants and in cement production; waste incineration in dedicated facilities; anaerobic digestion of biodegradable waste; production of waste-derived fuels (solid, liquid or gaseous); and other processes including pyrolysis or gasification. The Commission will adopt a waste to energy initiative in the framework of the Energy Union.

The EC has proposed in 2015 a full legislative package on waste, including a new Directive on Waste, Directive on Packaging Waste, Directive on Landfill, Directive on electrical and electronic waste, on end-of-life vehicles, and batteries and accumulators and waste batteries and accumulators. The legislative proposal on waste sets targets for waste management for reduction, recycling and landfilling for 2030. The package aims to achieve greater harmonisation and simplification of the legal framework on by-products and end-of-waste status. Additional provisions include improved definitions and common methodology for the calculation of the recycling rates and require the introduction of economic instruments to discourage landfilling, concrete measures to promote prevention, including for food waste, and reuse of waste and economic instruments to provide incentives for the application of waste hierarchy [14].

The proposal for a new Waste Directive defines municipal waste in line with the definition used for statistical purposes by the European Statistical Office (Eurostat) and the Organisation for Economic Co-operation and Development (OECD). Thus, MSW is defined as “(a) mixed waste and separately collected waste from households including: paper and cardboard, glass metals, plastics, bio-waste, wood, textiles, waste electrical and electronic equipment, waste batteries and accumulators; bulky waste, including white goods, mattresses, furniture; garden waste, including leaves, grass clipping; (b) mixed waste and separately collected waste from other sources that is comparable to household waste in nature, composition and quantity; (c) market cleansing waste and waste from street cleaning services, including street sweepings, the content of litter containers, waste from park and garden maintenance”. Bio-waste is defined, as “biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, comparable waste from food processing plants and other waste with similar biodegradability properties that is comparable in nature, composition and quantity” [14].

With the new legislative package on waste, the European Commission proposed new targets for municipal waste to review waste recycling, landfilling and other waste-related targets to reach 60% recycling and preparing for reuse by

2025 and 65% by 2030. In addition, new targets to reduce municipal waste disposed of in landfill and revised targets for packaging waste have been proposed [13]. The proposed targets include:

- 65% reuse and recycling target for MSW by 2030.
- 75% reuse and recycling target for packaging waste by 2030.
- Minimum targets for reuse and recycling for specific materials contained in packaging waste: 75% of wood; 85% of ferrous metal; 85% of aluminium; 85% of glass; 85% of paper and cardboard.
- Maximum 10% municipal waste landfilled of the total amount of generated MSW and a ban was set on landfilling of separately collected waste.

Materials and Methods

Overview of the Current Potential of Energy Production from Waste Resources in Europe

A broad overview of the current potential of energy recovery from waste resources in Europe was performed. It started with the examination and assessment of the available statistical data on waste generation and treatment in order to describe the current scenario with respect to MSW management and energy recovery in Europe. The results of this analysis are presented in “[Waste Management in Europe](#)” and “[Energy Recovery from Waste in Europe](#)” sections.

The data on MSW generation and treatment for European countries came from the Eurostat’s Environmental Data Centre on Waste [31]. The retrieved data correspond to country specific information on waste generation, recycling, and incineration and it has been used to identify the amount of waste which might be potentially available for incineration and which are currently sent to landfills (see “[Energy Potential of Waste and Perspectives for Energy Recovery](#)”).

Spatial Distribution of MSW in Europe

There is no available information regarding the spatial distribution of MSW at European scale. Therefore, considering there is a direct correlation between the amount of generated MSW and population distribution, an area-weighting method was used to spatially allocate the statistical data on waste generation based on population density map. The Global Human Settlements (GHS) project from the Joint Research Centre (JRC) was used as spatial proxy, which refers to a population density grid data set that express the number of people in a 1 km² cell for the target year of 2015 [32] (see “[Energy Potential of Waste and Perspectives for Energy Recovery](#)”).

Suitability Analysis for Identifying Potential Locations for WtE Plants in Europe

A suitability analysis was performed to identify the potential location for WtE plants based on the generated waste resources map. An algorithm was developed to examine the map area in order to locate hot-spot areas with highest density of resources and establish the optimal location for new potential WtE plants and their capacity.

