PROJECTS – EIB SECTOR PAPER 2024/01

Managing refuse-derived and solid recovered fuels

Best practice options for EU countries

European Investment Bank

Managing refuse-derived and solid recovered fuels

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Projects - EIB sector paper

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Table of contents

Executive summary

Despite significant ongoing efforts to avoid and reduce waste – such as “designing out waste,” separate collection of recyclables, and efficient recycling – waste treatment methods, as they exist at present and for the foreseeable future, inevitably result in approximately one-third of waste materials being left over. Most of these “left-over materials” are processed to form so-called refuse-derived fuel (RDF), which contains valuable calorific energy and can replace more traditional primary solid fossil fuels, while the remainder are sent for land disposal.

The present study, issued by the European Investment Bank and based on desktop research by the specialist consultancy company MVW Lechtenberg GmbH, finds that the overall level of RDF generation in several EU Member States (MSs) is lower than the potential maximum uptake. It appears that RDF utilisation in energy-intensive industrial processes could be appro ximately two to three times higher than is the case at present and 1.5 times higher than estimated future RDF generation.[1] At the EU level, however, the RDF-uptake capacity of the two main relevant industrial sectors - the cement industry and waste-to-energy (WtE) plants - is limited.

This desktop study aims to raise awareness in the waste sector regarding the options for RDF utilisation, particularly of plant operators, plant engineers/designers, and environmental authorities. The study provides an overview of various options for reducing the amount of material being sent to landfill by increasing the profitable management and uptake of RDF. Technical, environmental, and legal aspects need to be considered when implementing certain options. The study presents the following overall findings:

- In some MSs, the uptake for RDF is currently significantly lower than the amount of RDF generated, leading to considerable amounts of potentially valuable resources being sent to landfill and filling-up the landfills earlier than necessary.
- It is possible for cement and lime producers to substitute with RDF up to 85% of their energy need currently produced from solid fossil fuels, provided that the required qualitative and quantitative specifications are met.
- Many potential end-users of RDF (for example, the cement and lime industries, WtE and coal-fired power plants) are concerned about potential operational disturbances due to the frequently inconsistent quality of RDF (which can vary in terms of its calorific value and biogenic carbon, water, chlorine, and mercury content), compared to more standardised fossil fuels, coupled with uncertainty regarding the availability of feedstock. This results in potential RDF consumers continuing to use fossil fuels for operation of their main production lines, despite the higher energy costs and emissions.
- To meet end-user quality requirements and ensure profitability, RDF producers must apply rigid quality control management techniques, often requiring additional investment in specialised technical equipment.[2] New waste management plants may require relatively large investments from the outset.
- For users of RDF, the shift from fossil fuels to RDF also often requires additional investments, which, however pays back.[3]
- Even considering the additional transport costs and the additional investments in both RDF production and uptake plants, the replacement of fossil fuels by RDF can be financially profitable.
- The substitution of fossil fuels by RDF can help to reduce EU imports of primary fossil fuels, thus reducing CO_2 emissions and contributing to meeting EU landfill targets. The environmental benefit is obvious.
- From a legislative point of view, the uptake of RDF by energy-intensive operators is mostly influenced by waste disposal taxes (as higher landfill and/or incineration taxes can lead to greater RDF uptake) and may also be impacted by any future revisions to the emissions trading system (ETS), such as the possible inclusion of municipal waste incineration in the ETS.

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1 According to the study, the maximum production of RDF could reach approx. 2.4 million tonnes for these countries (based on Eurostat/EC data on waste data and assuming a 80% energy recovery rate for RDF), while the current uptake for RDF in the target countries is only approx. 1.4 million t/y. The maximum potential RDF uptake is estimated at 3.7 million t/y (assuming a maximum 85% thermal substitution rate)

2 Typically, approx. €8 million for a 35 t/h capacity sorting line for improved sorting, drying, etc

3 The additional investment is typically in the range of €12 million to €35 million for 70 000 t/y capacity, and the approx. additional operation costs for receiving, storage, conditioning, feeding, and firing systems are €2 to €3 per tonne of RDF.

- Finally, increasing EU recycling targets and implementing the waste hierarchy principle may have a negative impact on RDF quality (including its calorific value) and thus on its uptake.

One of the objectives of this report is to identify relevant options and elements to the development of more efficient and profitable RDF management. The report and its annexes are not meant to replace any independent data sourcing or case-by-case analysis taking local conditions (for example, energy costs) into consideration.

Neither the EIB nor MVW Lechtenberg GmbH is liable for the accuracy of the information contained in this report. The report is based on publicly available information, as interpreted with the expert knowledge of the authors. However, this information has not been confirmed against the corresponding sources and may, therefore, be subject to inaccuracies.

Abbreviations

ASK	annular shaft kiln
BAT	best available techniques
BSRW	bio-stabilised residual waste
BREF	BAT reference documents
BF-BOF	blast furnace-basic oxygen furnace
BT	biological treatment plant
C&I	commercial and industrial waste
CEN/TC	Comité européen de normalisation/Technical committee
CEMBUREAU	European Cement Association
CEPI	Confederation of European Paper Industries
CEWEP	Confederation of European Waste-to-Energy Plants
CLO	compost-like output
D10	disposal operation: incineration on land
DBB	dry-bottom boilers
dm	dry matter
EAF	electric arc furnace
EoW	end of waste
EPR	extended producer responsibility
ETS	emissions trading system
EU	European Union
EuLA	European Lime Association
EWC	European Waste Code
F&B	food and beverage
FBC	circulating fluidised bed
Gcal	giga calorie
IED	Industrial Emissions Directive
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
ISO	International Organisation for Standardization
Kcal	kilocalorie
kJ	kilojoule
LPG	liquefied petroleum gas
MBT	mechanical biological treatment plant
MJ	megajoule
MFSK	mixed feed shaft kilns
MW	municipal waste
MT/MTP	mechanical treatment plant
Mt/y	million tonnes per year
NCV	net calorific value
NIR	near infrared
NWMP	National Waste Management Plan
PFRKs	parallel flow regenerative kilns

PGNAA	prompt gamma neutron activation analysis
PJ	petajoule
PVC	polyvinylchloride
R1	recovery operation: use as a fuel (other than in direct incineration) or other means to generate energy/use principally as a fuel
RCF	recycled carbon fuel
RDF	refuse-derived fuel
RED	Renewable Energy Directive
RFNBO	renewable fuels of non-biological origin
RKs	rotary kilns
SRF	solid recovered fuel
TSR	thermal substitution rate
WtE	waste-to-energy
WSR	waste shipment regulation
WBB	wet-bottom boilers
WMC	waste management centre
t/h	tonnes per hour
t/y	tonnes per year
2D	two-dimensional particles or materials
3D	three-dimensional particles or materials

1 Introduction: scope, objectives and methodology

1.1 Scope and objectives

This study aims to identify and present options for the improved management of refuse-derived fuels (RDF) and solid recovered fuels (SRF)[4] produced during the treatment of solid municipal waste (MW), thus reducing the quantities of waste being disposed of in landfills. It aims to raise awareness of this issue in the waste sector, not only among mechanical treatment plant (MTP) and mechanical biological treatment (MBT) facility operators but also among the engineers and designers of such facilities and the environmental authorities involved in such projects. The study presents an overview of several options for reducing the landfilling of valuable waste materials while increasing the profitability of RDF management and uptake. It also addresses the various technical, environmental, and legal aspects that need to be considered when implementing such options. The study addresses the following research questions:

- What are the technical norms and standards applicable to RDF and/or SRF?
- What are the current RDF uses?
- What are the core technical, legal, and/or environmental constraints on increasing the uptake of RDF?
- What are the available options to increase efficient RDF management?
- What additional investments and operational costs would be associated with such options?
- Which actions should waste management plants and/or environmental authorities take to improve use of RDF?

