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Status of waste-to-energy in Germany, Part I – Waste treatment facilities

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Abstract

This study gives a detailed overview over the German waste-to-energy sector in 2015. The aim is to quantify the available treatment capacities and the energetic potential of waste in Germany. The work is based on an extensive data collection and evaluation, both from literature sources as well as from a survey among operators of waste treatment plants. The present Part I, gives an overview of all treatment facilities in Germany that convert waste into energy. It was found that in total, almost 320 PJ of end energy are produced in German waste treatment plants: 225 PJ a^{-1} of heat; and 90 PJ a^{-1} of electricity. This is a share of about 3.7% of the German end energy consumption.

Keywords

Waste-to-energy, waste treatment facilities, operator survey, Germany, waste incineration

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Introduction

According to the European Waste Framework Directive (European Parliament, 2008), energy recovery from waste is classified as the fourth stage of the hierarchy, after prevention, preparation for re-use and recycling. Nevertheless, a large amount of waste that is no longer suitable for recycling is sent for energy recovery. As a result, waste now accounts for a significant proportion of electricity, heat and process energy supplied in Germany and other countries with developed waste management systems. The importance of waste for energy supply is now also recognized at European Union (EU) level. On the basis of the EU's action plan for recycling management (European Commission, 2015), which explicitly refers to the importance of waste for energy supply as a supplement to material waste recycling, an initiative on "Energy generation from waste" is to be launched. Against this background, this work was originally carried out for the German Environment Agency and presented in German language in June 2018 (Flamme et al., 2018). The present study is an English summary of the original report, the status of waste-to-energy (WtE) in Germany in 2015. Due to the extent of the work, it was divided into two parts. This first part gives an overview of all WtE facilities in Germany. The status described in this study reflects the situation in Germany in the year 2015. In some cases, updated information from May 2019 was available (e.g. the status of plants that were under construction in the reference year) and added as a footnote to the respective sections.

Methodology

This study presents all facilities in Germany that convert waste into energy. The following waste treatment plants have been taken into account:

- Municipal solid waste incineration plants (MSWI plants),
- Refuse derived fuel power plants (RDF power plants),
- Hazardous waste incineration plants,
- Waste wood incineration plants and biomass power plants,
- Sewage sludge incineration plants,
- Cement works (co-firing of waste),
- Coal-fired power plants (co-firing of waste),
- Industrial power plants,
- Anaerobic digestion plants (AD plants),
- Mechanical-biological treatment (MBT) plants with fermentation stage.

The starting point for the data collection was the quantification of plant capacities and the quantities of waste that were actually treated in these plants. These could be determined with high accuracy, in particular on the basis of an operator survey that was carried out for MSWI plants, RDF power plants and hazardous waste incineration plants. Data collected in this survey included plant specifications, types of waste and heating value, auxiliary fuels and energy produced. The response rate varied between 39% (RDF

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incineration plant) and 92% (MWSI plant), with the percentage based on the total installed capacity. An estimation for the entire plant park was carried out by extrapolating the available information. In addition to this survey, the power plant list of the Federal Network Agency (Bundesnetzagentur, 2011) offered extensive information on the German power plant park. Plausibility checks and a search for missing information were carried out by comparison with the waste balances of the Länder (provinces), data of the Federal Statistical Office as well as information from respective associations and the literature. In addition to the capacities and mass flows (Mg a^{-1}), the quantities of energy exported by the plants in the form of electricity, heat and steam, the energy supply from waste in the industrial process and the energy content of the treated waste flows in the form of calorific values (MJ Mg^{-1}) were queried or otherwise determined. This enabled a calorific value-related capacity analysis to be carried out for the waste quantities used in each case. The total amount of energy per plant was calculated by multiplying the annual throughput with the average heating value of the waste input and accounting for the plants' own energy consumption and efficiencies.

For better readability, a more detailed description of the methodology including assumptions made is given in the respective sections.

Waste treatment facilities

MSWI plants

The distinction between MSWI plants and RDF power plants is not always clear. Waste incineration plants were originally built with the purpose to minimize the amount of waste and destroy potential pollutants but have by now also become energy suppliers. RDF power plants on the other hand were originally built with the purpose of generating energy in the immediate vicinity of consumers. RDF is produced by processing household and commercial waste (e.g. shredding and removal of non-combustible materials) (Giugliano and Ranzi, 2016). The combustion technology of RDF power plants and MSWI plants is often identical as grate firing (the common system for MSWI plants) is nowadays also generally used in RDF plants; less than one-third of these plants use fluidized bed combustion systems. Both types of plants incinerate untreated and pretreated municipal waste. RDF power plants usually have a more limited variety of waste types that can be processed. Within this study, incineration plants that were built more recently for the purpose of energy provision and designed for RDF as input are consequently listed as RDF incineration plants.

Table 1 shows the 66 MSWI plants that are currently operated in Germany, all of them equipped with a grate firing system. A total incineration capacity of 20,634,782 Mg a^{-1} is available. There are currently no concrete plans for new constructions. The MSWI plant in Göppingen has been approved for an expansion of 20,000 Mg a^{-1}.

The plant sizes of the German waste incineration plants vary between 50,000 Mg a^{-1} and 780,000 Mg a^{-1}. Most plants are operated in combined heat and power (CHP) generation, with some transferring the generated process steam to external plants for power generation and heat utilization (each noted as a footnote in Table 1 – CHP operation is shown). Six plants generate electricity only.

An operator survey has been conducted for German MSWI plants. Detailed data on operating parameters, waste use and energy marketing could be collected. The response rate to the questionnaires was 89.4% (of the total number of MSWI plants), covering 92.1% of German waste incineration capacity. With this high proportion, it was possible to extrapolate to the entire plant park with only a minor error.

Figure 1 shows the total annual throughput of all German MSWI plants for the years 2012 to 2016 compared to the available capacity (the values for throughput also include quantities of imported waste, which amounted to about 700,000 Mg a^{-1} in the last two years). The data clearly reflect the known increase in capacity utilization in recent years. Although a number of plants have been continuously exceeding their design capacity limits for several years (cf., for example, 320grad, 2017), in 2016, the year of the highest capacity utilization to that date, a total capacity of just under half a million Mg was still unused. In the opinion of many experts, however, this is already too little to guarantee safe long-term operation. The downtime of a single larger plant would already consume this capacity reserve.

The total amount of energy that enters MSWI plants as waste input is shown in Figure 2. Energy produced in and exported from these facilities is also shown in Figure 2. With 205 PJ a^{-1}, the energy supplied to waste incineration plants corresponds to about 1.5% of the annual primary energy consumption in Germany (Umweltbundesamt, 2017b). About 110 PJ a^{-1} of this is converted into electricity, heat and steam, corresponding to a gross efficiency of more than 50%. After deduction of own consumption, most of which is spent on emission reduction, around 90 PJ a^{-1} are supplied to consumers and contribute about 1% to the final energy consumption in Germany. Figure 3 shows the total utilization rates (gross and net). The calculation was based on the total values aggregated from all plants, taking into account the auxiliary energies used.

RDF power plants

As for MSWI plants, data on RDF power plants were collected by contacting plant operators. As the number of plants organized in an association is smaller than for MSWI plants, the response rate was significantly lower. Nevertheless, 39.4% of the German capacity of RDF power plants could be covered by the survey. Table 2 gives an overview of all German RDF plants.

The total capacity of German RDF power plants is 6,310,750 Mg a^{-1}. This number includes plants at paper mills that are used for incinerating residues from the pulp and paper industry. Consequently, not the entire capacity is available for the incineration of RDF. The current market situation has led to plans to expand the RDF power plant park to a moderate

Table 1. Waste incineration plants in Germany (Flamme et al., 2018).

Number	Plant	Grate	Lines	Start-up	Energy delivery	Thermal firing capacity [MW]	Capacity (Mg a^{-1})
1	Augsburg	FAG	3	1994	CoG	75	255,000
2	Bamberg	CAG	3	1978	CoG	53	145,000
3	Berlin *	RG	5	1967	CoG		550,000
4	Bielefeld	CAG	3	1981	CoG	180	400,000
5	Böblingen	FAG	2	1999	CoG	58	157,000
6	Bonn *	FAG	3	1992	CoG	86	315,000
7	Bremen	FAG	4	1969	CoG	221	550,000
8	Bremerhaven	FAG	4	1977	CoG	140	401,500
9	Burgkirchen	FAG	2	1994	CoG		230,000
10	Coburg	RAG	2	1988	CoG	53	142,000
11	Darmstadt	FAG	3	1967	CoG	77	212,000
12	Düsseldorf *	RG	6	1965	CoG	137	450,000
13	Emlichheim (Laar)	FAG	2	2008	E		454,176
14	Essen	RG	4	1987	CoG		745,000
15	Frankfurt	FAG	4	1965	CoG		525,300
16	Freiburg/ Eschbach	FAG	1	2005	CoG	61	185,000
17	Göppingen	RG	1	1975	CoG	57	157,680
18	Hagen	RG	3	1966	CoG		144,000
19	Hamburg MVB	FAG	2	1994	CoG	116	320,000
20	Hamburg MVR	FAG	2	1999	CoG	120	320,000
21	Hameln	FAG | RG	3	1977	CoG	141	300,000
22	Hamm	FAG	4	1985	CoG		295,000
23	Hannover	FAG	2	2005	E	105	280,000
24	Helmstedt/ Buschhaus	FAG	3	1998	E	173	525,000
25	Herten	FAG | CAG	4	1982	CoG	208	600,000
26	Ingolstadt	RAG | CAG	3	1977	CoG	99	255,000
27	Iserlohn	FAG	3	1970	CoG	102	295,000
28	Kamp-Lintfort	RG	2	1997	CoG	99	270,000
29	Kassel	FAG	2	1968	CoG	61	200,000
30	Kempten	RAG	2	1996	CoG	52	160,000
31	Kiel	RG	2	1996	CoG	44	140,000
32	Köln (Cologne)	RG	4	1998	CoG	241	780,000
33	Krefeld	RG	3	1975	CoG	162	375,000
34	Lauta	FAG	2	2004	CoG	87	225,000
35	Leuna	FAG	2	2005	CoG	153	420,000
36	Leverkusen	FAG	3	1970	CoG	84	280,320
37	Ludwigshafen *	RG	3	1967	CoG	88	210,000
38	Ludwigslust	FAG	1	2005	E	16	50,000
39	Magdeburg/ Rothensee	FAG	4	2006	CoG	267	650,000
40	Mainz *	RAG	3	2004	CoG		350,000
41	Mannheim	FAG	3	1965	CoG	263	650,000
42	München (Munich)	RAG	4	1983	CoG	172	685,000
43	Neunkirchen	RAG	2	1969	CoG	56	150,000
44	Neustadt	FAG	1	1984	CoG	24	56,000
45	Nürnberg (Nuremberg) *	FAG	3	2001	CoG	105	230,000
46	Oberhausen/ Niederhein	RG	4	1972	CoG	267	700,000
47	Offenbach	RG	3	1970	CoG	84	250,000
48	Olching/ Geiselbullach	FAG	3	1975	CoG	44	120,000
49	Pirmasens	FAG	2	1998	CoG	70	180,000
50	Rosenheim	CAG	1	1964	CoG	28	100,000
51	Salzbergen *	FAG	1	2004	CoG	47	130,000
52	Schwandorf	CAG	4	1982	CoG	205	450,000
53	Schweinfurt	FAG	3	1994	CoG	62	196,806
54	Solingen	FAG	2	1969	CoG	63	175,000