The first step was to survey all the existing WtE plants in Europe from multiple sources (see Table 1). The resources used by these plants were then removed from the generated waste map. The remaining resources were successively scanned in order to find the optimal location of new energy plants.

Results

Waste Management in Europe

Municipal waste treatment includes several operations: recycling, composting/digestion, landfilling, and incineration with and without energy recovery. In this context, energy recovery can be achieved through waste incineration; advanced thermal treatment (gasification and pyrolysis) or anaerobic digestion of biodegradable waste [12]. In Europe, energy recovery from waste is dominated by the combustion (incineration) technologies mostly based on moving grate and stoker boiler incinerator for heat and/or power production [33].

More than 2400 million tonnes of non-hazardous waste have been generated in the EU from various economic activities, with additional 96 million tonnes of hazardous waste in 2015 [15].

Excluding major mineral wastes, 832 million tonnes of waste were generated in 2014, equivalent to 35% of the total generated waste. Apart for construction waste (852 million tonnes) and mining and quarrying waste (690 million tonnes), the highest levels of waste generation were recorded for manufacturing waste (232 million tonnes), water and waste management (210 million tonnes) and household waste (204 million tonnes).

The generation of waste from water and waste services increased by 90% between 2004 and 2014 and the quantity of waste generated from construction grew by 58%. At the same period, waste generated (excluding major mineral waste) by households remained quite stable while waste originated from manufacturing and mining/quarrying activities fell by 34 and 24%, respectively. Figure 1a shows the evolution of selected waste generation in the EU.

There are considerable variations across EU Member States in the activities that contributed to the amount

Table 1 Capacity and number of existing WtE plants in Europe in 2015

	CHP		Electricity only		Heat only		No info		Total	
	Capacity	No	Capacity	No	Capacity	No	Capacity	No	Capacity	No
Andorra			60	1		0		0	60	1
Belgium	1092	7	1099	8	568	2			2759	17
Czech Republic	646	3		0					646	3
Denmark	2899	22		0	975	12			3873	34
Estonia	220	1		0		0			220	1
Finland	528	3		0	595	3			1123	6
France	7048	37	6691	54	1823	28	22	2	15,584	121
Germany	19,312	78	3401	13	1970	7			24,683	98
Hungary	420	1		0		0			420	1
Ireland			300	2		0			300	2
Italy	2356	10	4223	38	114	2	45	2	6738	52
Lithuania	250	1							250	1
Luxemburg			150	1					150	1
Malta			13	1					13	1
Netherlands	5463	7	1342	3	519	2			7324	12
Austria	1171	5	152	1	1711	6			3033	12
Poland	562	4							562	4
Portugal			1238	3					1238	3
Slovakia	215	2							215	2
Spain			1352	8	1210	2			2562	10
Sweden	4905	26		0	1178	13			6083	39
UK	3498	14	5726	26	352	1			9576	41
Norway	885	8	0	0	726	9	57	2	1668	19
Switzerland	3026	22	232	2	625	7	0	0	3883	31
EU	50,584	221	25,687	158	11,016	78	68	4	87,354	461
EEA	54,494	251	25,919	160	12,367	94	124	6	92,904	511
Europe	54,494	251	25,979	161	12,367	94	124	6	92,964	512

Capacity in thousands tonnes

of generated waste and their respective shares, reflected mainly by different economic structures, management and collection systems, and country sizes. The overall amount of generated waste is related to the population and economic size of a country. High amounts of waste are related to mineral waste production from mining activities, counting for about two-thirds of the total generated waste in the EU-28. Large differences between EU Member States can be observed in the generation of various wastes, including household and similar waste, animal and vegetal waste, and wood or mixed waste (Fig. 1b).

Biowaste represents a special category of waste. According to the WFD 2008/98/CE, biowaste includes organic waste from gardens and parks, food and kitchen waste from households, restaurants, caterers and distribution networks, and comparable waste from food-processing plants. Biodegradable waste also covers other biodegradables such as wood, paper, paperboard, and sludge. If landfilled, it can produce significant environmental and climate adverse impacts due to the potential of GHG emissions.