1.2 Methodology

This report constitutes a desktop study based on publicly available information (for example, online reports, publications, standards, databases such as Eurostat, and selected EU legislation) and the expert knowledge of the authors. It should be noted, however, that the information referenced has not been assessed by or reconfirmed with the corresponding sources (for example, plant operators, MSs, etc.).

For the estimation of current and future RDF potential, the EU recycling targets (i.e., a minimum of 65% of MW by 2035) and landfilling (a maximum of 10% of MW by 2030) are taken into consideration.

Moreover, the study addresses the potential expenditures linked to the increased RDF uptake, as well as the RDF production cost factors needed to satisfy quality and quantity requirements.

[4] In this report, RDF and SRF are commonly referred to simply as RDF, as outlined in Chapter 2.

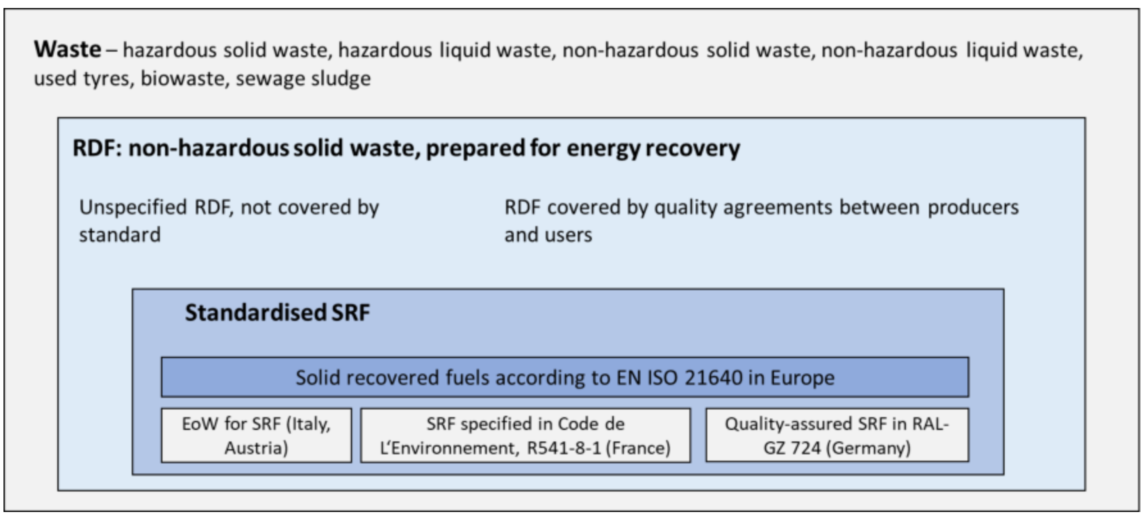
2 General overview of the sector and existing standards

2.1 Definitions and concepts

The management of solid waste, and particularly of solid municipal waste (MW), typically includes some type of mechanical treatment during which, part of the waste is separated for recycling and the remaining part (refuse) is either recovered (for example, energy recovery) or disposed of in landfills. Refuse typically contains high-calorific combustible (energy-rich) fractions such as plastics, paper, textiles, and/or wood. Such refuse, which may be used for energy recovery, is typically referred to as refuse-derived fuel (RDF).

For several decades, industrial combustion processes, particularly in the energy-intensive cement industry, have made use of the recovered thermal energy in RDF.[5]

In certain situations, RDF may require further treatment (for example, shredding, screening, and air classification)[6] to meet specific technical requirements prior to final energy recovery. This is usually the case in a cement kiln, for instance. Such RDF may be classified as a solid recovered fuel (SRF) if it meets the requirements set out in the EN ISO 21640:2021[7] standard. In addition, SRF may have to meet supplementary requirements set by national standards, legislation, or end users to ensure a specific level of quality. In some MSs, for example, Italy and Austria, additional specific end-of-waste (EoW) criteria may also apply. Figure 1 provides a schematic overview of the various definitions and their interconnections.



Based on Le Bihan et al.[8]

Figure 1: Interconnections between waste, RDF, and SRF

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5 Chatziaras, N., Psomopoulos, C.S., & Themelis, N.J. (2016). Use of waste derived fuels in cement industry: a review. Management of Environmental Quality: An International Journal, 27(2), 178–193

6 Duckett, E.J., & Weiss, D. (1980). RDF as a kiln fuel. In: Proceedings of the 1980 National Waste Processing Conference, 9th Biennial (New York: American Society of Mechanical Engineers, 1980), 387–400.

7 EN ISO 21640:2021 – Solid recovered fuels – Specifications and classes.

8 Le Bihan, M., De Caevel, B., & Michel, F. (2018). RDF/SRF utilisation plants – legislative status and economic balance (PowerPoint presentation). RDC Environment.

2.2 Standards

On the one hand, there are no common (EN or ISO) standards for RDF. On the other hand, RDF that complies with the European standard EN ISO 21640:2021 is classified as SRF. This main SRF standard was developed under the work programme of the European Committee for Standardization Technical Committee CEN/TC 343, along with a number of other relevant standards, technical specifications, and reports (a list of publications is provided in the annexes, see Section 8.1.1).

The referred EN ISO standard excludes the use of hazardous waste and requires the specification of several characteristics (physical and chemical properties to be reported in a specific format, see the annexes, Section 8.1.2). The separation into five classes is based on the net calorific value and chlorine and mercury content of the SRF, as per Table 1.

Table 1: Classes of SRF according to EN ISO 21640:2021

Classification characteristics	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	mean	MJ/kg	≥25	≥20	≥15	≥10	≥3
Chlorine (Cl)	mean	% in mass (dm)	≤0.2	≤0.6	≤1.0	≤1.5	≤3
Mercury (Hg)	median	mg/MJ	≤0.02	≤0.03	≤0.05	≤0.10	≤0.15
	80^{th} percentile	mg/MJ	≤0.04	≤0.06	≤0.10	≤0.20	≤0.30

Note: dm = dry matter

Beyond the classification requirements set out in Table 1, additional quality requirements may be defined at the national level, leading to more specific classifications (see the annexes, Section 8.1.3).

To simplify the presentation, **for the remainder of this report, both RDF and SRF are referred to as RDF**.

2.3 Sources of RDF

The main RDF sources are:

- municipal (non-hazardous) waste, including residues from sorting separately collected waste, and
- waste from commerce and industry (usually non-recyclable and/or non-hazardous packaging and/or scrap).