(Continued)

Table 1. (Continued)

Number	Plant	Grate	Lines	Start-up	Energy delivery	Thermal firing capacity [MW]	Capacity (Mg a^{-1})
55	Stapelfeld	FAG	2	1979	CoG	116	350,000
56	Staßfurt	FAG	2	2007	CoG	111	380,000
57	Stuttgart *	FAG | RG	3	1965	CoG	193	420,000
58	Tornesch-Ahrenlohe	FAG	2	1974	CoG	29	80,000
59	Ulm	FAG	2	1997	CoG		165,000
60	Velsen/ Saarbrücken	FAG	2	1997	E	83	255,000
61	Weißenhorn	FAG	2	1991	E	48	116,000
62	Weisweiler/ Eschweiler *	RAG	3	1996	CoG	135	360,000
63	Wuppertal	RAG	5	1976	CoG	186	400,000
64	Würzburg	FAG | FAG - RAG	3	1984	CoG		219,000
65	Zella-Mehlis	RAG	1	2008	CoG	60	160,000
66	Zorbau	FAG	2	2005	CoG	107	338,000
						Σ	**20,634,782**
	Plants under construction/in planning						
	Extension MSWI Göppingen to 180,000 Mg a^{-1}						22,000

* external conversion into electricity; FAG: forward acting grate; RAG: reverse acting grate; CAG: counter acting grate; RG: roller grate; CoG: cogeneration of heat and power; E: only electricity production.

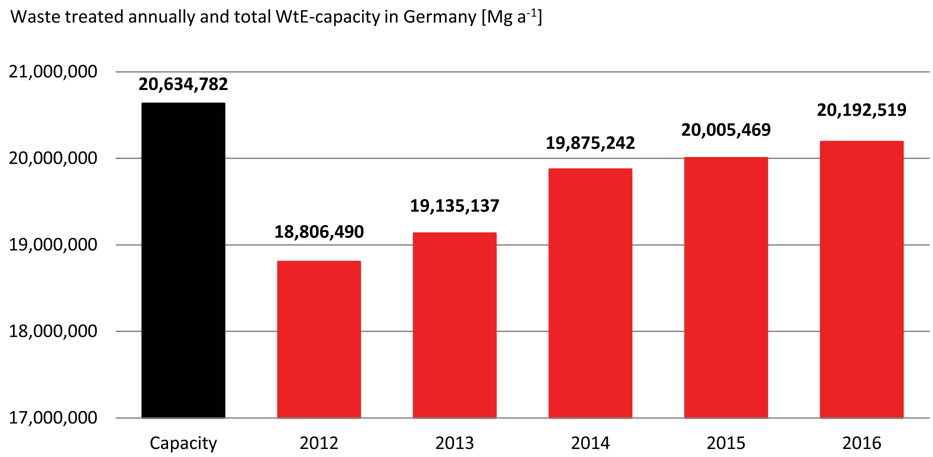

Figure 1. Annual amount of waste incinerated in German municipal solid waste incineration plants between 2012 and 2016 and the total available incineration capacity (extrapolation based on operator survey with a response rate of 92%).

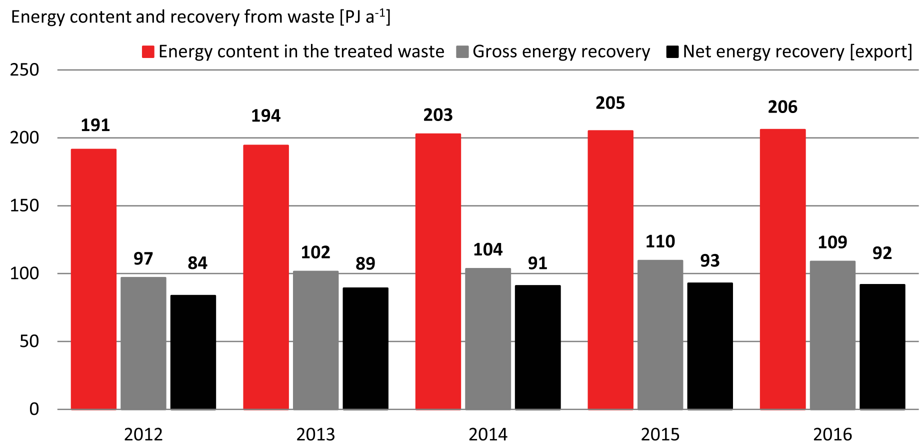

Figure 2. Energy input and generation (sum of electricity, heat and steam) in German waste incineration plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 92%).

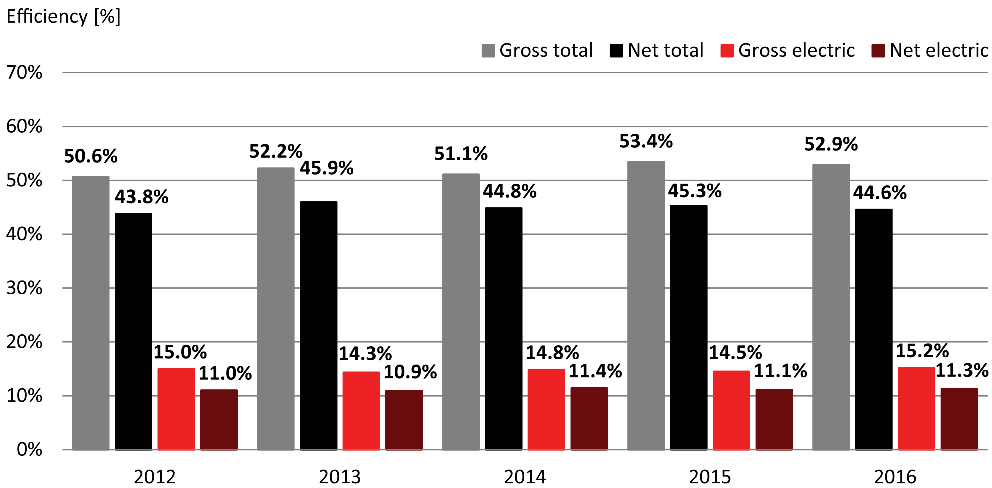

Figure 3. Electrical and overall efficiency of German waste incineration plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 92%).

Table 2. Refuse derived fuel (RDF) power plants in Germany (Flamme et al., 2018) (shown are the total incineration capacities. In addition to RDF, some plants also use other fuels, such as paper sludge).

Number	Plant	Type	Lines	Start-up	Energy delivery	Thermal firing capacity (MW)	Capacity (Mg a^{-1})
1	Amsdorf	GF	2	2004	CoG		120,000
2	Andernach	GF	1	2008	CoG		114,000
3	Bernburg *	GF	3	2009	CoG	214	552,000
4	Bitterfeld-Wolfen	GF	1	2010	CoG	56	130,000
5	Bremen Blumenthal	GF	1	2005	CoG	31	60,000
6	Bremen MKK	GF	1	2009	CoG	110	330,000
7	Eisenhüttenstadt **	CFBC	1	2011	CoG	150	340,000
8	Erfurt Ost	GF	1	2006	CoG	26	63,900
9	Essen ****	SFBC	1	2010	CoG	12	26,500
10	Frankfurt (T2C)	RFBC	3	2012	CoG		700,000
11	Gersthofen I Augsburg	GF		2009	CoG	35	90,000
12	Gießen	GF	1	2009	CoG	10	25,000
13	Glückstadt **	CFBC	1	2009	CoG		250,000
14	Großräschen	GF	1	2008	CoG	102	258,750
15	Hagenow	GF		2009	CoG	35	80,000
16	Heringen *	GF	2	2010	CoG	117	297,600
17	Hürth/ Knapsack	GF	2	2008	CoG	130	320,000
18	Korbach	GF	1	2008	CoG	36	75,000
19	Lünen ***	CFBC	1	1982/2005	CoG		165,000
20	Meuselwitz-Lucka ****	GF		2005			50,000
21	Minden	GF	1	2002	CoG	15	35,000
22	Neumünster	CFBC	1	2005	CoG	83	150,000
23	Pforzheim	CFBC	1	1990	CoG		50,000
24	Premnitz	CFBC/GF	2	2001	CoG	106	270,000
25	Rostock	GF	1	2010	CoG	87	230,000
26	Rudolstadt/Schwarza	GF	1	2007	S	29	80,000
27	Rüdersdorf	GF	1	2008	E	110	226,000
28	Schwedt **	CFBC	1	2011	CoG		442,000
29	Spremberg/Schw. Pumpe **	GF	1	2012	CoG	110	240,000
30	Stavenhagen	GF	1	2007	CoG	49	90,000

(Continued)

Table 2. (Continued)

Number	Plant	Type	Lines	Start-up	Energy delivery	Thermal firing capacity (MW)	Capacity (Mg a-1)
31	Weener/Leer	GF	1	2008	CoG		120,000
32	Witzenhausen **	GF	1	2009	CoG	124	330,000
						Σ	**6,310,750**
	Plants under construction/ in planning						
	Gießen, 2nd plant	GF	1	2019	CoG	10	28,670
	Stade	GF	1				175,000
	Stellinger Moor	GF	1	2023	CoG	48	100,000

* external electricity production; ** also, incineration of rejects and sludge from paper recycling; *** co-combustion with other fuels (e.g. biomass, animal meal, and coal); **** plant (currently) out of operation[1]; GF: grate firing; SFBC: stationary fluidized bed combustion; CFBC: circulating fluidized bed combustion; RFBC: rotary fluidized bed combustion; CoG: cogeneration of heat and power; E: only electricity production; S: only steam production.

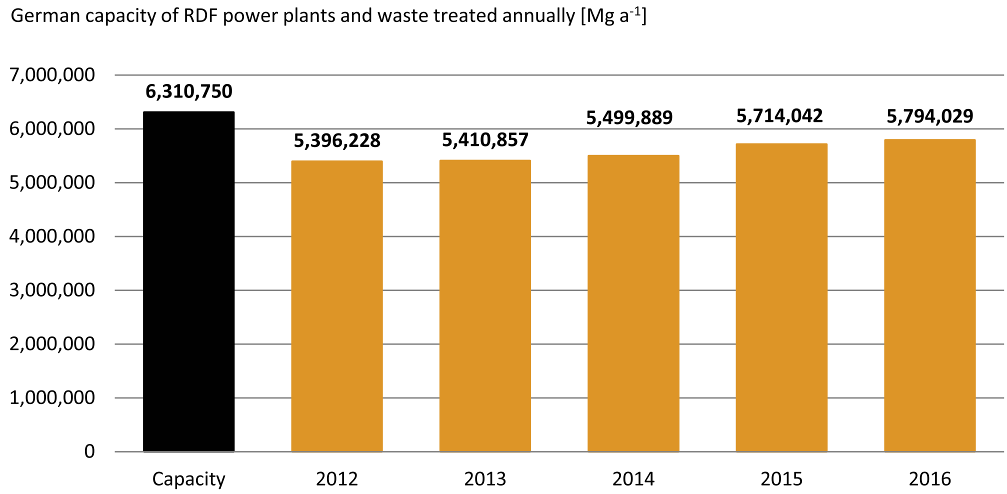

Figure 4. Annual amount of waste incinerated in German refuse derived fuel power plants between 2012 and 2016 and the total available incineration capacity (extrapolation based on operator survey with a response rate of 39%).

extent. For example, efforts are being made to complete a plant in Stade, which has been under construction for years. Concrete plans for a waste utilization center with an RDF power plant at the site of the former Stellinger Moor waste incineration plant in Hamburg exist. In addition, a second plant is under construction in Giessen (TREA II), which was planned to go into operation at the end of 2017. This was later moved to the end of 2018[2].