Table 2 shows the amount of biodegradable waste generated in Europe in 2014.

In 2014, 2248 million tonnes of non-hazardous waste were treated in the EU [15]. Almost 44% of it was subject to disposal operations (landfilling), 36% was sent to recovery operations for recycling, and just over 10% was sent to backfilling in excavated areas for the purpose of land reclamation. Only 6% of the waste was sent for incineration, either for incineration alone or with energy recovery. Waste disposal dominates in several countries with about 90% of the waste being sent to landfills (Bulgaria, Romania and Greece), while waste recovery dominates other countries (such as in Belgium, Italy and Denmark). Waste incineration is a widespread option in Norway, Denmark, Sweden and Germany, with a significant share in the waste treatment options observed.

The amount of MSW generated in 2015 reached 243 million tonnes in the EU and 255 million tonnes in the European countries considered in this study [15], representing around 10% of the total generated waste. Each person produced, on

Fig. 1 Waste generation: **a** evolution of selected generation waste in the EU; **b** waste generation by type in European countries [31]

average, almost half of tonne of waste per year (472 kg per person in 2005 and 477 kg per person in 2015). In 2015, the highest amount of MSW per capita was produced in Denmark (789 kg per person), followed by Switzerland, Cyprus and Germany. In contrast, Romania (286 kg per person) generated the lowest amount of MSW per capita, preceded by Poland and Czech Republic. The variations reflect differences in consumption patterns and economic conditions.

The amount of waste generated in the EU remained at about the same level between 1995 and 2015, with some variation during this period. However, in the same period was not observed uniform trends in MSW generation across countries, with increase trends in 21 countries and decrease trends in ten countries (Fig. 2a) [13].

Among different MSW treatment options, waste recycling has become the first treatment option at EU level with 69 million tonnes, followed by incineration (with or without

energy recovery) with 64 million tonnes, landfilling with 62 million tonnes and composting with 40 million tonnes (Table 3). Major MSW producers are Germany with 51 million tonnes, France with 33 million tonnes, UK with 32 million tonnes and Italy with 30 million tonnes. With respect to incineration, Germany is the leading country with 16 million tonnes, followed by France with 12 million tonnes and UK with 10 million tonnes. Large amounts of waste with no other uses are landfilled every year, mostly in Spain (11 million tonnes), France (9 million tonnes) and Italy (8 million tonnes).

The Directive 31/1999 on landfill requiring Member States to reduce the amount of biodegradable municipal waste going to landfills has led to significant changes in the management system to avoid landfilling through increased recycling, use of composting (including fermentation) or incineration (Fig. 2b). The progress made in increasing the

Table 2 Generation of biodegradable waste in 2014 in European countries (thousands tonnes) [31]

	W101 Households and similar	W091 Food waste	W092 Vegetal wastes	W072 Paper and cardboard	W075 Wood wastes	W11 Common sludges	Total bio- degradable
EU	157,420	25,420	52,660	45,930	48,470	18,280	348,180
Belgium	4091	1119	4458	4310	3265	579	17,822
Bulgaria	2775	87	322	416	266	79	3944
Czech Republic	2941	72	512	789	183	349	4845
Denmark	2476	135	926	836	410	188	4970
Germany	21,107	1819	11,966	8100	10,863	1615	55,469
Estonia	307	29	32	91	551	27	1038
Ireland	2737	983	243	396	200	409	4966
Greece	4086	399	169	480	92	138	5363
Spain	18,169	1835	1768	3087	1070	1438	27,367
France	21,332	4055	6949	7204	6140	1394	47,075
Croatia	1342	33	115	221	91	17	1819
Italy	16,798	4041	2791	5171	4414	5455	38,672
Cyprus	148	38	69	125	12	7	399
Latvia	552	25	80	108	79	23	868
Lithuania	933	67	447	172	125	49	1793
Luxembourg	212	39	56	94	38	11	450
Hungary	3294	77	227	762	143	164	4668
Malta	207	7	8	17	15	10	263
Netherlands	6844	2242	8950	2243	2493	638	23,409
Austria	2774	685	1148	1441	1130	432	7610
Poland	6935	2574	1819	1395	3864	626	17,212
Portugal	4476	81	82	1046	300	687	6673
Romania	5082	132	916	506	2303	213	9151
Slovenia	360	82	125	140	275	180	1162
Slovakia	1396	52	414	243	254	294	2651
Finland	1433	606	391	631	4228	398	7685
Sweden	2165	659	935	1130	1194	423	6508
UK	22,455	3448	6746	4773	4473	2440	44,335
Iceland	60	124	11	23	16	3	237
Norway	1023	688	179	769	1347	152	4159
Montenegro	254	25	19	13	9	10	331
FYROM	5	2	3	484	1	0	496
Albania	1229	0	0	0	0	0	1229
Serbia	1602	19	181	98	58	143	2101
Bosnia and Herzegovina	14	7	20	5	236	6	288