In certain MSs, construction and demolition (non-hazardous) waste may also feed into RDF.[9]

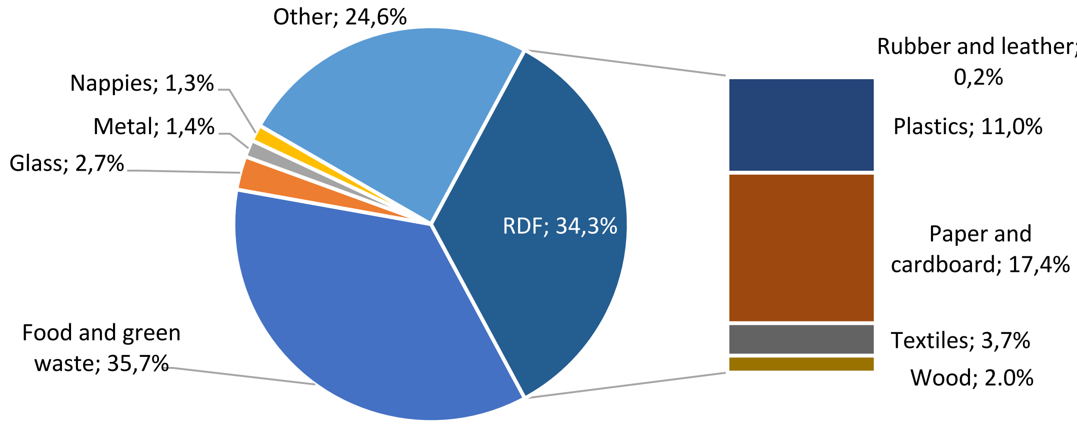
Municipal waste (MW) is typically the primary source of waste used in RDF production. MW encompasses waste generated by households and other waste that is similar in nature and composition. MW is collected either as a mixture or in separate fractions, and RDF is produced from residual/mixed MW and residues from the sorting of specific MW fractions.

The average European MW composition taken from four European regions, as presented by the Intergovernmental Panel on Climate Change (IPCC),[10] serves as an illustrative example of RDF share and composition (see Figure 2). Typically, the predominant fraction of MW is organic matter (green waste, food leftovers, etc.), which accounted for nearly 36% of MW in the past. According to the IPCC report, the

9 Le Bihan, M., De Caevel, B., & Michel, F. (2018). Use of SRF and RDF in Europe: literature review and administrative situations encountered in the field. RDC Environment, Study N° 16-0250/1A.

10 Intergovernmental Panel on Climate Change (IPCC). (2019). Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Section 2: Waste Generation, Composition and Management Data, 2.11. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_2_Ch02_Waste_Data.pdf

approximately 34% of total MW that contains mostly paper and cardboard, plastics, textiles, wood, and rubber is suitable for RDF production.



Based on the IPCC numbers, the bar to the right of the chart shows the theoretical yield of materials suitable for RDF production

Figure 2: Average MW composition in Europe and potential yield of RDF around 2010

It should be noted that actual local waste composition may deviate significantly from the averages presented here. This variation is typically related to elements such as the consumption level/GDP; urban vs. rural environment; level of implementation and acceptance of separate collection of recyclables; local/regional/national ambition to reach higher recycling targets and reduce landfilling, etc.

The figures presented for the potential share and composition of RDF do not reflect EU legislation or ongoing efforts to reduce waste disposal through landfilling and/or incineration. EU legislation (see Section 5) is encouraging other waste management routes that are higher in the waste hierarchy, such as recycling or preparing a number of waste streams for reuse (including packaging waste and municipal waste more generally) and promotion of waste prevention. Furthermore, when considering the potential RDF share, the losses attributable to collection and processing systems need to be considered on a case-by-case basis.

Waste from Commerce and Industry (C&I) is an additional source of RDF and generally consists of dry waste materials such as packaging waste (particularly paper and cardboard, wood, textiles, and plastic packaging). Furthermore, unsold or off-spec products that are discarded as waste by commerce and industry may also be of interest for RDF production. In Europe, in such cases, a prerequisite is compliance with the waste hierarchy principles, that is, the prevention of product use or waste not suitable for reuse, preparing for reuse, or recycling.

An example of suitable waste for RDF production is provided in the German RAL GZ 724[11] (see also the annexes, Section 8.2).

[11] German Institute for Quality Assurance and Certification. (2001). Solid Recovered Fuels – Quality Assurance RAL-GZ 724.

2.4 Potential users of RDF

Energy-intensive industries[12] have traditionally been the main RDF users. The table below provides an overview of the main RDF-consuming industrial sectors in the European Union. It also indicates the current share of alternative fuels in the total energy mix of the sector (including RDF, biomass, sewage sludge, waste oils, end-of-life tyres, and other types of waste), the share of RDF (expressed as w./w. percentage of the alternative fuels share, if not otherwise indicated), an estimation of the fossil fuel substitution potential (expressed as a w./w. percentage), and an indication of the RDF quality required to substitute for the fossil fuels that would otherwise be used (Table 2 is based on data and information presented in the annexes, Section 8.3). The table confirms that the cement and WtE sectors have the highest potential for RDF uptake, followed by coal-fired power plants.

Table 2: Overview of the main energy-intensive industries and their potential uptake of RDF

Industrial sector	Current share of alternative fuels* (%)	RDF share of alternative fuels (%)	Substitution potential (%) for fossil fuels	Required RDF quality (expressed as SRF class equivalent)
Cement	52%**	45%	>60%	1, 2, and 3
Lime	6–8%	-	<30%	1 and 2
Waste-to-energy:				
Waste incineration	100%	-	-	3, 4, and 5
Pulp & paper	<2%	-	-	3 and 4
Chemical	<1%	-	-	3 and 4
Coal-fired power plants	5–10%*	100%	-	2, 3, and 4
Metal:				
Ferrous	***	-	-	1****
Non-ferrous	-	-	-	1****
Others:				
Food and beverage	-	-	-	-
Glass	-	-	-	-
Ceramics	-	-	-	-

* RDF, biomass, sewage sludge, waste oils, end-of-life tyres, and other types of waste, expressed as w./w. percentage of the alternative fuels share, if not otherwise indicated
** Expressed as thermal energy/total thermal energy input
*** Use of waste plastic as reduction agent is documented, but the share of alternative fuels is not known
**** Mostly plastic waste from C&I waste or waste oils

12 Cornell Law School, Legal Information Institute. 42 U.S. Code § 17111 – Future of industry program. https://www.law.cornell.edu/uscode/text/42/17111#a_2

2.5 Technical and/or economic limitations on the RDF uptake

The uptake of RDF by various industrial sectors is subject to certain technical and economic limitations or requirements (references and more detailed analysis provided in Sections 3 and 4).

The following are the primary technical limitations of the RDF uptake:

- **Energy content** (Net calorific value, NCV): RDF must provide a minimum energy content to reach a targeted temperature, for example, min. 1 450° Celsius for the main burner of a cement plant, and min. 950° C in the calciner (NCV is one of the criteria in the EN standard for SRF mentioned above).
- **Moisture content:** RDF needs to be as dry as possible, for high energy density and ease of grinding and pulverisation and better overall combustion properties.
- **Contaminating elements content (**which may react during the process and impact either the quality of the product or the efficiency of the process):
  - chlorine may cause coating, blockages in the ducts, refractories damage or corrosion. Chlorine content is one of the SRF classification criteria in the EN standard.
  - sulphur and phosphorus may decrease the reactivity of quicklime (CaO) in the lime industry.
  - ashes may contain reactive elements such as metal oxides that can affect the quality of lime in the lime industry or of cement in the cement industry.
- **Polluting elements content (**which may impact environmental performance and emissions levels):
  - metal content, particularly of mercury, may be a criterion for rejection if it goes above the specifications for the cement industry or coal-fired power plants (mercury content is also one of SRF classification criteria in the EN standard).
- **Physical requirements:** depending on the retention time in the furnace/boiler, the temperature and the feeding system, the particle size, bulk, density, and shape may be cause for rejection if they do not fall within the specifications. This has the potential to cause partial combustion and/or to damage the process (for example, slagging). These specifications are specific to each plant, depending on the sector, process, and technology.