As shown in Figure 4, the capacities of German RDF power plants are well used. The amount of waste incinerated given in Figure 4 also includes imported waste, about 200,000 Mg a^{-1} in 2016. The last years have been characterized by a moderate increase in throughput. As for MSWI plants, there are several RDF power-plants that operate continuously above their design capacity. Nevertheless, there is currently a capacity reserve of about half a million Mg a^{-1}.

Figure 5 shows the (aggregated) values of the energy used and utilized (sum of electricity, heat and steam) from the combusted waste. With around 45 PJ a^{-1}, the amount of energy exported is about half as much as the corresponding value for MSWI plants.

Figure 6 shows the average and maximum electrical and total efficiencies for the years 2012 to 2016. The overall better performance of RDF plants compared to MSWI plants is mainly due to the optimized location, but also due to the chosen steam parameters (pressure and temperature), favorable for electricity generation. A more detailed analysis was not conducted due to the low response rate of the survey, which does not guarantee good representability.

Hazardous waste incineration plants

There are 31 facilities for the incineration of hazardous waste in Germany. Most of these plants use rotary kilns, in which solid, liquid, and to some extent gaseous wastes undergo thermal treatment. Liquid and gaseous material may also be combusted in combustion chambers. Table 3 lists all hazardous waste incineration plants with their capacities. The data required for the determination of energy generated by the incineration of hazardous waste were also collected via an operator survey supported by BDSAV e.V. and VCI e.V. (two associations for hazardous waste

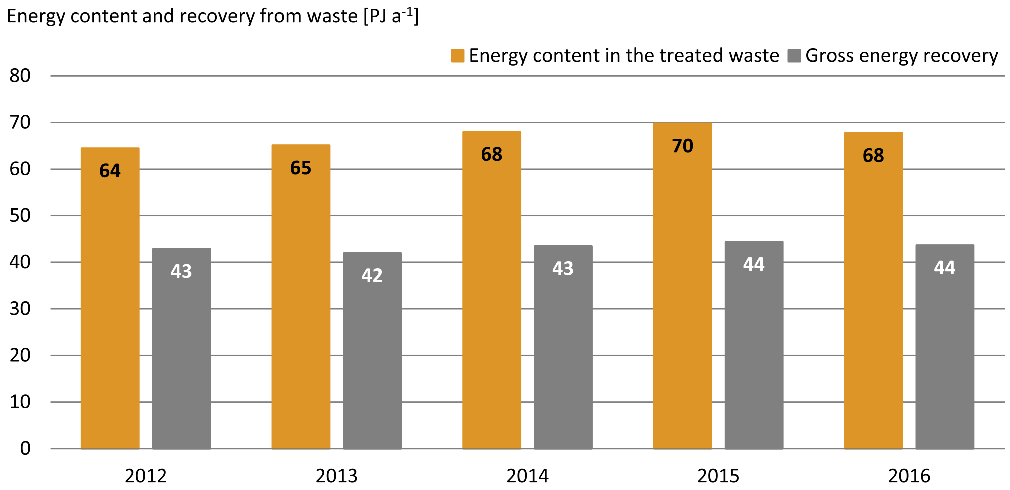

Figure 5. Energy input and generation (sum of electricity, heat and steam) in German refuse derived fuel power plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 39%).

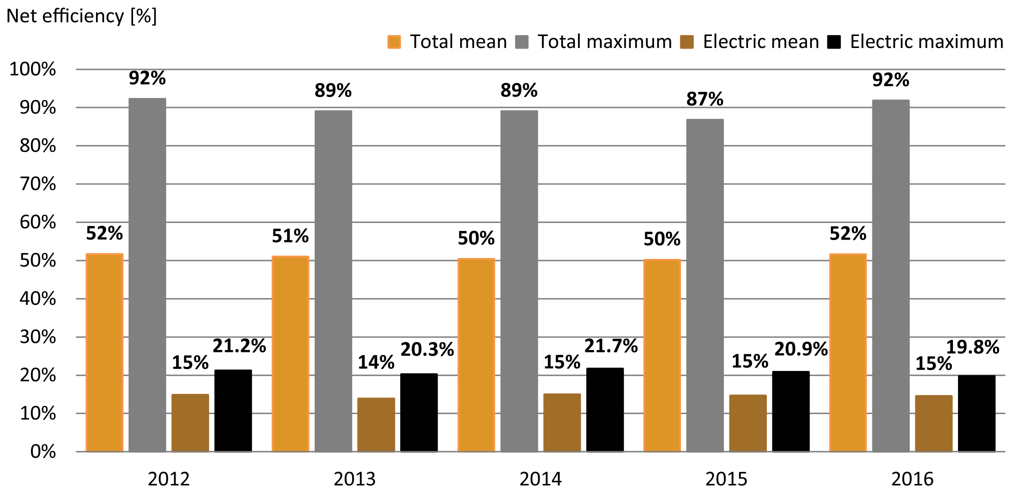

Figure 6. Electrical and overall net efficiencies of German refuse derived fuel power plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 39%).

Table 3. Hazardous waste incineration plants in Germany (Flamme et al., 2018).

Number	Plant	Operator	Lines	Furnace	Fuel types	Energy delivery	Capacity (Mg a^{-1})
1	Baar-Ebenhausen	GSB	2	RK	s/l	CoG	180,000
2	Bergkamen	Bayer Schering Pharma					12,000
3	Biebesheim	Indaver HIM	2	RK	s/l	CoG	120,000
4	Bramsche	Remondis		BC	l/g		2000
5	Brunsbüttel	Remondis	1	RK	s/l	CoG	55,000
6	Brunsbüttel	Currenta		BC	l		27,000
7	Burghausen	Wacker	2	RK/2 × BC	s/l/g	S	32,000
8	Dormagen	Currenta	1	RK	s/lg	S	75,000
9	Frankfurt Höchst	Infraserv	2	RK	s/lg	S	60,000
10	Gendorf	Infraserv *		RK	l	S	4000
11	Hamburg	Indaver AVG	2	RK	s/l	S	130,000
12	Herten	AGR Gruppe	2	RK	s/l	CoG	112,000
13	Hürth/Knapsack	Vinnolit	2				11,360
14	Kehlheim	Kehlheim Fibres	1	RK		S	5000
15	Köln (Cologne)	INEOS					70,000

(Continued)

Table 3. (Continued)

Number	Plant	Operator	Lines	Furnace	Fuel types	Energy delivery	Capacity (Mg a^{-1})
16	Krefeld	Currenta	1	RK	s/lg	S	25,000
17	Leverkusen	Currenta	2	RK	s/l	S	140,000
18	Leverkusen	DNES Dynamit Nobel		RK		S	26,280
19	Lingen	BP	1	RK	l	S	9440 **
20	Ludwigshafen	BASF	6	RK		S	165,000
21	Marl	Evonik	1	RK		S	20,000
22	Münster	BASF Coatings	1	RK	s/l	S	13,000
23	Muldenhütten	MRU	1	RK	s/l	CoG	33,000
24	Nünchritz	Wacker	2			S	37,000
25	Schkopau	Dow	1	RK	s/l	S	45,000
26	Schöneiche	MEAB	1	RK	s/lg	CoG	25,000
27	Schwarzheide	BASF	1	RK	s/l	S	40,000
28	Schwedt	PCK Raffinerie	1	RK	s/l		30,000
29	Stade	Dow	1	RK	s/l	S	40,000
30	Trostberg	AlzChem	1	2 BC	l/g	s	30,000
31	Wesseling	Basell	2	RK	s/l	CoG	60,000
						Σ	**1,634,080**

* plant (currently) out of operation; ** calculated from 1.18 Mg h^{-1} throughput and (estimated) 8,000 h a^{-1} operation time; s: solid waste; l: liquid waste; g: gaseous waste; RK: rotary kiln; BC: burning chamber; CoG: cogeneration of heat and power; S: only steam production.

combustion and chemical industry, respectively (BDSAV, 2019; VCI, 2019)). The response rate was 56.1% of the installed capacity. An extrapolation to the entire plant capacity was done based on these data.

The total capacity for the incineration of hazardous waste in Germany is 1,634,080 Mg a^{-1}. About 80% of this capacity are currently used (cf. Figure 7). The total amount of incinerated waste in these plants was roughly 1.3 mio. Mg a^{-1} for the last years. Most of the facilities are situated at integrated locations (waste treatment centers of chemical parks) and the recovered energy is provided as steam, which can be used directly at the location (cf. column "Energy delivery" in Table 3). As a result, comparably high overall efficiencies of about 60% on average can be reached (cf. Figure 8 and Figure 9), with single values ranging between 40% and more than 90%. No electrical efficiencies are given as most facilities do not produce electricity. In 2016, the total amount of 22 PJ contained in 1.3 mio. Mg of hazardous waste was converted into 15 PJ final energy, mostly steam.

Waste wood incineration plants and biomass power plants

Biomass (CHP) plants include plants that use waste wood as well as plants in which natural wood (or another natural biomass) is used. This distinction is not always straightforward and therefore also not clearly made in statistical evaluations. The first step was therefore the determination of plants that incinerate waste wood.

A study by Deutsches Biomasseforschungszentrum on biomass (heating and) power plants in Germany showed that the number of plants with an electrical output of more than 5 MW_{el} is small (Deutsches Biomasseforschungszentrum, 2015). It can be assumed that these plants mainly combust waste wood because the emission reduction requirements according to the 17th BImSchV (emission reduction for waste derived fuel combustion) require a certain minimum plant size for an economic operation. Therefore, only plants with an electrical output of more than 5 MW or a thermal capacity of more than 20 MW were considered for this study. From the corresponding lists, plants that burn natural wood were eliminated. The remaining facilities, which can be assumed to burn waste wood, are listed in Table 4. Installations in the wood-based products and paper industries that are not eligible for the Renewable Energy Sources Act (EEG) (BMWi, 2017) are not taken into account, nor are industrial plants that recycle production residues.

Finally, a total of 56 waste wood incineration facilities with an annual capacity of 6,579,671 Mg and a thermal capacity of 2979 MW are identified based on this selection process. Assuming an average electrical efficiency of 26.3%, this thermal capacity corresponds to 783 MW_{el}. This is in good agreement with the total capacity of waste wood plants named by Bundesverband der Altholzaufbereiter und -verwerter, that is 821 MW_{el}. This agreement confirms the selection of the plants listed in Table 4 (Bundesverband der Altholzaufbereiter und -verwerter, 2016; Uffmann, 2016).