total recycling rate is mainly due to the fact that many countries have increased the recycling of materials such as glass, paper and cardboard, metals, plastic and textiles [13]. As a result, the amount of waste recycled grew in the EU from 25.0 million tonnes (52 kg per capita) in 1995 to 69 million tonnes (137 kg per capita) in 2015.

Waste incineration has also grown steadily in this period. The amount of MSW incinerated in the EU has increased from 32 million tonnes (67 kg per capita) in 1995 to 64 million tonnes (128 kg per capita) in 2015. Thus, the total

amount of MSW landfilled in the EU fell by 84 million tonnes, or 58%, from 146 million tonnes (302 kg per capita) to 62 million tonnes (120 kg per capita) in the same period. As a result, the landfilling rate compared with MSW generation dropped from 64.2 to 25.6% in the EU, and from 63.5 to 25.8% in the EEA member countries for the period 1995–2015. In Fig. 2a, the ‘other treatment’ category was calculated as the difference between the amounts of treated waste and generated waste. This difference arises in countries that have to estimate waste generation in areas not

Fig. 2 Municipal solid waste: **a** waste generation per person; **b** waste generation and treatment in the EU Municipal waste generated per person in European countries for the period 1995–2015 [31]

covered by a municipal waste collection scheme and thus report more generated waste than treated waste.

Despite significant improvements in waste management performance, significant differences in municipal waste management performance among countries could be observed [13]. Figure 3a presents detailed information on the type of waste treatment operations that were employed in various countries in 2015. In Switzerland, Sweden, Belgium, Denmark, or Norway, practically no MSW is sent to landfill. On the other hand, Malta, Greece and Croatia still landfill > 80% of their generated MSW. Some Member States had very high recycling rates (e.g. Italy, Belgium and Denmark), indicating recycling waste as one of key resources, while in others most of the waste was disposed in landfills (e.g. Bulgaria, Romania and Greece) [14, 15]. The amount of MSW

landfilled in 2015 ranged from 1.3 kg/person in Germany, 3.6 kg/person in Sweden and 3.8 kg/person in Belgium to 415 kg/person in Greece, 476 kg/person in Cyprus and 561 kg/person in Malta, with an average of 119 kg/person in EEA countries [13, 15]. Most countries reduced landfilling in the period 1995–2015 with six countries increasing the amount of waste sent to landfills.

The changes in the treatment operations of MSW between 1995 and 2015 at EU level are shown in Fig. 3b. A significant decrease in the shares of waste landfilling could be noticed, complemented by the increased shares of recycling, composting and incineration. Thus, the share of MSW recycled increased from 11 to 29% between 1995 and 2015. Recycling and composting together accounted for 45% in 2015 relative to waste generation, in comparison to 17.5% in 1995. This change

Table 3 Generation and treatment of MSW in 2015 (thousands tonnes) [31]