Table 3 provides typical values for the above-listed elements of interest with respect to the quality requirements for RDF according to specific industries. The listed values are obtained from the authors' own experience.

Table 3: Examples of typical technical requirements in selected industrial sectors

Sector / Requirements	Cement	Lime	WtE	Coal-fired power plants
Energy content (NCV)	>21 MJ/kg main burner >14.7 MJ/kg calciner	>16–23 MJ/kg kiln technology dependent	7.5–11 MJ/kg furnace technology dependent	Usually >11 MJ/kg
Moisture content	<15% main burner <20–25% calciner	<7–12% kiln technology dependent	usually <35%	<20–50% lignite dry-bottom boilers (DBBs) <12%–20% coal wet-bottom boilers (WBBs)
Chlorine	Usually <0.8% (dm)	Usually <1% (dm)	Usually <2% (dm)	<0.5% lignite fluidised bed combustion (FBC) <2% coal WBB
Sulphur		<0.5–0.8% (dm) kiln technology dependent	<1–1.2% furnace technology dependent	
Ashes	<15% (dm) main burner <20% (dm) calciner	<2–10% kiln technology dependent	not always defined, <25% for FBC	<15–30% combustion technology dependent
Mercury	<1.2 mg/kg (dm) 0.6 mg/kg (dm) as the median value			
Metals				<2 000–3 800 mg/kg typically
Particle size and type	<30 mm (2D) main burner <50–300 mm (2D, 3D) calciner technology dependent	<2–30 mm (2D) kiln technology dependent	<80–1 000 mm furnace technology dependent	<5–50 mm (usually 2D, 3D; with the exception of WBB, which takes 2D only)
Bulk density	~60-200 kg/m3 main burner			
Standardise class equivalent	1, 2, or 3	1, 2, or 3	1,2, 3, or 4 (possibly 5 for MW incinerators)	1, 2, or 3 (possibly 4 for coal FBC)

Note: dm = dry matter

The main **economic** limitations are as follows:

- RDF competitiveness: RDF usually represents a source of energy at a lower cost compared to fossil fuels. Nevertheless, the main drivers influencing RDF competitiveness are:
  - The cost of fossil fuels.
  - The quality of RDF (higher quality, higher cost/value) and the consistency of quality, ensuring safe continued replacement of fossil fuels.
  - Security of supply, ensuring continued operation of the user's main business/production lines.
  - Taxes and/or fees directly or indirectly linked to RDF use (for example, landfill and/or incineration gate fees or taxes).
  - Transport distance/cost.
- CO_2 savings: when containing biogenic carbon, RDF may, in certain circumstances, also reduce CO_2 emission costs, in the context of the EU Emission Trading System (EU-ETS).

2.6 Conclusion

- RDF is a residue of the treatment of non-hazardous MW and C&I waste.
- RDF is a wide term that encompasses standardised alternative fuels such as SRF (EN ISO 21640).
- The EN standard defines five SRF classes, of which class 1 has the highest NCV and the lowest chlorine and mercury content.
- Energy-intensive industries are typically the main users of RDF, with the cement industry and WtE plants having the highest consumption potential.
- The broad quality requirements for the use of RDF in different sectors are as follows:
  - Cement industry — class 1, 2
  - Lime industry — class 1, 2, 3
  - WtE – MW incineration — class 5
  - WtE – Pulp and paper industry — class 3, 4
  - WtE – Chemical industry — class 3, 4
  - Coal-fired power plants — class 2, 3, 4
  - Steel industry (only using waste plastics as a reducing agent) — class 1
  - Non-ferrous metal industry (only using waste plastics) — class 1
- The steel industry uses waste plastics of only high quality as an alternative reducing agent in blast furnaces.
- The final user sets the required RDF specifications and quality, based on its process and technological requirements.
- Uptake agreements/contracts typically stipulate consistency in RDF quality and security of supply – otherwise, operators are likely to opt for lower-risk fossil fuels.

3 RDF uses – current status, market considerations, and general market mechanisms in European countries

3.1 Market considerations

The main market drivers for the RDF uptake – apart from those legal aspects that may influence market considerations (see Section 5) – are related to economic factors:

- Energy costs/market prices: lower energy costs and market prices may have a negative impact on RDF uptake. This is because RDF is intended as a substitute for other fuels such as fossil fuels, meaning that it competes directly with these fuels on price. This is the main market driver of RDF uptake.
- Availability of suitable MW and C&I waste for the production of higher-quality RDF: lower availability of suitable waste may have a negative impact on RDF uptake, as lower availability of suitable waste increases the cost of high-quality RDF production.
- Landfill gate fees and/or taxes: higher fees and/or taxes can have a positive impact on RDF uptake by energy-intensive industries (provided that these are higher than incineration gate fees and/or taxes).
- Incineration gate fees and/or taxes: higher fees and/or taxes may have a negative impact on RDF producers (but may be positive for certain RDF users).
- CO_2 emission cost: higher CO_2 market prices may have a positive impact on RDF uptake, so long as MW installations are not included in the scope of the EU-ETS (see Section 5) and the RDF contains biogenic carbon (see the discussion of **CO_2 cost** below).

Pricing mechanisms for RDF: The German waste management service ALBA applies a concise pricing mechanism to RDF.[13] As a rule, fees are requested for the incineration of waste-derived materials, regardless of whether this is for disposal or recovery and regardless of the destination of the RDF (for example, cement or power plant). For example, an RDF producer may receive €150/t for treating commercial waste and eventually pay €50/t of RDF to the cement factory for the uptake. The RDF producer's margin is the difference between the gate fee it receives as a buyer of waste, and the price it pays for the RDF uptake (that is, final treatment and disposal). The margin (i.e., €100/t), therefore, needs to cover the RDF producer's depreciation, operating costs, and profit margin.

Waste disposal cost: Waste disposal costs vary significantly across the EU-27. For sending to landfill, waste costs can vary from €0 to €950/t (see Section 8.5), while incineration costs range from €70 to €254/t (see Section 8.6). This large variation in price depends mainly on the hazardousness and/or type of waste, as well as on the possible landfill restrictions/costs in place. The prices for waste disposal in landfills tend to be correlated with restrictions on the use of landfills.

CO_2 costs: RDF can help reduce fossil-fuel-related CO_2 emissions in industrial thermal processes when biogenic material content (paper, cardboard, or textiles made from natural fibres) is present, thus reducing the cost of related CO_2 emission certificates. The carbon contained in biogenic materials does not count towards greenhouse gas emissions.[14] An example of a CO_2 cost reduction when substituting RDF for fossil fuels is provided in the annexes (see Section 8.7).

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[13] ALBA Europe Holding plc & Co. KG, Berlin. (no date). Hintergrundpapier – Ersatzbrennstoffe – wie Abfall Kohle ersetzen kann.

[14] According to Part A (and B) of Annex IV to Directive 2003/87/EC, as last amended by Directive (EU) 2023/959, "the emission factor for biomass that complies with the sustainability criteria and greenhouse gas emission-saving criteria for the use of biomass established by Directive (EU) 2018/2001, with any necessary adjustments for application under this Directive, as set out in the implementing acts referred to in Article 14 of this Directive, shall be zero." In addition, according to Article 2(24) of Directive (EU) 2018/2001, as last amended by Directive (EU) 2023/2413, "'biomass' means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin."