The total amount of energy utilized in these facilities was calculated by the thermal capacity and the annual operation of 8000 hours. This yields 85.8 PJ a^{-1}, which is used in the subsequent calculations.

The provision of electricity from these facilities was estimated using the installed electrical output (783 MW_{el}) and the annual operation of 8000 hours. For larger biomass plants, the amount of heat provided is also known (Umweltbundesamt, 2017a). The

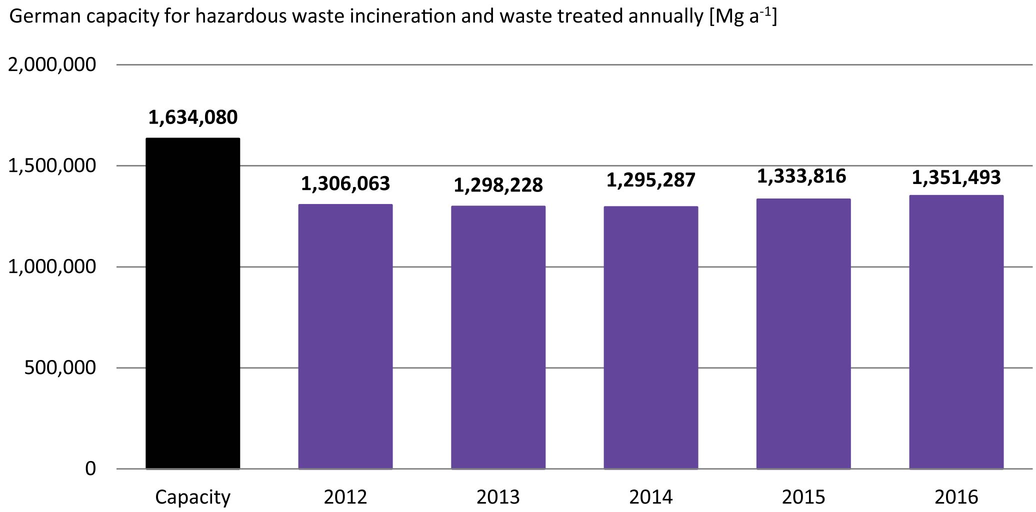

Figure 7. Annual amount of waste incinerated in German hazardous waste incineration plants between 2012 and 2016 and the total available incineration capacity (extrapolation based on operator survey with a response rate of 57%).

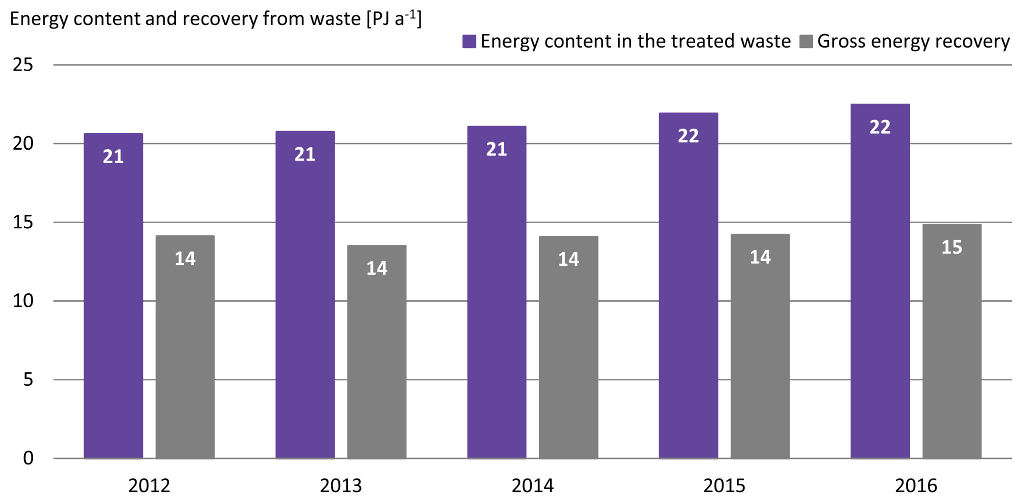

Figure 8. Energy input and gross generation (sum of electricity, heat and steam) in German hazardous waste incineration plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 57%).

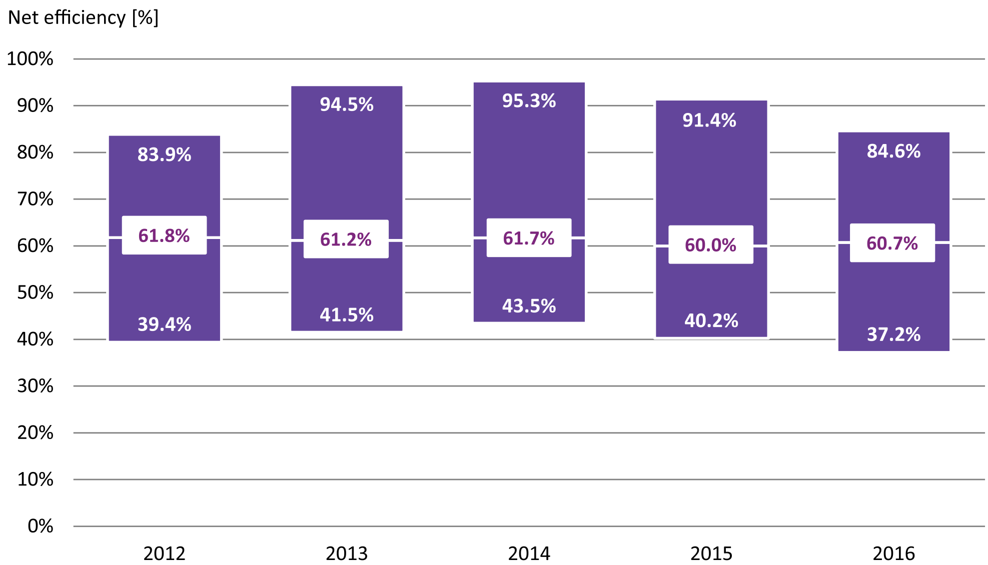

Figure 9. Net efficiencies of German hazardous waste incineration plants between 2012 and 2016 (extrapolation based on operator survey with a response rate of 57%). The maximum, minimum and mean values of all plants are shown.

Table 4. Incineration plants for waste wood with a thermal power > 20 MW in Germany (Flamme et al., 2018).

Number	Plant	Start-up	Fuel/waste types	Thermal firing capacity [MW]	Capacity [Mg a^{-1}]
1	Altenstadt	1999	AI-AIII/LM	40	100,000
2	Baruth/Mark	2002	AI-AIV/WD	110	245,000
3	Beeskow	2001	AI-AIV	130	235,000
4	Bergkamen	2005	AI-AIII/BW	23	160,000
5	Berlin	2005	AI-AIV	66	200,000
6	Borken	2006	AI-AIV	36	74,000
7	Brilon	1990	Wood/BW	150	340,000
8	Buchen	2003	AI-AIV	30	60,000
9	Delitzsch	2004	AI-AIV	69	147,000
10	Dresden	2004	AI-AIV	27	56,000
11	Elsterwerda	2004	AI-AIV/BW	44	90,000
12	Emden	2005	Waste wood	67	150,000
13	Emlichheim	2006	AI-AIV	67	170,000
14	Flörsheim Wicker	2003	AI-AIII	50	90,000
15	Frankfurt Main	2004	AI-AIV	44	120,000
16	Großaitingen	2002	AI-AIII	21	40,000
17	Gütersloh	2001	AI-AIV	58	110,000
18	Hagen	2004	AI-AIV	86	219,000
19	Hagenow		AI/AII	36	97,671
20	Hamburg	2005	AI-AIV	90	160,000
21	Hameln	2002	AI-AIV	55	100,000
22	Heiligengrabe	2002	AI-AIV/| PR/FWC	65	130,000
23	Helbra	2001	AII-AIV	28	45,000
24	Herbrechtingen	2004	AI-AII I PR I FWC	49	128,000
25	Hoppstädten		AI-AIV	29	60,000
26	Horn-Bad Meinberg	2000	AI-AIV/ PR/FWC	102	190,000
27	Hückelhoven		AI/AII	39	60,000
28	Ilmenau	2005	AI-AIII	20	50,000
29	Ingelheim	2004	AI-AIV	70	90,000
30	Karlsruhe	2010	AI-AIII/RDF/FS	170	230,000
31	Kassel	1988	AI/AII/SS	42	80,000
32	Kehl	2002	AI-AIV	47	110,000
33	Kehl	2011	AI/AII	21	40,000
34	Königs Wusterhausen	2003	AI-AIV/BW	20	120,000
35	Landesbergen	2005	AI-AIV	22	140,000
36	Liebenscheid	2006	AI-AIV	50	100,000
37	Lünen	2006	AI-AIV/SR	65	135,000
38	Malchin	2003	AI-AIII/Straw/LP	44	130,000
39	Mannheim	2003	AI-AIV	66	135,000
40	Neufahrn	2004	AI-AIII	21	40,000
41	Neumarkt i.d. Opf.	1997	AI-AIV	100	200,000
42	Neuwied	2004	AI-AIV	30	60,000
43	Obrigheim	2008	AI-AIII	22	67,000
44	Papenburg	2003	AI-AIV	20	155,000
45	Pforzheim	2004	AI-AIII	45	105,000
46	Recklinghausen	2004	AI-AIV	50	120,000
47	Rietz-Neuendorf		AI-AIV/BW	25	55,000
48	Silbitz	2003	AI-AIV	27	55,000
49	Ulm	2003	AI-AIV	58	140,000
50	Ulm	2012	AI-AII	25	90,000
51	Wiesbaden, ESWE	2014	AI-AIV	46	90,000
52	Wiesbaden, InfraServ	2003	AI-AIV	50	96,000
53	Wismar, Egger		AI-AIV/PR	80	96,000
54	Wismar Pellets		AI/AII	39	80,000
55	Zapfendorf	2009	AI-AIV	27	64,000
56	Zolling	2003	AI-AIV	66	130,000
				Σ	**6,579,671**

AI, AII, AIII, AIV: waste wood categories; LM: landscape material; WD: wood dust; BW: bulky waste; PR: production residues; FWC: forest wood chips; RDF: refuse derived fuel; FS: fiber sludge; SR: screening residues; LP: lemon peels; SS: sewage sludge.

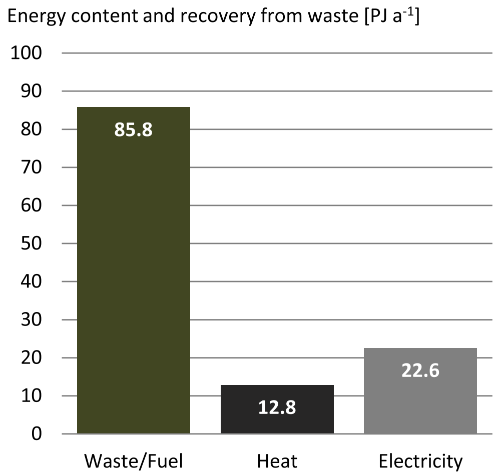

Figure 10. Annual energy input in German waste wood incineration plants and generated electricity and heat in PJ a^{-1} (Flamme et al., 2018).

resulting ratio of electricity to heat was used for all plants, thereby estimating the total amount of heat provided. The results are shown in Figure 10 (left). It should be noted that more electricity than heat is generated. This is likely the result of older versions of the Renewable Energy Act (EEG), which led to the construction of numerous biomass incineration plants for electricity generation in the beginning of the 21st century.