	Generated	Composting	Recycling	Incineration	Landfilling
Belgium	4708	901	1615	2043	43
Bulgaria	3011	311	573	82	1994
Czech Republic	3337	141	851	590	1755
Denmark	4485	852	1223	2359	51
Germany	51,046	9304	24,414	15,973	106
Estonia	473	17	117	243	35
Ireland	2693	156	829	427	1028
Greece	5585	209	869	0	4507
Spain	20,151	3316	3393	2342	11,101
France	33,399	5764	7433	11,600	8603
Croatia	1654	28	270	0	1319
Italy	29,524	5203	7649	5582	7819
Cyprus	541	25	72	0	403
Latvia	857	47	182	0	494
Lithuania	1300	132	298	150	702
Luxembourg	356	70	101	121	63
Hungary	3712	231	963	525	1991
Malta	269	0	17	1	241
Netherlands	8855	2400	2179	4152	125
Austria	4836	1511	1196	1854	121
Poland	10,863	1750	2867	1439	4808
Portugal	4710	665	765	974	2307
Romania	4953	391	253	133	3558
Slovenia	926	71	430	158	210
Slovakia	1784	130	136	191	1226
Finland	2738	341	770	1312	315
Sweden	4377	684	1417	2241	35
United Kingdom	31,567	5124	8602	9907	7124
Iceland	175	15	37	7	116
Norway	2187	365	572	1145	74
Switzerland	6030	1256	1924	2850	0
Montenegro	332	0	18	0	304
FYROM	765	0	0	0	765
Serbia	1840	0	14	0	1360
Bosnia and Herzegovina	1249	0	0	0	942
European Union	242,710	39,774	69,484	64,399	62,084
EEA	251,102	41,410	72,017	68,401	62,274
Europe	255,288	41,410	72,049	68,401	65,645

EEA European Economic Area

can also be observed with respect to the significant rise in the use of incineration with energy recovery (R1) as compared to incineration without energy recovery (D10).

Energy Recovery from Waste in Europe

Primary Energy Production from MSW

Bioenergy is the largest source of renewable energy today in the EU, providing heat, electricity and transport fuels.

Despite high growth rates in the solar and wind sectors, bio-energy is expected to remain, at EU level, the major renewable energy source until 2030, when it could reach a share of 60–70% of renewable energy, which represents 16–19% of bioenergy in the final energy supply and a bioenergy contribution of about 7.2–8.6 EJ (173–205 Mtoe). In a short term (until 2020), biomass is expected to provide 5.8 EJ (140 Mtoe) of energy, which represents a share of about 60% of the renewable energy and 12% of the final energy use in the EU [8].

Fig. 3 MSW treatment: **a** waste treatment in European countries in 2015; **b** treatment operations in the EU in 1995 and 2015 [31]

Biomass availability and the sustainability issues are major concerns for bioenergy deployment. The use of waste and residues for energy production could have a major role in covering biomass demand, with lowest impact on environment, GHG emissions, land use/land use change or competition between the alternative uses of biomass.

As result of the waste and renewable energy legislation, significant increase in the energy generation from the renewable MSW has been achieved. Statistical evidence shows that primary energy supply increased from 111 PJ (2.7 Mtoe) in 1995 to 252 PJ (6.0 Mtoe) in 2005 and 406 PJ (9.7 Mtoe) in 2015 (Fig. 4). Due to strong development in bioenergy sector, the contribution of renewable waste to bioenergy production increased from 5.1% in 1995 to 7.2% in 2015 [15].

Energy production from waste in 2015 showed significant differences between EU Member States. Germany was the leading country with 125 PJ (3.0 Mtoe), followed by France with 51 PJ (1.2 Mtoe), Netherlands with 41 PJ (1.0 Mtoe), and Sweden with 38 PJ (0.9 Mtoe) (Fig. 5a). The highest share of renewable waste contribution to bioenergy production was registered in 2015 in the Netherlands (35%), followed by Norway (17.5%), Cyprus (16.5%) and Denmark (15.1%). However, at the same time, 18 out of 31 EEA countries had a share below 5% in bioenergy production from waste resources [15].

Energy recovery from renewable MSW is directed in the EU mainly toward electricity generation, in combined heat and power (CHP) or electricity only plants. In this context, heat plants represent only 13% of the capacity of energy

Fig. 4 Evolution of energy production form MSW in the EU [31]

generation from waste. Electricity generation and electricity capacity of waste plants in 2015 showed significant differences between EU Member States (Fig. 5b). Germany was the leading country in terms of electricity capacity in WtE plants, with 1925 MW, followed by UK with 925 MW, Sweden with 876 MW, and Italy with 830 MW (Fig. 5b). Electricity generation from waste was the highest in Germany with 5768 GWh, followed UK with 2782 GWh, Italy with 2344 GWh, France with 1999 GWh, and the Netherlands with 1997 GWh.