3.2 Typical gate fees for RDF uptake

RDF end users typically expect to be paid for RDF uptake (positive gate fee), rather than pay for it (which would correspond to a negative gate fee). The level of the gate fee depends on several factors: the feedstock (i.e., MW, commercial or industrial waste), the waste disposal costs, fossil fuel prices, and, finally, the market (i.e. supply and demand). Hence, the typical (positive) RDF gate fees (that is, the cost for the RDF producer) vary significantly across the European Union, as the following examples show:

- €75/t of RDF class 2 – high-calorific plastic film, transport from Malta to Germany included.
- €130 to €150/t for RDF class 3, excluding transport from Italy.
- €40/t of class 2 RDF for firing main burners in German cement plants, including transport.
- Up to €20 revenue per tonne of RDF (unknown class), paid by cement factories in Germany, including transport.

3.3 Current and future RDF production and uptake in the EU-27

Projected RDF generation

Last decade Eurostat[15] data on energy recovery and/or incineration in the EU-27 point to 12–18% of MW being converted into RDF by 2030.[16]

In a recent modelling exercise, the European Environment Agency (EEA) concluded that meeting the 2030 recycling target could imply residual waste to account for 25–38% of MW.

Furthermore, without entering into detailed methodologies for how the different targets are calculated (in which specific system designs and related losses in the waste management chain need to be accounted for), it is obvious that the scenario in which the 65% recycling target for MW and the 10% landfill target are met by 2035, would lead to a maximum of 25% of MW being made into RDF. Simply put, if MW generation in the EU-27 reaches some 232 million tonnes in 2035,[17] EU MSs will potentially need to deal with up to 58 million t/y of RDF.

This projection seems to be in line with the Confederation of Waste-to-Energy Plants (CEWEP) estimates,[18] which target a potential conversion of 28% of MW into RDF by 2035, with a 7% landfill rate. The projected conversion of 28% of MW into RDF corresponds to ~69 million tonnes of RDF out of a projected 246 million tonnes of MW. In addition, CEWEP estimates the RDF from C&I waste at ~73 million tonnes (see Figure 3).

Projected RDF uptake options

According to CEMBUREAU,[19] in 2020, the European cement industry substituted 52% of total thermal energy demand using various types of alternative fuels[20] estimated at 12.1 million tonnes, with RDF accounting for 45% of them. Based on best practice examples, up to 85% of energy demand could potentially be covered by alternative fuels instead of fossil fuels (thermal substitution rate – TSR). Thus, the EU-27 cement industry could, in theory, use up to ~20.4 million tonnes of alternative fuels.

This would represent ~15 million tonnes potential RDF uptake (minimum class 2 and class 3, depending on the needs of the related user) by the cement industry, that is, equivalent to a fuel share of 74%.

According to CEWEP, the projected RDF production in the EU-27 in 2035 may reach an estimated 142 million tonnes (when EU recycling targets are achieved, see Figure 3). In addition, according to CEWEP, the current RDF-uptake capacity in the EU-27 is ~90 million tonnes for WtE and ~11 million tonnes for co-incineration. This means, that considering the future RDF production and assuming the current WtE and co-incineration capacities, ~41 million tonnes of RDF may remain available for other energy intensive industry sectors (indicated as capacity gap in Figure 3).

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15 Eurostat ENV_WASMUN database. https://ec.europa.eu/eurostat/databrowser//product/view/ENV_WASMUN

16 Based on Eurostat, the share of residual waste sent to energy recovery or incineration varied from 56% in 2012 to 47% in 2021, with an almost constant decrease.

17 European Commission, Directorate-General for Environment, Karigl, B., Neubauer, C., Kral, U., et al. (2022). Scoping study to assess the feasibility of further EU measures on waste prevention: final report, https://data.europa.eu/doi/10.2779/21588

18 Facts and data maps - Circular Economy Calculation tool, https://www.cewep.eu/circular-economy-calculations-2/

19 CEMBUREAU's KEY FACTS & FIGURES, 2021, https://cembureau.eu/media/lfqjyve5/key-facts-figures-2021.pdf

20 CEMBUREAU – The European Cement Association. Waste-to-Energy. https://www.cembureau.eu/policy-focus/environment/waste-to-energy

Therefore, the EU cement industry, with an estimated potential RDF-uptake capacity of ~15 million tonnes, could uptake a part of these ~41 million tonnes, providing that the required quality and requirements are met.

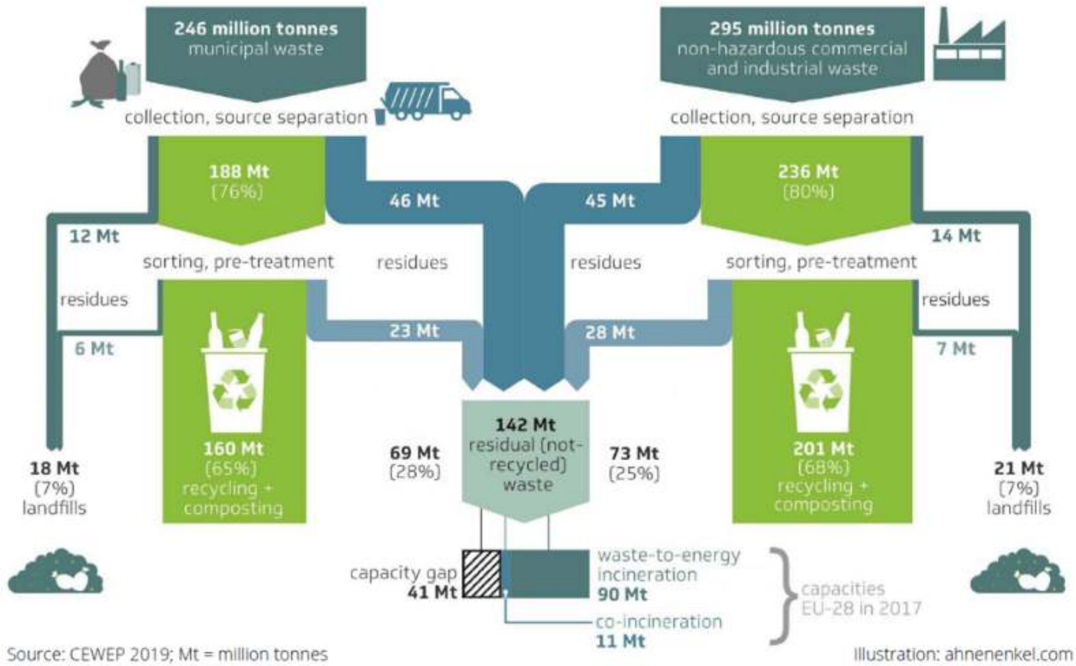

Figure 3: RDF production projections in the EU-27 in 2035

This means that RDF generation in the EU-27 is expected to exceed uptake capacities. Nevertheless, the situation in individual MSs is expected to vary, depending mainly on their current recycling and landfill rates, energy needs, resources for cement production, and current and future TSRs.

Further detailed analysis concerning five specific MSs is provided in the annexes (see Section 8.12). This analysis of RDF generation and potential uptake, both currently and as predicted in the future, reveals the following:

- Based on Eurostat data, waste incineration (D10+R1) in these MSs was about 0.5 million t/y in 2021;
- The uptake of RDF and other alternative fuels in cement plants is two to three times higher than the reported waste incineration (D10+R1 Eurostat data) – about 1.4 million t/y;
- The potential generation of RDF derived from MW in the future (considering the circular economy targets) is twice as high as the current uptake – about 2.5 million t/y; and
- The potential additional RDF uptake for both cement and WtE is estimated at an additional ~2.3 million t/y (mostly due to cement capacities adopting a TSR of 85%; only a few WtE projects were identified), thus reaching a total future capacity of ~3.7 million t/y.