Sewage sludge incineration plants

In addition to co-firing in cement works and coal-fired power plants (see below), sewage sludge is combusted in 20 mono-incineration plants in Germany. These mainly treat sludge that arises in municipalities. In addition, there are seven combustion facilities for industrial sludge, located at larger chemical companies or chemical parks. Table 5 lists all facilities including their most important characteristics. In addition to the plants that are already in operation, there are several facilities planned for construction or already under construction.

A comparison of the available capacity of 913,145 Mg a^{-1} with the total amount of incinerated hazardous waste reported by the Federal Statistical Office (432,500 Mg in 2015) suggests a large capacity reserve. However, in addition to about 446,900 Mg a^{-1} that are co-incinerated in other facilities, the Statistical Office also lists 269,300 Mg that are not allocated to any sort of treatment (Statistisches Bundesamt, 2016, 2017). It may be assumed that at least part of this is also incinerated, so that the total amount of sewage sludge treated at mono-incineration plants is presumably much higher than the reported 432,500 Mg a^{-1}. Due to the poor data situation, more precise information cannot be given.

The average dry matter content of the sludges treated in the facilities listed in Table 5 is 33%. These sludges can only be incinerated after a preceding drying step or by using highly preheated combustion air. Both cases require a significant amount of energy input. From a balancing point of view, exporting a noteworthy amount of thermal or electrical energy from such a facility seems unlikely. In practice, operators aim for an energetically self-sufficient process. In addition to drying, a (small) turbine is sometimes operated for this purpose. Some plants are integrated into an operational supply network, but also in these cases a noteworthy amount of exported energy cannot be realized. This could be influenced if the sludge were pre-dried using otherwise unused low-temperature heat or solar heat. These options strongly depend on the location and a general evaluation is therefore not possible.

In summary, there is no significant energy export from sewage sludge incineration plants. Accordingly, this study does not consider any contribution of sewage sludge to the total energy supply from waste.

Cement works (waste co-firing)

All 34 cement works with clinker production and two lime plants are licensed to use waste-derived fuels. These plants are listed in Table 6. A capacity for the co-incineration of waste in cement works is not specified, because of the interaction between the properties of the raw materials and the clinker. In theory, the use of 100% waste is possible, if the mineral matter content of the fuel meets the requirements of the clinker production. In addition, data on the individual plants are difficult to obtain. For this study, aggregated numbers from Verein Deutscher Zementwerke e.V. (waste types, quantities, and calorific value) are used, as the secondary fuel consumption in German cement works is regularly collected and published (Verein Deutscher Zementwerke e.V., 2012a, 2012b, 2014, 2015, 2016).

Figure 11 shows the use of waste in German cement works between 2011 and 2015. The total amount of waste used was 3.2 mio. Mg in 2015, corresponding to an energy input of just below 60 PJ a^{-1}. Both lime plants combined have an approved capacity of 391,676 Mg a^{-1} of secondary fuel. No other waste-derived fuels (such as liquid fuels) were taken into account as no information was available.

The range of fuels used in German cement works is diverse. In addition to animal meal, sewage sludge or used tires, processed fractions from industrial, commercial and municipal waste, which also include the fractions referred to as "plastics" in Figure 12, are mainly used (Oerter, 2017). Figure 12 shows specifications of the waste types used, including their quantities and the resulting energy input. The fuels used release their energy directly, immediately and completely in the clinker burning process. This leads to a high energy efficiency, which was set to 70% (Vodegel et al., 2018). In addition, the combustion residues are fully integrated into the product.

Coal-fired power plants (waste co-firing)

In 2015, 22 power stations in Germany were licensed to co-incinerate waste, of which 11 each are fired with lignite or hard coal as their basic fuel. Table 7 lists these plants, including their permitted and currently co-combusted amounts of waste fuel.

Table 5. Facilities for mono-incineration of sewage sludge (Wiechmann et al., 2012).

Number	Plant	Type	Lines	Start-up	DM-content	Capacity (Mg a^{-1})	
						FM	DM
1	Altenstadt *	GF	2	2008	34%	160,000	55,000
2	Balingen	FBG	1	2002	80%	3000	2400
3	Berlin-Ruhleben	SFBC	3	1985	26%	325,000	84,100
4	Bitterfeld-Wolfen	SFBC	1	1997	30%	50,700	15,200
5	Bonn **	SFBC	2	1981	27%	29,100	8000
6	Bottrop	SFBC	2	1991	40%	110,000	44,000
7	Burghausen (Wacker)	SFBC	1	1976	21%	20,000	4125
8	Düren	SFBC	1	1975	40%	35,000	14,000
9	Frankfurt (Hoechst)	SFBC	2	1994	39%	205,000	80,000
10	Frankfurt (Kommunal) **	EtW	4	1981	28%	188,000	52,560
11	Gendorf (Infraserv)	SFBC	1	2006	25%	40,000	10,000
12	Hamburg **	SFBC	3	1997	40%	197,100	78,840
13	Herne	SFBC	1	1990	44%	50,000	22,200
14	Homburg	PY		1916	28%	5000	1400
15	Karlsruhe **	SFBC	2	1982	25%	80,000	20,000
16	Leverkusen (Currenta)	MHF	1	1988	30%	120,000	36,000
17	Linz-Unkel	PY	1	2015	30%	2300	700
18	Ludwigshafen (BASF)	SFBC	2	1992	26%	420,000	110,000
19	Lünen	SFBC	1	1997	40%	235,000	95,000
20	Mannheim	FBG	2	2010	46%	10,800	5000
21	Marl (Chemical Park)	SFBC	1	1980	25%	40,000	10,000
22	München (Munich) **	SFBC	2	1997	25%	88,000	22,000
23	Straubing **, ****	GF	1	2012	28%	9000	2500
24	Stuttgart **	SFBC	2	2007	25%	130,000	32,000
25	Neu-Ulm **	SFBC	2	1979	25%	64,000	16,000
26	Werdohl-Elverlingsen ***	SFBC	1	2002	28%	200,000	61,320
27	Wuppertal **	SFBC	2	1977	25%	128,000	32,000
					Σ	**2,943,500**	**913,145**
	Plants under construction *****						
	Rügen	SFBC	1	2017			2500
	Mainz	SFBC	1	2019			30,000
	Koblenz	FBG	1	2017	90%	14,000	3000

* the plant also incinerates fermentation residues; ** construction, upgrading or extension planned or already in progress; *** plant additionally incinerates 4000–6000 Mg refuse derived fuel per year; **** plant out of operation; ***** due to a change of the German sewage sludge ordinance, about 30 new projects are in discussion. Industrial sewage sludge incineration plants (which may also treat municipal sewage sludge); GF: grate firing; SFBC: stationary fluidized bed combustion; MHF: multiple-hearth furnace; MHFBC: MHF with SFBC; FBG: fluidized bed gasification; PY: pyrolysis; SF: shaft furnace; FM: fresh matter; DM: dry matter.

Table 6. German cement and lime works, with permission for energetic utilization of waste fractions (Verein Deutscher Zementwerke (ed.), 2016).

Number	Cement works		Number of kilns	Type
1	Allmendingen	Schwenk Zement	1	Cyclone furnace
2	Amöneburg	Dyckerhoff	1	Cyclone furnace
3	Beckum	Phoenix Zementwerke	1	Cyclone furnace
4	Beckum	Holcim WestZement	1	Cyclone furnace
5	Bernburg	Schwenk Zement	1	Cyclone furnace
6	Burglengenfeld	HeidelbergCement	2	Cyclone furnace
7	Deuna	Deuna Zement	2	Cyclone furnace
8	Dotternhausen	Holcim	1	Cyclone furnace
9	Ennigerloh	HeidelbergCement	1	Cyclone furnace
10	Erwitte	Wittekind Hugo Miebach	1	Cyclone furnace
11	Erwitte	Gebr. Seibel	1	Cyclone furnace

(Continued)

Table 6. (Continued)

Number	Cement works		Number of kilns	Type
12	Erwitte	Spenner Zement	1	Cyclone furnace
13	Erwitte	Seibel & Söhne[3]	3	Lepol kilns
14	Geseke	HeidelbergCement	1	Cyclone furnace
15	Geseke	Dyckerhoff	1	Cyclone furnace
16	Göllheim	Dyckerhoff	2	Cyclone furnace
17	Großenlüder Müs	Zement- und Kalkwerke Otterbein	1	Cyclone furnace
18	Hannover	HeidelbergCement	1	Cyclone furnace
19	Harburg	Märker Zement	1	Cyclone furnace
20	Höver	Holcim	1	Cyclone furnace
21	Karlstadt	Schwenk Zement	1	Cyclone furnace
22	Karsdorf	Opterra Zement	3 *	Cyclone furnace
23	Lägerdorf	Holcim	1	Cyclone furnace
24	Leimen	HeidelbergCement	2	Lepol kilns
25	Lengerich	Dyckerhoff	2	Cyclone furnace
26	Lengfurt	HeidelbergCement	1	Cyclone furnace
27	Mergelstetten	Schwenk Zement	1	Cyclone furnace
28	Paderborn	HeidelbergCement	1	Cyclone furnace
29	Rohrdorf	Portland-Zementwerk Gebr. Wiesböck	1	Cyclone furnace
30	Rüdersdorf	Cemex Zement	1	Cyclone furnace
31	Schelklingen	HeidelbergCement	1	Cyclone furnace
32	Solnhofen	Solnhofener Portlandzementwerke	1	Cyclone furnace
33	Üxheim	Portlandzementwerk Wotan H. Schneider	1	Cyclone furnace
34	Wössingen	Opterra Zement	1	Cyclone furnace
	Lime works with permission for waste utilization			
1	Wülfrath	Rheinkalk/Werk Flandersbach	6/4	SF/RK
2	Menden	Rheinkalk/Werk Hönnetal	4/1	SF/RK

* only two of three kilns in operation; SF: shaft furnace; RK: rotary kiln.

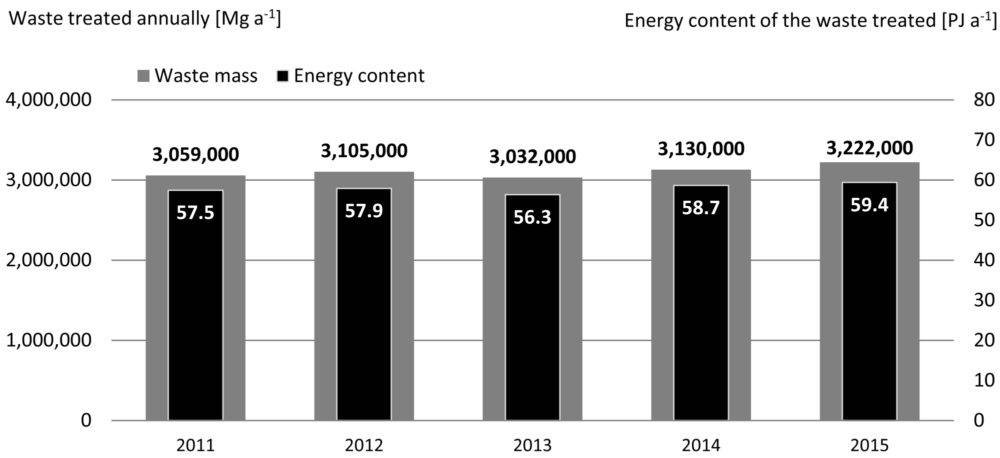

Figure 11. Waste input (mass and energy) in German cement works between 2011 and 2015 (Flamme et al., 2018).