Trade of Waste for Incineration

The analysis of the waste incineration capacities requires the consideration of the imports and exports of waste for incineration. In the EU, the transboundary shipments of waste are regulated by Regulation 1013/2006 on shipments of waste (the Waste Shipment Regulation WShipR), implementing the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. According to the Basel Convention, the contract parties should transmit annual reports containing information on the category and disposal method of traded waste [15, 20].

In order to analyse the waste incineration capacities and to have an indication on how much of the incineration capacities is fed with waste from import operations, the waste trade flows were assessed. The amount of waste streams undergoing incineration with energy recovery (R1) and without energy recovery (D10) has been included in the analysis.

Two categories of waste are relevant for this study: residues arising from industrial waste disposal operations (Y18), and wastes collected from households (Y46). Waste streams

classified as Y18 covers waste from various sources (e.g. MSW and industrial waste) with no distinct classification among categories, creating an uncertainty about the share of MSW in the total waste flow. In contrast, streams classified as Y46 consist of waste from households, which represents a share of the MSW.

The trade flows of household waste (which is a part of MSW) for incineration (R1 and D10) in Europe is shown in Fig. 6 for 2012 and 2014. The main source countries as well as destination countries are visible. Few countries were involved in the waste trade. Especially the Netherlands, Sweden and Germany imported high amounts of waste for incineration over the years, with some exporting countries including the UK, Norway and the Netherlands. This trade flows were related to the existing waste incineration capacities and different economic conditions for waste incineration (Fig. 7).

The analysis of household waste trade flows for incineration shows a quite complex picture. The results show that the trade of household waste for incineration in the EU involves a limited number of countries. Imported waste is used in available incineration plants in countries with high plant capacities. The evolution of net trade of household waste for incineration in the EU has an upgrade trend, but amounts vary largely over time and between countries, as depicted in Fig. 7. The variation over time is particularly significant for the countries with large volumes of waste trade.

Waste Incineration Capacities

The data for MSW incineration show that in the EEA countries, 27% of MSW generated in 2015 was incinerated in

Fig. 5 Energy from waste in European countries in 2015: **a** primary energy production from waste and share of bioenergy; **b** electricity generation from waste and installed capacity [31]

D10 and R1 plants. A number of 18 countries have an incineration capacity of less than a quarter of their generated MSW, of which 10 countries have no incineration capacities; in some cases they have high share of waste going to landfills. Table 4 shows the comparison of the generation and incineration of MSW with energy recovery (R1) and without energy recovery (D1) as well as the capacity of the waste incineration plants across the European countries.

Germany and France have the largest capacities for MSW incineration, with 24 million tonnes and 16 million tonnes, respectively. Several countries, such as Sweden, Netherlands, Denmark, Norway and Austria, have significant large capacity in comparison to their MSW generated amount.

In countries with high capacities compared with generated MSW, the risk of incineration competing with recycling needs to be managed accordingly [20].

Countries with a much higher share of incineration capacities use their capacities with non-municipal waste (e.g. refuse derived fuel, packaging waste, waste wood, etc.) or MSW from imports. In addition, the internal trade of waste within Europe has to be considered in order to have the real picture of the waste incineration in different countries.

A survey of existing WtE plants has been performed to identify the capacity, type of plants and location, using several sources. For further data gathering, comprehensive internet research (e.g. on national webpages or webpages

Fig. 6 Trade flows of household waste in Europe for 2012 and 2014 [31]

from plant operators) was done and provided the appropriate capacity and plant type data. Data was analysed and visualised, providing an overview of the incineration situation in Europe.

The waste to energy plants are dedicated plants for incineration of mixed MSW, but these plants could use other types of waste, such as wood waste, Refuse Derived Fuel (RDF), etc. The available data on the plants does not provide a complete overview of how much non-MSW is incinerated in MSW dedicated WtE plants.