For the five selected MSs, contrary to the overall EU-27 projection, there is the potential to absorb the expected RDF generation almost exclusively via cement plants. Furthermore, the analysis demonstrates the need for case-by-case assessments when developing options for improved RDF utilisation.

3.4 Conclusion

- The RDF market is mostly driven by energy costs (particularly for fossil fuels), availability of waste suitable for RDF generation, waste disposal taxes and/or gate fees (for example, landfill or incineration), and the price of CO_2 (that is, the CO_2 allowances in the EU-ETS). In addition, quality and security of supply are also important market drivers.
- Across Europe, the cost for waste disposal in landfills ranges from €0/t to €950/t, and incineration costs range from €70/t to €254/t.
- CO_2 emission certificates are currently around €91/t-CO_2e.
- RDF can help reduce fossil-fuel-related CO_2 emissions in industrial thermal processes, thus reducing the costs for CO_2 emission certificates.
- Current and future RDF generation is higher than current and future uptake capacities and is expected to remain so.
- In the future, the EU-27 cement industry has the potential to double or almost triple its RDF uptake (from 5–6 million t/y at present to ~15 million t/y), provided that RDF producers can meet the requirements for quality and security of supply and that required additional investments are made in cement plants to reach a TSR of 85% (which is considered reasonably attainable).
- By 2035, based on projected waste and RDF generation, the EU-27 WtE sector alone will not have the capacity to absorb all of the RDF produced (capacity gap).
- Case-by-case analyses on regional/national levels may lead to different results and conclusions than on EU-27 level – therefore, it is recommended that specific case studies be implemented for every project.

4 Technical considerations

4.1 RDF users' perspective

4.1.1 General considerations for RDF uptake

As outlined in Section 2.4, the cement (and, to a lesser extent, lime) industries and WtE are the main users of RDF. In the cement and lime industries the production process and product quality dictate the RDF type, quality, and quantity that can be utilised. To ensure continuous delivery of high-quality RDF, dedicated specialised equipment for the reception, storage, feeding, and dosing of RDF, alongside relevant quality-management procedures and reporting, are necessary and present the precondition to enable sustainable, reliable, and financially beneficial operation of the user's main business.

Cement kilns can absorb a broad range of waste-derived fuel varieties, for instance RDF, tyres, sewage sludge, solvents, oils, wood, and animal meal. In cement kilns with pre-calciners, the typical distribution of the heat energy provided by fuels is 60% in the pre-calciner and 40% in the main burner. As outlined in Section 8.3, calciner RDF has to match at least class 3, and main burner fuel has to match at least class 2. If the required heat energy in a pre-calciner is already covered 100% by RDF, then the TSR of the whole kiln is 60%. A further increase in the kiln TSR can then only be achieved by utilising class 2 or higher RDF in the main burner; however, the use of RDF in the main burner is limited. Experience has shown that the higher the TSR, the higher RDF quality requirements. Usually, TSRs with class 2 RDF are technically limited to 75%. To achieve a TSR of 80–85%, the additional required RDF can be further dried, pelletized, and milled (into fine particles) to improve both the ignition of the material and its NCV.

To reduce the CO_2 emission costs, cement and lime plants tend to look for waste-derived fuels with higher biogenic carbon content. However, a drawback of this approach is that an increase in the proportion of biogenic material in an RDF recipe, generally reduces the NCV, thus limiting the technical applicability of such an RDF in cement and many lime kilns. Nevertheless, in the lime industry, commercial technologies able to run on 100% biomass do exist, for example, using waste wood with an NCV >16 MJ/kg (see Section 8.4.2).

4.1.2 Specific considerations for compost-like output

Compost-like output (CLO) from MBTs is an organic-rich substance derived from aerobic digestion of MW. CLO is a subfraction of bio-stabilised residual waste (BSRW) that is typically screened to include only particle sizes smaller than 10 mm and subject to additional processing to remove glass and plastics. This subfraction is also known as a stabilised fraction.[21] CLO derived from mixed waste is generally considered to be of a lower quality and value compared to compost derived from source-segregated bio-waste, mainly due to its higher contamination level.[22] CLO may, therefore, not be mixed with material that is foreseen to become compost.

The following table shows a compilation of quality data on CLO and compost.

[21] Graça, J., Murphy, B., & Kelleher, B. (2023). Valorisation alternatives to landfill for organic residues. Environmental Protection Agency, Government of Ireland. Report No. 432.

[22] Mechanical biological treatment of municipal waste. Department for Environment Food & Rural Affairs (UK). February 2013.

Table 4: Quality data on various CLOs and compost materials

Type of material	Moisture (%)	Ash (%)	Net calorific value NCV (MJ/kg)	Chlorine (%)	Source
Various CLOs	37.2–53.3				Simpson[23]
"MW compost"*	25.6	29.4	9.2	3.4	Phyllis2 Database[24]
"Humus from digested MW" *	18.4	38.3	7.7	0.5	
Compost, original substance	38	40.3	3.9		Malat'ák et al.[25]
Compost, air dried	4.3	59.1	7.6		Malat'ák et al.
Various composts	28.3–72.3	40.5–65.1	0.54–2.47		Ondrej Zajonc et al.[26]

*Note: * means that these materials can be regarded as CLO*

CLO can typically not be mixed with RDF destined to be used in thermal processes requiring higher-quality RDF, such as the cement, lime, or steel industries, because it is usually not able to meet the minimum requirements regarding NCV or ash and moisture content. Moreover, the deleterious effects of chlorine may also be a limiting factor. It is suggested that CLO cannot be used as an ingredient in RDF of classes 1, 2, and 3.

CLO can, however, be considered a component of class 4 or 5 RDF, which are typically used by power plants (see also Section 8.3), provided the minimum NCV and maximum chlorine content requirements are met.

4.1.3 Typical technical and cost challenges for enhancing RDF uptake

In the discussion below, the focus is on cement plants due to their status as primary users of higher-quality RDF (classes 2, 3).

Drying of RDF: drying can help reduce moisture content and boost the NCV, which may help to reach the class 2 quality requirements needed by, for example, kiln burners. The additional energy and technology needed for drying RDF represents an extra cost for RDF generation. A mitigation measure for RDF producers is to work in cooperation with cement plants and use the excess heat from the latter in a flash, belt, or drum dryer.

Switch to new (emerging) techniques: the residence time needed for RDF to incinerate completely can be increased using new technologies such as the Step Combustor or Pyrorotor (see Section 8.15.2), which allow for the use of RDF with particle sizes up to 300 mm, thus reducing the cost of RDF production (as no additional shredding is needed).

Adaptation of the reception, feeding, and dosing system: this is a site-specific cost. The following table lists the typical additional investment costs (excluding transportation and import duty costs) associated with handling 70 000 t/y RDF in a theoretical cement plant.

Along with the necessary investment costs, there are additional operational costs associated with quality control, emission monitoring, emission reporting, auditing, and validation. According to experience, average operational costs are considered to range from €2/t to €3/t of RDF.

23 Simpson, E.W. (2008). *Long Term Behaviour of Compost-Like-Output and its Associated Soils*. Doctoral Thesis, Durham University.
24 Phyllis2 – Database for the physico-chemical composition of (treated) lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar. https://phyllis.nl/Browse/Standard/ECN-Phyllis#compost
25 Malat'ák, J., Bradna, J., Velebil, J., Gendek, A., & Ivanova, T. (2018). Evaluation of dried compost for energy use via co-combustion with wood. *Agronomy Research* 16(1), 157–166.
26 Zajonca, O., Frydrych, J., & Jezerska, L. (2014). Pelletization of compost for energy utilization. *IERI Procedia*, 8, 2–10.