It should be noted that the approved annual capacity of 4.8 mio. Mg a^{-1} is only used to about one third, with about 1.5 mio. Mg a^{-1}. Of this amount, about 1.3 mio. Mg a^{-1} are used in lignite-fired power plants and only 200,000 Mg a^{-1} in hard coal-fired facilities. Overall, almost half of the plants with a co-incineration permit forego the use of waste. Despite the relatively large selection of permitted fuels, only a manageable number of these are used in practice. Secondary fuels from waste (i.e. solid recovered fuels (SRF) and RDF) are also the dominating waste fuels in co-firing applications. In addition, there are noteworthy amounts of paper sludge and sewage sludge (cf. Figure 13) that are utilized.

Based on these numbers, the annual amount of energy fed into German coal-fired power plants via waste fuel is calculated at 11.4 PJ. Depending on the type of power plant (hard coal/lignite), secondary fuels with properties (i.e. energy content) corresponding to the design fuel are used. Therefore, typical efficiencies for

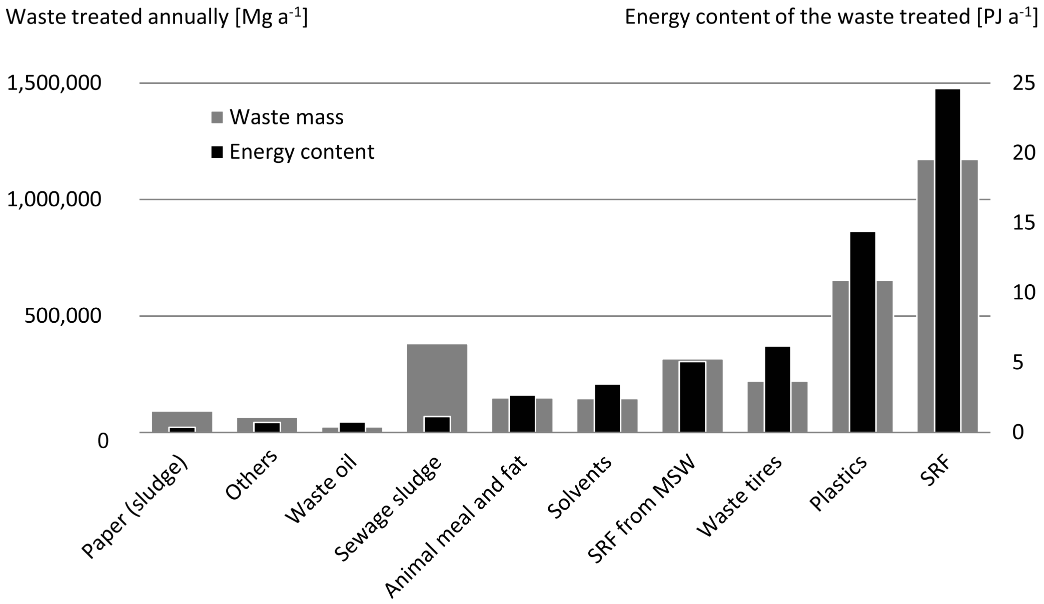

Figure 12. Overview of waste types (mass and energy) used in German cement works (Flamme et al., 2018).

Table 7. German coal-fired power plants licensed to co-combust waste (Flamme et al., 2018).

Number	Plant	Type	Start-up	Waste types	CoG	Co-incineration (Mg a^{-1})	
					y/n	Approved	Incinerated
1	Boxberg	Li		SS/AM		190,000	–
2	Duisburg Huntsmann	Li	1962	Pl/Fo	y	35,000	–
3	Eschweiler Weisweiler	Li	1965/1974	SS/PS	n/y	540,000	73,000
4	Frechen Wachtberg	Li	1959	SS	y	260,000	50,000
5	Grevenbroich Frimmersdorf *	Li	1966	PS	y	262,800	150,000
6	Hürth Ville Berrenrath	Li	1991	SRF/SS	y	337,300	–
7	Hürth Goldenberg **	Li	1993	PS/SS	y	600,000	286,000
8	Neukiritzsch Lippendorf	Li	2000	SS/AM		192,500	–
9	Peitz Jänschwalde	Li	1981–1989	SRF	y	560,000	500,000
10	Spremberg Schwarze Pumpe	Li		FS/SRF		345,000	235,000
11	Zülpich	Li	2010	Rj	y	20,148	–
12	Duisburg HKW I ***	HC	1985	SS/AM/Tx/WC	y	90,000	9,000
13	Ensdorf ****	HC	1971	AM/SS	n	18,933	18,933
14	Flensburg HKW	HC	1992	RDF/WC	y	80,000	–
15	Ibbenbüren	HC	1985	SS	y	30,000	–
16	Kassel	HC	1987	SS		216,000	–
17	Lünen	HC	1962/1969	SS/AM	n	81,118	–
18	Marl	HC	1971	OrgL	y	542,400	–
19	Oberkirch	HC	1986	SRF/SS/FS/PS	y	128,016	35,874
20	Pforzheim HKW	HC	1990	RDF	y	42,000	9,600
21	Werne Gersteinwerk *****	HC	1984	SRF	n	240,000	120,000
22	Wuppertal HKW Elberfeld ******	HC	1989	SRF	y	40,000	22,000
					Σ	**4,851,215**	**1,509,407**
	Planned shutdowns						
*	Shutdown end of 2017 (cold reserve)						
**	Electricity production ended in 2015, the plant continues to produce steam						
***	Shutdown in March 2018						
****	Shutdown end of 2017						
*****	Shutdown March 2019						
******	Shutdown July 2018						

Li: lignite; HC: hard coal; SS: sewage sludge; AM: animal meal; Pl: plastic; Fo: foils (plastic); PS: paper sludge; SRF: solid recovered fuels; FS: fiber sludge; Rj: rejects; Tx: textile residues (carpet); WC: wood chips; RDF: refuse derived fuels; OrgL: organic liquids; CoG: cogeneration of heat and power.

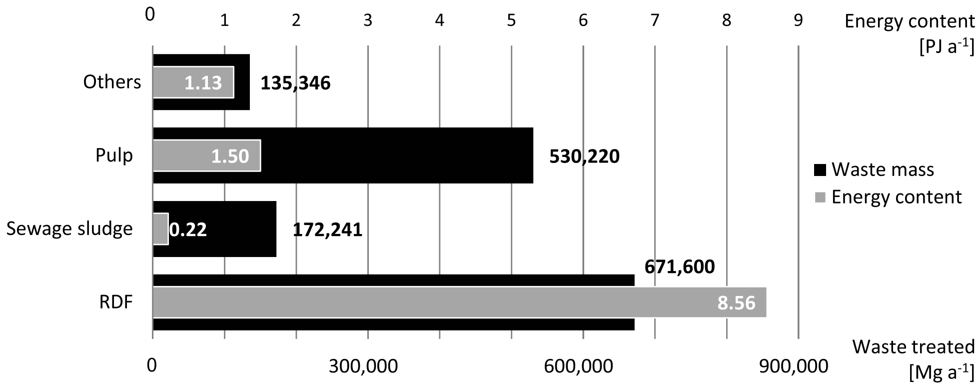

Figure 13. Waste types (mass and energy) combusted in German coal-fired power plants.

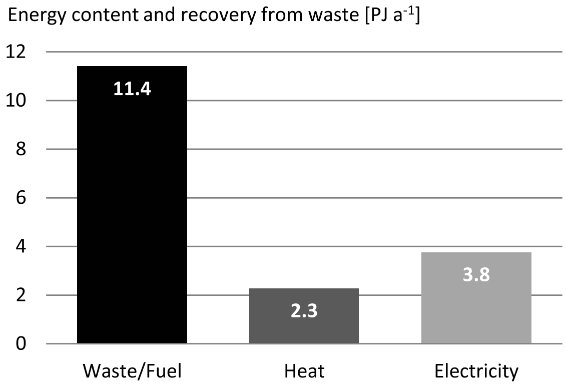

Figure 14. Annual energy input from waste into coal-fired power plants and heat and electricity produced (PJ a^{-1}).

coal-fired power plants are also used for the determination of the energetic contribution of waste in these facilities.

As SRF is preferably used in older power plants, an electrical efficiency of 33% was assumed for the estimation of electricity generation, with a resulting electricity quantity of 3.8 PJ a^{-1}. Compared to electricity, the use of heat from coal-fired power stations is rather low. The reasons for this are the location, size and operational mode of these plants that are optimized for the electricity supply. Therefore, the thermal efficiency was assumed to be 20%. The results are shown in Figure 14.

Industrial power plants

Within this study, industrial power plants (utility boilers) are facilities that primarily incinerate production residues and wastes and, at the same time, provide energy to the respective industries. There is generally little information available on these plants, because their operation is not the main focus of the industries and known activities in associations or publications are accordingly few. Plants that incinerate production residues but obtain the larger share of fuel from other sources (such as SRF/RDF or sewage sludge) are listed in the respective other sections. As one of the few reliable information, the thermal firing capacity of 80.6% of all industrial power plants could be identified, which was extrapolated to the total number of plants. An electrical efficiency of 25% and a thermal efficiency of 50% were assumed. This comparably large value stems from the fact that industrial power plants are designed for providing year-round heat to nearby industrial consumers. Table 8 lists all industrial power plants in Germany licensed to incinerate waste.

Based on these assumptions, a fuel energy of 82.9 PJ a^{-1} was estimated to enter industrial power plants. Using the above-mentioned efficiencies, this corresponds to 41.5 PJ a^{-1} heat and 20.7 PJ a^{-1} electricity (cf. Figure 15).

The fuel mass flow treated in these facilities was calculated from the fuel energy entering the plants and the heating value of the waste. In many facilities, production residues from the wood industry (e.g. bark, wood residues, black liquor, etc.) are incinerated. Therefore, a heating value between 12 and 15 MJ kg^{-1} seemed realistic. This would result in a fuel mass flow between 5.5 mio. Mg a^{-1} and 6.9 mio. Mg a^{-1}.

AD plants

The identification of AD plants was not straightforward. As with waste wood incineration facilities, there is an overlap and some confusion with plants processing renewable resources (i.e. biomass that is not considered waste).

According to Kern and Raussen (2014), there are currently 112 biogas plants in Germany existing for the fermentation of biowaste. The total capacity is 4.25 mio. Mg a^{-1}, but 3.15 mio. Mg of which were used in the reference year 2015 (Table 9). The installed electrical output of the plants is about 100 MW.