The results of this analysis show that there were 512 WtE plants in Europe in 2016, with 251 plants generating CHP, 161 generating electricity only, and 94 generating heat only. There is no precise information about the plant type for the remaining 6 plants. The total incineration capacity was estimated at 93 million tonnes in 2016 [12, 19, 20, 22, 23]. Detailed information of the type of waste to energy plants (CHP, electricity only or heat only) as well as the capacity and number of plants are shown in Table 1.

Fig. 7 Evolution of net trade of household waste for incineration in the EU [31]

Although Germany has a higher waste incineration capacity than France in 98 plants, France has the largest number of WtE (121). While the European average waste incineration capacity is about 170,000 tonnes waste per year, in some countries (such as Netherlands, Portugal, Hungary, Spain or Austria) very large WtE plants (above 400,000 tonnes per year) are common, while in other countries (Norway, Denmark, Switzerland, France) smaller plants (80,000–120,000 tonnes per year) are more common.

Energy Potential of Waste and Perspectives for Energy Recovery

The analysis of the energy potential of waste included the investigation of waste management practices in European countries and the estimation of the amounts of waste which could be available for this purpose, after various options were applied according to waste hierarchy. This evaluation considered the spatial location of the waste generation, the various treatment options applied and the current waste incineration in existing WtE plants.

Figure 8 shows the spatial distribution of MSW generated in Europe, developed on the basis of waste generation data and spatial distribution of population.

Figure 9 shows the potential location of the new energy plants, together with the spatial location of existing waste incineration plants in Europe. Every single plant is marked with a point on the map, the specific capacity per year is marked with circles with varying sizes depending on the

capacity. The colours represent the type of the plant (CHP, electricity only, heat only or no info available). At present, there are no incineration plants several countries, such as Bulgaria, Cyprus, Estonia, Greece, Croatia, Latvia, Liechtenstein, Lithuania, Malta, Romania and Slovenia.

The results of WtE suitability analysis, grouped by national level (Table 5), show that the MSW resources are underexploited for energy production in most of the European countries. There is a potential to implement around 248 new WtE plants in the EU, with a total capacity of 37 million tonnes. On the other hand, some countries, such as Belgium, Germany and the Netherlands, are already using this resource at maximum extent, with little room for further expansion of the waste to energy plants. In Europe, 330 new WtE plants could be built to recover energy from waste, with a total capacity of about 50 million tonnes and an average capacity of about 150,000 tonnes. The construction of new WtE plants would contribute to the decrease of the waste landfilling, to the generation of renewable energy and decrease of GHG emissions from landfills and from the replacement of fossil fuels. The priority should be however given to waste recycling and recovery, the competition between waste incineration and recycling and recovery should be avoided and the risk of diversion of waste toward incineration instead of recycling and recovery has to be taken into account when deciding on the building of a WtE plant.

The new WtE plants would imply an additional primary energy production of 260 PJ (6.2 Mtoe) in the EU

Fig. 8 Spatial distribution of municipal waste generated in Europe

(contribution of waste to bioenergy production increasing from 7.2 to 11.8%) and about 352 PJ (8.4 Mtoe) in all European countries considered.

Discussions and Conclusions

The present study, based on statistical and geospatial analysis techniques, assessed the status of the energy recovery from waste resources and the potential for further development of MSW as renewable energy resource in Europe.

The waste legislation led to significant improvements in waste management over the past years: a large increase in waste recycling, a decrease in landfilling rate and increasing energy recovery. However, this study revealed important differences in municipal waste management practices across Europe and a large resource potential that is still unused.