Table 5: Cement plant additional CAPEX estimates for equipment associated with the enhanced uptake of RDF

Description of systems	CAPEX (€ million)
Equipment for reception and storage	1.5–4.0
Feeding/conveying systems	1.0–5.0
New combustion technology for calciner firing	4.7–10.0
New main burner system	1.0–1.5
Drying system	3.0–5.0
Civil and structural works	1.0–6.8

Source: MVW
(it should be noted that the above values are highly subject to variation on a case-by-case basis)

4.2 RDF producers' perspective

4.2.1 Challenges and solutions for MBT/MT plants to improve RDF uptake

The focus below is on MBTs/MTs due to their status as the primary producers of RDF from MW. The challenges faced by MBTs/MTs in producing RDF can be summarised as follows:

Availability of waste: The Waste Framework Directive[27] for 2020–2035 sets ambitious recycling targets (see Section 5). Following its implementation, it is to be anticipated that less residual waste will be generated than at present, due to more efficient separate collection systems and increased recycling of packaging and MW (see Section 3.3). This means that smaller quantities of energy-valuable materials (for example, plastic, wood, paper, and cardboard) will need to be disposed of, resulting in a lower NCV of the residual waste. To address this challenge, MBT plants will need to be better equipped to increase the efficiency of separation of energy-rich residual materials to recover them for the RDF fraction rather than sending them to landfills. This typically means investment in automated sorting and specialised conditioning equipment (see examples of how sorting efficiency can be increased in Section 8.9).

Variable feedstock: The key component in the production of high-quality class 1 and 2 RDF is plastic. In the European Union, mechanical recycling rates are rising, with chemical recycling gradually also becoming more established.[28] As more plastic is recovered for recycling, the refuse from MW will be less suitable to produce class 1 and 2 RDF, thus the improved recycling is impacting the possible RDF quality. This translates into a need for MBTs to invest in quality control systems for both MW inputs and MBT outputs (see examples of quality control systems in Section 8.9).

Satisfying customer requirements: For RDF producers, the customer requirements often imply the need to invest in additional specialised treatment machinery (for shredding, sieving, and drying) to achieve the technical specifications set by the user, and for quality control of the produced RDF. Thus, MBTs need to invest in quality control for both MW inputs and MBT outputs (see the examples of quality control systems and drying techniques in Section 8.9).

Comparison with other fuels: RDF derived from MW is not only compared by potential end users against other more typical fuels (for example, fossil fuels, waste oils, biomass, etc.), but also against RDF derived from C&I

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27 DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2008/98/EC on waste.

28 See for example: https://plasticenergy.com/total-and-plastic-energy-announce-a-strategic-partnership-and-the-construction-of-the-first-chemical-recycling-plant-in-france/

waste (see Section 3.3). MW can vary significantly in composition and quantity, both over time and from region to region, leading to significant variations in RDF quality across Europe at any moment in time. To ensure quality, producers of MW-derived RDF may have to opt for slightly lower quality but more standardised RDF to offer a stable quality, as is usually the case for other fuels.

4.2.2 Causes for poorly performing MBT/MT plants and possible improvements

Various factors can cause MBT/MT plants to operate poorly. An overview of the considerations and possible improvements (further detailed information and data can be found in Section 8.10) follows:

Little or no input control and acceptance of unsuitable waste inputs: acceptance of non-desired waste can lead to lower-quality RDF output. At a minimum, visual inspection of all waste deliveries should be carried out, and management procedures for a negative list of waste should be established.

Poor maintenance of the final shredder: this leads to quality issues regarding the RDF output. Regular and planned maintenance should be put in place.

Unfavourable installation design: poor design and positioning of the metal separator may lead to higher levels of metal content in the RDF. Proper design, including separation of the metals early in the treatment process (potentially at the discharge point) and parallel with the flow should decrease the level of metal content in the RDF.

Undesired high chlorine content: the main source of chlorine is PVC-containing waste that should be separated from the waste input used to produce RDF. This is typically achieved by addition of NIR separation technology.

Too high moisture levels in the RDF: as stated in the previous section, drying may be required to improve RDF quality.

Poor quality control: efficient quality control of both inputs and outputs, including sampling, can improve the final quality of RDF.

4.2.3 Case study – Best current practice of an RDF-producing MBT

The **AWG Ennigerloh MBT**, located in Nordrhein-Westfalen in the western part of Germany, approximately 30 km east of Münster, can be considered a good example of process design of an MBT in the field of MW management, producing two classes of RDF (class 2 and 4) from MW and industrial waste input. The MBT is close to several cement kilns, as well as several power stations and WtE facilities. The plant went into operation in 2002, with a total capacity of 160 000 t/y (74 000 t/y household waste, 66 000 t/y commercial waste, and 20 000 t/y bulky waste).[29]

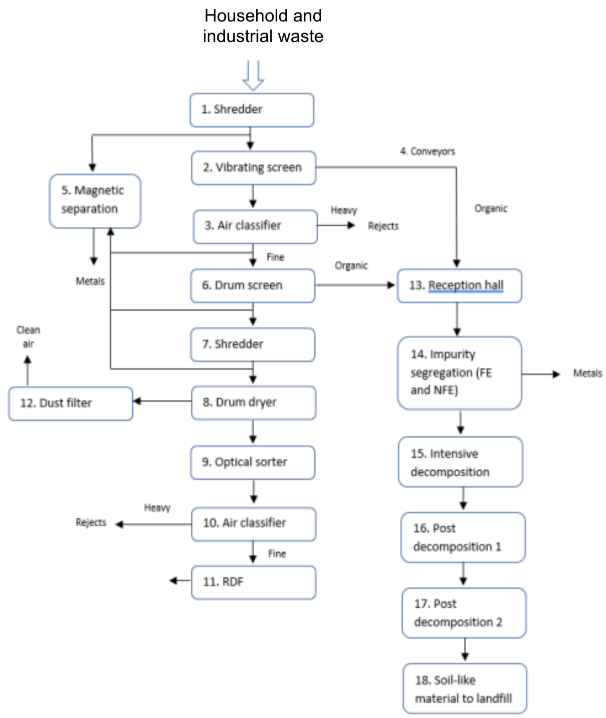
The mechanical treatment (separation process) is fully automated and includes screening equipment, air classification, and ballistic separators.

The biological fractions are composted (aerobic treatment).

The whole process is shown in Figure 4 and includes, among others:

- Quality control.
- Visual control and removal of impurities and undesired waste (for example, PVC).
- Removal of organics and biological treatment.
- Automated sorting (metal separators and NIR).
- Fine particles control.
- Classification, screening, shredding, drying processes.

[29] class 1https://task36.ieabioenergy.com/wp-content/uploads/sites/34/2016/06/Report-5_MBT_Ennigerloh.pdf



Source: Ecowest Entsorgungsverbund Westfalen GmbH[30]

Figure 4: Process flow diagram for the AWG Ennigerloh MBT plant in Germany

4.2.4 Typical financial metrics

Retrofitting an RDF production plant

The requirements for equipment and the expense of retrofitting and upgrading an existing facility are dependent on various factors. If it is necessary for facilities to upgrade their RDF production line to meet customers' demands, the following table provides indicative investment costs for the various types of equipment that may be needed.