The estimation of the energy provided by biogas plants was based on the total installed electrical capacity, standardized to the actual mass throughput. This also accounts for plants feeding the grid with biomethane. A value of 2.29 PJ a^{-1} was obtained for all facilities. If typical biogas cogeneration (CHP) units are used, heat can be provided to at least the same extent as electricity. The problem with many of these plants is that no consumers are available nearby, because the facilities are often located in rural areas in order to minimize disturbance caused by odors and traffic.

MBT plants with fermentation stage

There are 44 plants for the mechanical-biological treatment of waste. Of these, 12 have a fermentation stage and four only mechanical processing steps (cf. Table 10).

Table 8. Industrial power plants licensed to incinerate waste (Flamme et al., 2018).

Number	Plant		Start-up	Fuel/waste types	Thermal firing capacity [MW]
1	Alfeld	Sappi Alfeld	1998	Sl/PPR	79
2	Arneburg	Zellstoff Stendal	2004/2013	BL/Ba	662
3	Aschaffenburg	Pollmeier	2007	WPR	10
4	Blankenstein	Papierfabrik Rosenthal	1999	BL/Ba/PR	412
5	Burgbernheim	Rettenmaier Holzindustrie	2001	WPR	23
6	Düsseldorf	Henkel	1948	OrgL	104
7	Eberhardzell	biopower SKW (Schneider-Holz)	2004	WPR	28
8	Ehingen	Sappi Ehingen	1990	BL/Ba/WPR	120
9	Eilenburg	Kombikraftwerk Eilenburg	1991	PR	
10	Ettenheim	J. Rettenmaier & Söhne		WPR	20.2
11	Hohenstein	SchwörerHaus		WPR	25
12	Kalletal	Ziegelwerk Otto Bergmann	1992	FS	
13	Kösching	BinderHolz Deutschland	2007	WPR	50
14	Kühbach	Pfeifer Holz	2007	WPR	42
15	Lampertswalde	Kronospan	2002	WPR	48
16	Landsberg Lech	Ilim Timber Bavaria		WPR	23
17	Lauterbach	Pfeifer Holz Lauterbach		WPR	60
18	Mannheim	SCA Hygiene Products	1966/2000	BL/Ba/PR	160
19	Markt Bibart	Rauch Spanplattenwerk		WPR	57
20	Marsberg	WEPA Kraftwerk	1997	Sl/SS/RDF	22.5
21	Oberrot	EnBW Klenk Holzenergie	2000	WPR/Ba	40
22	Rietberg	Wienerberger Ziegelindustrie	2012	PPR/MW/SD	
23	Saalburg-Ebersdorf	Mercer Holz	2008	WPR	49
24	Schongau	UPM	1989	PPR	
25	Stefanskirchen	Hamberger Flooring	2004	PR	50
26	Steinheim	Otto Bergmann Ziegelwerk	2007	RDF/Sl/FS	
27	Stockstadt	Sappi Stockstadt	2003	BL/PR	105
28	Torgau	Hit Holzindustrie Torgau	2014	WPR	40
29	Uelzen	Pfeifer Holz		WPR	42
30	Warburg	August Lücking Ziegelei Betonwerke	2013	RDF/PPR/MW	
31	Wörth	Palm Power	2008	PPR	52
				Σ	**2323**

BL: black liquor; Ba: bark; WPR: wood production residues; OrgL: organic liquids; FS: fiber sludge; Sl: sludges in general; RDF: refuse derived fuel; SD: sawdust; PPR: paper production residues; SS: sewage sludge; MW: mineral wastes.

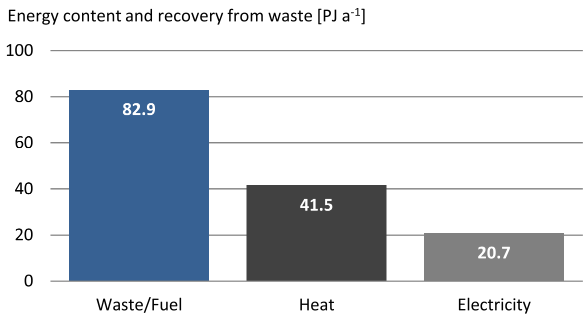

Figure 15. Annual energy input from waste into German industrial power plants and heat and electricity produced.

Related to the total input into German MBT facilities, about 1% of the total mass is converted into biogas. This corresponds to 36.5 mio. m^3 biogas with a volumetric methane content of 61%, or a fuel energy content of 0.08 PJ a^{-1} (Ketelsen and Kanning, 2016). After electricity generation in a typical cogeneration unit with about 40% electrical efficiency, about 0.03 PJ a^{-1} electricity and about the same amount of heat can be provided.

Summary and conclusions

The total amount of energy (electricity, heat and steam) provided by waste treatment facilities in Germany in 2015 is shown in Table 11 and Figure 16. Figure 16 also shows the waste quantities treated in the respective plant category.

The greatest share of the German energy supply from waste is provided by the incineration plants (MSWI), which deliver about one-third of the total energy from waste. Together with the RDF power plants, this share increases to almost 50%. Industrial power plants also make a major contribution to the energy supply from waste, although the lack of information for this sector must be noted.

The role of cement plants is remarkable. Despite the relatively low input quantities of about 3.2 million Mg a^{-1} of waste, the plants make a significant contribution to the substitution of fossil fuels. This is due to the fact that the energy content of the fuels can be used to a large extent directly and without any losses in the clinker burning process.

Furthermore, the energy contribution of the incineration of hazardous waste is relatively high, regarding the throughput of

Table 9. Facilities for fermentation of biowaste in Germany (Kern and Raussen, 2014).

Number	Plant	Capacity (Mg a^{-1})	Throughput (Mg a^{-1})	Waste types	Electrical power P_{el} [kW]
1	Alterhofen	40,000	35,307	BW/Cu	364
2	Altenholz	21,000	21,000	BW/FW/Cu/CW	536
3	Alteno	85,000	30,000	FW	1323
4	Altenstadt	50,000	35,000	FW/CW	0
5	Amtzell	20,000	14,500	BW/Cu/CW	875
6	Aschaffenburg	15,000	13,200	BW	500
7	Augsburg	70,000	60,182	BW/Cu	0
8	Backnang	41,000	39,574	BW/Cu	1600
9	Baden-Baden		176,500	BW/FW/Cu/Oth	
10	Bad Köstritz	51,944	33,202	FW/CW/Oth	4172
11	Bad Rappenau	7500	5000	FW/CW	400
12	Bardowick	36,300	33,000	FW/CW	2128
13	Bassum	55,000	55,427	BW/Cu/Oth	625
14	Bergrheinfeld	32,000	18,000	BW/Cu	1600
15	Berlin	60,000	60,000	BW	
16	Bernau	6000	4800	FW/CW/Oth	330
17	Boden	51,000	32,509	BW/FW/CW	986
18	Borgstedt	50,000	42,000	BW/Cu	1150
19	Brake	15,000	10,800	BW/Cu	440
20	Braunschweig	20,000	16,450	BW/CW	
21	Brensbach	70,055	17,500	FW/CW/Oth	1480
22	Burgberg	13,000	11,000	Cu	300
23	Coesfeld	68,640			
24	Deißlingen	25,000	25,000	BW/Oth	1030
25	Demen				
26	Diespeck	10,000	7265	BW	191
27	Dörpen	19,600		BW/Cu	260
28	Eiselfing-Aham	31,000	10,000	Cu/Oth	265
29	Eitting	40,000	29,431	BW	921
30	Engstingen	18,000	18,000	FW/CW	890
31	Ennigerloh	52,000	49,000	BW/Cu	680
32	Erfurt-Schwerborn	23,500	20,759	BW/Cu/CW/Oth	660
33	Erkheim	18,000	17,160	BW/FW/CW	1065
34	Essenheim	48,000			1200
35	Eurasburg	35,000	34,500	BW/Cu	800
36	Flörsheim-Wicker	55,000	38,700	BW	5300
37	Framersheim	28,750	22,943	BW/Cu	738
38	Frankfurt	43,000	32,957	BW/Cu/CW	680
39	Frankfurt-Höchst	205,000	170,000	Oth	5100
40	Freiburg	45,000	36,000	BW/CW/Oth	1800
41	Freising	18,000	18,000	FW/Cu/CW/Ma/Oth	690
42	Freudenstadt-Sulzhau	18,000			550
43	Friedberg	18,000	18,000	FW/CW/Ma	734
44	Garmisch-Partenkirchen	10,500			
45	Geislingen	40,000	15,000	FW/CW	1400
46	Genthin	73,000	49,676	FW/CW/Oth	1886
47	Gescher	17,500	17,500	BW/FW/CW/Oth	500
48	Göttingen	22,500	19,199	BW/Cu	252
49	Gröden	110,000	110,000	FW/CW/Ma/Oth	1600
50	Großefehn	60,000	56,115	BW/Cu	590
51	Großenlüder	65,000		BW/Cu/Ma	
52	Gütersloh	65,000		BW/Cu	800
53	Halle-Lochau	110,000	85,000	BW/FW/Cu/CW/Oth	1896
54	Hamburg	20,000	18,929	FW	1000
55	Heidelberg				
56	Heidesee	32,000	27,523	FW	1400
57	Hennickendorf	18,000	15,500	BW/FW/Cu/CW/Oth	610
58	Heppenheim	32,000			750

(Continued)

Table 9. (Continued)

Number	Plant	Capacity (Mg a^{-1})	Throughput (Mg a^{-1})	Waste types	Electrical power P_{el} [kW]
59	Hille	50,000	50,000	BW/Cu	
60	Hoppstädten-Weiersbach	24,500	16,907	BW	800
61	Iffezheim	18,000	17,000	BW	527
62	Ilbenstadt	35,000	30,000	BW/Cu	625
63	Karbow-Vietlübbe	18,250	16,000	FW/CW/Ma/Oth	230
64	Karlsruhe	16,000	7856	BW	380
65	Kempten	18,000	18,000	BW/Cu	930
66	Kirchheim-Stausebach	30,000			
67	Kirchstockach	35,000	30,407	BW	630
68	Kißlegg-Rahmhaus	17,500	17,500	FW/CW	960
69	Kogel	57,000	36,000	FW	2400
70	Langenau	17,100	16,452	Cu/Oth	540
71	Lemgo	60,000	44,875	BW/Cu	938
72	Leonberg	36,500	33,485	BW/Cu	2213
73	Lindlar	55,000	34,051	BW	1829
74	Lingen	19,600		Cu	365
75	Lohfelden	26,000	26,150	BW/Cu	450
76	Malching	76,500	58,000	FW/CW/Oth	2042
77	Marburg	12,000	12,000	BW/Cu/CW	370
78	Marl	120,000	27,719	FW	3120
79	Mertingen	37,166	14,000	BW/Cu/CW	760
80	München	22,500	19,748	BW	570
81	Münster	22,000	16,114	BW	650
82	Nentzelrode	12,000			250
83	Nieheim	85,000	80,000	BW/Cu	680
84	Parum	50,000	50,000	FW/CW/Oth	2100
85	Passau	40,000	40,000	BW	1487
86	Peine	10,000	10,000	BW	384
87	Putbus	100,000	76,759	FW/CW/Ma/Oth	1250
88	Radeberg	61,000	61,000	FW/Ma/Oth	830
89	Regen	18,000	18,000	Cu/Oth	625
90	Rhadereistedt	40,000	28,600	FW/CW/Oth	1020
91	Roding	12,000	11,800	FW/CW	700
92	Saalfeld	80,000	80,000	BW/Cu/Oth	1050
93	Saerbeck	50,000			1056
94	Schwabach	16,000	12,000	FW/CW	861
95	Schwallungen	115,000	79,432	FW/Ma	1886
96	Senftenberg	12,000			569
97	Stammham	23,000	21,750	BW/Cu	630
98	Strullendorf	18,000	17,545	BW/GWA/Sonst	1140
99	Tangstedt-Bützeburg	70,000	52,775	BW/Cu	
100	Taufkirchen		9,000	BW/Ma	450
101	Teugn	22,000	11,000	BW/FW/Oth	360
102	Trittau	30,000	25,000	BW	800
103	Uelzen	18,000	12,000	BW/Cu	500
104	Vechta	10,000	10,000	BW	330
105	Volkenschwand	35,000	35,000	BW/FW	
106	Waldmünchen	13,000	13,000	BW/Cu/Oth	840
107	Warngau	18,250	15,374	BW/Cu/CW	365
108	Weißenfels	30,000	25,023	BW/Cu/Oth	856
109	Witten-Stockum	29,990	29,500	BW/Cu/Oth	700
110	Würselen	29,999	29,999	BW	537
111	Wüschheim	13,000	9450	BW/Cu	830
112	Zobes	62,000	21,800	BW/FW/Cu/CW/Ma	744
	ΣMio. Mg a^{-1}	**4.25**	**3.15**		**100.2 MW**