The survey of existing WtE plants showed that in 2016, there were 512 plants in Europe, with 251 CHP plants, 161 electricity-only and 94 heat-only plants, which provide a total incineration capacity of 93 million tonnes. Several countries (especially Sweden, Netherlands, Denmark and Norway) have significant large plant capacities that are used

Table 4 MSW generation, incineration and waste to energy capacity in 2015

	Generation	MSW incineration			WtE capacity
		D10	R1	D10+R1	
Belgium	4708	848	1195	2043	2759
Bulgaria	3011	0	82	82	0
Czech Republic	3337	4	586	590	0
Denmark	4485	0	2359	2359	3873
Germany	51,046	4709	11,264	15,973	24,683
Estonia	473	0	243	243	220
Ireland	2693	0	427	427	300
Greece	5585	0	0	0	0
Spain	20,151	0	2342	2342	2562
France	33,399	364	11,236	11,600	15,584
Croatia	1654	0	0	0	0
Italy	29,524	3071	2511	5582	6738
Cyprus	541	0	0	0	0
Latvia	857	0	0	0	0
Lithuania	1300	0	150	150	250
Luxembourg	356	0	121	121	0
Hungary	3712	0	525	525	420
Malta	269	0	1	1	13
Netherlands	8855	97	4055	4152	7324
Austria	4836	0	1854	1854	3033
Poland	10,863	121	1318	1439	562
Portugal	4710	0	974	974	1238
Romania	4953	0	133	133	0
Slovenia	926	0	158	158	0
Slovakia	1784	0	191	191	215
Finland	2738	0	1312	1312	1123
Sweden	4377	0	2241	2241	6083
UK	31,567	297	9610	9907	9576
Iceland	175	0	0	7	0
Norway	2187	0	1145	1145	1668
Switzerland	6030	0	2850	2850	3883
EU	242,710	9511	54,888	64,399	86,558
EEA	251,102	9511	58,883	68,401	92,108

Data in thousands tonnes

for the treatment of some non-municipal waste (e.g. refuse derived fuel, packaging waste, waste wood, etc.) or municipal waste from imports.

The results demonstrated that the use of MSW as energy source is underexploited in most of the European countries. Only a fraction of the existing resources is being converted to energy. Therefore, the use of MSW for energy production brings an excellent opportunity for most of the European countries to increase the share of renewable energy in

the final energy production and, at the same time, to reduce environmental impacts associated to landfill operations.

The suitability analysis showed that there is a potential to implement around 248 new waste to energy plants in the EU and 330 in all Europe, with a total capacity of 37 and 50 million tonnes, respectively. This represents an additional primary energy production of 260 PJ (6.2 Mtoe) in the EU, in comparison to 406 PJ (9.7 Mtoe) already

Fig. 9 Suitability map for waste-to-energy plant location

produced in 2015, and about 352 PJ (8.4 Mtoe) in all European countries considered in this analysis.

The use of MSW for energy production could play an important role in the transition to a circular economy provided that prevention, reuse, and recycling processes are

priorities in the waste management systems. Moreover, the competition between waste incineration and recycling needs to be addressed properly and the risk of diversion of waste toward incineration instead of recycling and recovery need to be managed with caution.

Table 5 Number of new potential waste-to-energy plants in Europe

	Number of plants	Average capacity	Total capacity
Bulgaria	12	123,223	1,478,674
Czech Republic	7	98,135	686,942
Germany	2	62,963	125,927
Estonia	1	129,962	129,962
Ireland	10	157,325	1,573,248
Greece	19	206,207	3,917,937
Spain	36	192,985	6,947,443
France	16	81,187	1,298,992
Croatia	6	127,657	765,944
Italy	36	156,175	5,622,288
Cyprus	2	143,434	286,868
Latvia	1	204,921	204,921
Lithuania	3	127,840	383,520
Hungary	10	92,336	923,355
Austria	2	87,955	175,911
Poland	24	109,439	2,626,526
Portugal	6	197,052	1,182,312
Romania	21	119,679	2,513,269
Slovenia	2	117,736	235,472
Slovakia	5	75,793	378,964
Finland	4	71,521	286,084
United Kingdom	23	225,919	5,196,138
Iceland	1	83,128	83,128
Montenegro	2	102,892	205,785
FYROM	5	110,182	550,911
Albania	2	274,067	548,133
Serbia	7	154,158	1,079,105
Bosnia and Herzegovina	5	130,256	651,279
Kosovo	2	203,630	407,259
Moldova	2	104,533	209,066
Ukraine	56	169,878	9,513,143
European Union	248	148,954	36,940,698
EEA	249	148,690	37,023,826
Europe	330	152,086	50,188,508

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