BW: biowaste; FW: food waste; Cu: cuttings; CW: commercial waste; Ma: manure; Oth: others.

Table 10. Mechanical–biological treatment (MBT) plants for the mechanical–biological waste treatment (Flamme et al., 2018).

Number	Plant		Type	Biological step	Capacity (Mg a^{-1})
1	Bardowick	MBV Bardowick	MBT	CC/PC	120,000
2	Bassum *	RABA Bassum	MBT	TM TVG/MR	115,000
3	Berlin	MPS Berlin-Pankow	MPS	none	160,000
4	Berlin	MPS Berlin-Reinickendorf	MPS	none	160,000
5	Chemnitz	RABA Chemnitz	MPS	none	150,000
6	Dresden	BMA Dresden	MBS	RB	105,000
7	Ennigerloh	EBS-Aufbereitung	MBT	C	160,000
8	Echzell **	MBA Wetterau	MT	none	49,500
9	Erftstadt	VZEK Rhein-Erft-Kreis	MBS	TR	170,000
10	Erfurt	RABA Erfurt-Ost	MBT	TR	90,000
11	Friedland *	MBA Südniedersachsen	MBT	VS NVG	130,000
12	Gardelegen	MBA Deponie Lindenberg	MBT	R	50,000
13	Gescher	MBA Gescher	MBT	R	115,000
14	Großefehn	MBA Großefehn	MBT	TC	47,600
15	Großpösna	MBA Cröbern	MBT	TC	300,000
16	Großräschen *	MBA Freienhufen	MBT	WAD	37,000
17	Hannover *	MBA aha Hannover	MBT	FS DAD	200,000
18	Hille *	MBA Pohlsche Heide	MBT	PS DAD/WC	100,000
19	Ihlenberg **	MA Ihlenberg	MT	none	120,000
20	Ingenried	MBA Erbenschwang	MBT	TC	40,000
21	Kleinfurra, OT Hain *	MA Nentzelrode	MBT	DAD	140,000
22	Königs Wusterhausen	MBS ZAB Nuthe-Spree	MBS	RB	150,000
23	Linkenbach	MBA Linkenbach	MBT	TC	90,000
24	Lübben (Spreewald)	MBV Lübben-Ratsvorwerk	MBS	RB	28,000
25	Lübeck *	MBA Lübeck	MBT	PS WAD	146,000
26	Mertersdorf	MBT Mertersdorf	MBS	TC	220,000
27	Münster *	MBRA Münster	MBT	PS DAD/ WC	70,000
28	Nauen	MBA Schwanebeck	MBT	C	72,500
29	Neumünster	MBA Neumünster	MBS	RB	260,000
30	Neuss	WSAA Neuss	MBS	TC	300,000
31	Oelsnitz Vogtland	MBS Vogtland	MBS	RB	100,000
32	Oldenburg **	MA Oldenburg	MT	none	34,000
33	Osnabrück	MBS Osnabrück	MBS	RB	105,000
34	Pößneck	MBRA Wiewärthe	MBT	C	85,000
35	Rennerod	MBS-Anlage Westerwald	MBS	RB	120,000
36	Ringsheim *	MBA Kahlenberg	MBT	WAD/C	110,000
37	Rosenow	ABA Rosenow	MBT	TC	190,000
38	Rostock *	RABA Rostock	MBT	AD	135,000
39	Sachsenhagen *	MBA Schaumburg	MBT	FA WAD	70,000
40	Singhofen	MBA Singhofen	MBT	TC	90,000
41	Stralsund **	MBS Stralsund	MT	none	130,000
42	Wangerland-Wiefels *	MBA Wiefels	MBT	FS WAD	113,500
43	Wilsum	MBA Wilsum	MBT	TC	63,000
44	Zossen	MBA Schöneiche	MBT	C	180,000
				Σ	**5,421,100**

* plant with anaerobic digestion (AD) step; ** purely mechanical treatment (MT); MBS: mechanical–biological stabilization; MPS: mechanical–physical stabilization; CC: container composting; WC: windrow composting; PC: post-composting; C: composting; RB: rotting box; TC: tunnel composting; WAD: wet AD; DAD: dry AD; FS: full stream; PS: partial stream.

only 1.3 million Mg a^{-1}. Most plants export steam to nearby consumers and have therefore only small efficiency losses.

The contribution of biological processes, that is, MBT and biowaste fermentation, is relatively low (< 6 PJ a^{-1}). This applies with 0.06 PJ a^{-1} in particular to MBT plants with a fermentation stage.

The incineration of sewage sludge was not considered a contributor, as the energy content of dewatered sludge (balancing is based on this state) is not sufficient to realize any energy export, without the use of additional heat for drying.

Each year, more than 570 PJ of fuel energy from around 50 million Mg a^{-1} of waste are fed into German waste treatment facilities. This corresponds to about 4.3% of the German primary energy demand. In total, almost 320 PJ of end energy are produced, around 225 PJ a^{-1} of heat and 90 PJ a^{-1} of electricity (rest: 5 PJ a^{-1} of steam).

Table 11. Overview of energy from waste treatment facilities in Germany in 2015.

	Input		Output			Utilization rates			
	Mass (Mg a^{-1})	Energy (PJ a^{-1})	E_{total} (PJ a^{-1})	Heat (PJ a^{-1})	Electricity (PJ a^{-1})	η_{total}		η_{el}	
						gross	net	gross	net
Municipal solid waste incineration plants	20,005,469	205.05	109.53	79.77	29.76	53.4%	44.6%	14.5%	11.1%
Refuse derived fuel power plants	5,714,042	69.79	44.37	31.96	12.42	63.6%	60.1%	17.8%	14.7%
Hazardous waste incineration plants	1,333,816	21.92	14.21	13.78	0.43	64.9%	56.6%	**	**
Waste wood incineration plants	6,579,671	85.78	35.39	12.84	22.55	41.3%			
Sewage sludge incineration plants	957,932	37.12 *	0 ***	0	0				
Cement works	3,222,000	59.40	41.58	41.58	0	70%			
Coal-fired power plants	1,509,407	11.41	6.05	2.28	3.76	53.0%		33%	
Industrial power plants	6,100,000	82.95	62.21	41.47	20.74	75.0%		25%	
Anaerobic digestion plants	3,643,093		5.85	2.92	2.92				
Mechanical–biological treatment plants	4,375,620		0.06	0.03	0.03				
Σ	**53,441,050**	**573.42**	**319.25**	**226.64**	**92.62**				

* in fully dried condition; ** due to the low quantities of electricity generated, no utilization rate is specified here; *** when only dewatered sludge is used, hardly any energy can be recovered.

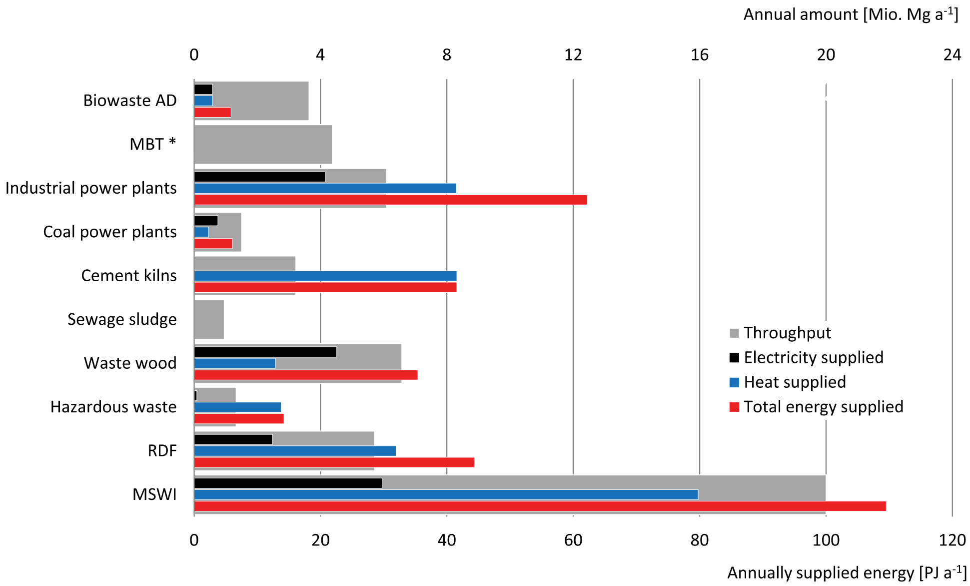

Figure 16. Energy from waste in Germany (2015).
* for mechanical–biological treatment, only the plants with energy generation by fermentation are taken into account.

This results in a contribution of waste-based energy in Germany of about 3.7% of the end energy consumption.

Abbreviations

DM	dry matter
FM	fresh matter
RDF	refuse derived fuel (a secondary waste fuel produced by pre-treating non-hazardous waste, for example, by drying, sorting and comminution)
MSW	municipal solid waste
MSWI	municipal solid waste incineration
MBT	mechanical–biological treatment
MT	mechanical treatment
WtE	waste-to-energy
SRF	solid recovered fuel (a secondary waste fuel produced by pre-treating non-hazardous waste in compliance with EN 15359)

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Notes

1. Update: in January 2018, it was decided that the refuse derived fuel plant in Meuselwitz-Lucka remains out of operation permanently (Leipziger Volkszeitung, 2018).
2. Update: after a six-year planning and construction period, TREA II in Giessen was inaugurated in April 2019 (Möller, 2019)
3. Update: the cement work of Seibel & Söhne in Erwitte was sold to Dyckerhoff, who plan to take the facility out of operation in 2019 in order to increase production in their other cement works (Dyckerhoff, 2019).

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