It should be noted that any required (additional) equipment needs to be determined on a case-by-case basis, considering the existing type and condition of equipment, desired throughput, and desired RDF quality. Adding the full range of machines to a line with 35 tonnes of MW per hour input (that is, optical sorting, pre-shredding and final shredding, air classification, ballistic separation, drying, and conveyors), will typically require a budget CAPEX of around €8 million. In every case, an individual assessment is necessary.

30 Ecowest Entsorgungsverbund Westfalen GmbH, Mechanical Biological Waste Treatment Plant of Ennigerloh- Brochure.

Table 6: CAPEX per unit of equipment for retrofitting RDF production plants

Equipment	Approximate CAPEX per unit (€ million)
Pre-shredder (35 t/h)	0.65
Air classifier (10 t/h)	0.26
Optical separator (10 t/h)	0.45
Final shredder (8 t/h)	0.80
Ballistic separator (20 t/h)	0.24
Others (conveyors, engineering, transportation, installation, and commissioning)	0.84
Drying (20 t/h)	4.70
Total approximate CAPEX budget for retrofitting	**7.94**

Source: MVW

Transport costs of RDF

Depending on the agreements established, the cost of transport may be borne by either the producer or the end user. Typical considerations and indicative costs of transport are detailed in Section 8.13 and are summarised here:

- Baling: typical CAPEX for equipment is about €500 000, with a typical OPEX of ~€12/t to €14/t.
- Road transport: typical total cost of transport for a 23.5 t load is in the range of ~€0.10/km/t (calculated for 500 km) to €0.50/km/t (calculated for 20 km).
- Rail transport is economically viable for long distances and in specific regions. By way of indication, the expected cost of rail transport in Germany is ~€0.05/km/t.
- Sea freight is typically used for very-long distance transportation. Sea transport costs are very volatile; however, indicatively, a cost of transport of €45/t to €60/t from Baltic states to the Amsterdam-Rotterdam-Antwerpen-Ghent region, that is, ~€0.02/t/km, has been observed.

4.3 Future trends in RDF generation and utilisation in the EU

RDF generation – waste treatment facilities should consider increasing their recycling targets and adopting more stringent landfilling rates (see Section 5). Future facilities ought to be able to sort materials efficiently, utilising technologies such as artificial intelligence (see Section 8.15.1). Automated quality control (for example, optical sensors and imaging coupled with artificial intelligence for data analysis) should enable all necessary data and information about the waste input, such as the calorific value, chlorine content, moisture content, type and quantity of plastics, proportion of inert matter, and/or mass flow, to be collected in real time. These live analytics should, therefore, enable the operator to separate materials "worthy of sorting" for recycling from residues/refuses, effectively using automated separation systems, additionally allowing operators to adapt to possible fluctuations in waste composition to ensure stable RDF quality. With future trends such as new generations of detectors able to penetrate through materials, it should be possible to provide more complete information on materials, analysing not only the surface of the waste but also its inner layers. In combination with automated separation systems, the use of such technologies should increase RDF quality.

RDF utilisation – the cement sector has developed emerging techniques (for example, combustion chamber technologies) to increase TSR (see Section 8.15.2). On the one hand, these techniques enable larger particle sizes RDF use (up to 300 mm); on the other hand, the lime industry can use RDF with particle sizes of less than 2 mm in the most efficient kilns (see Section 8.15.3). Other techniques such as cooling RDF pellets with liquid nitrogen during the grinding process to improve its pulverisation are under development.

Finally, chemical recycling (for example, pyrolysis, gasification, hydro-cracking, or depolymerisation) may be implemented at commercial scale in the upcoming years, which would, in turn, result in diversion of significant waste plastic flows from RDF, potentially having a major negative impact on RDF quality. More details on emerging techniques are provided in Section 8.15.

4.4 Conclusion

- RDF end users (for example, cement plants) may be able to achieve thermal substitution rate (TSR) levels of above 60%, provided that the RDF is of high quality (class 1 or 2).
- To achieve higher TSRs, increased efforts to improve the net caloric value (NCV) and ignitability of RDF by additional drying, pelletising, and fine milling may be required.
- Compost-like output (CLO) cannot be mixed with RDF class 1, 2, or 3 because of its low NCV and high moisture and ash content.
- CLO can be used in RDF class 4 or 5 for less challenging thermal processes, for example, WtE facilities.
- The typical CAPEX required to enable the uptake of RDF in cement plants is in the range of €12 million to €32 million for a 70 000 t/y RDF-uptake capacity. The typical OPEX for such equipment is estimated at €2 to €3 per tonne of RDF.
- The typical CAPEX required to improve RDF quality in MBTs/MTs is estimated at €8 million for an RDF production line with 35 t/h of MW capacity.
- The main challenges for RDF production in MBT plants are availability of waste, variable feedstock quantity, quality and composition of inputs, and competition with other fuels.
- By increasing sorting efficiency (for example, using automated and real-time controlled sorting), implementing quality control (of both waste input and RDF output) for critical parameters (NCV, moisture, chlorine, metals/mercury), and including additional drying of RDF, the final quality can be improved.
- Future trends in technologies may have a positive impact on RDF quality and hence uptake.
- With the increasing prevalence of chemical recycling, more plastics will be diverted from RDF production, which is expected to have a negative impact on RDF quality.

5 Legal considerations

5.1 Assessment of RDF – relevant EU legislation

RDF use in the cement and other industries is mainly driven by cost savings, by limiting the use of fossil fuels such as coal, pet coke, and natural gas and by savings on fossil CO_2 emission costs.

In the European Union, other legal drivers may impact the future quantity of RDF production, its composition and therefore also its uptake.

For the purposes of this study, the following EU legislation was identified as relevant (the list is non-exhaustive, and other legal texts may be relevant):

- Council Directive 1999/31/EC on the landfill of waste;[31]
- Directive 2000/76/EC on the incineration of waste;[32]
- EU Emission Trading System (EU-ETS) Directive 2003/87/EC;[33]
- the Regulation on Shipments of Waste – Regulation (EC) No 1013/2006;[34]
- the Waste Framework Directive 2008/98/EC;[35]
- the Industrial Emissions Directive 2010/75/EU;[36]
- the Renewable Energy Directive 2018/2001;[37] and
- the Packaging and Packaging Waste Directive 94/62/EC.[38]

The assessment identified several key elements that may have positive or negative influences on the RDF market and hence on RDF uptake.

The following were identified:

- The EU-ETS Directive was identified to have a negative impact on the uptake of RDF due to:
  - Possible future inclusion of MW incineration in the scope of the Directive.
  - Further reduction of the free CO_2 allowances cap and eventually no free allowances.
- The Landfill Directive was identified to have a positive impact on the uptake of RDF due to:
  - 10% municipal landfill target by 2035, expected to require more incineration (at least in a transitory period) to reach the target, while separate collection and recycling capacities are fully rolled-out in a number of MSs.
- The Waste Shipment Regulation was identified to have a neutral impact on RDF uptake.
- The Waste Framework Directive was identified to have a negative impact on RDF uptake due to:
  - The waste hierarchy principle, promoting higher waste treatment operations such as prevention, preparing for reuse, recycling, and material recovery.
  - Higher recycling targets, aimed at reducing residual waste and thus landfill and energy recovery.
- Industrial Emissions Directive was identified to have a neutral/positive impact on RDF uptake since it:
  - Provides high environmental standards for installations (co-)incinerating RDF.

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31 Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. https://eur-lex.europa.eu/eli/dir/1999/31/oj

32 Directive 2000/76/EC on the incineration of waste https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000L0076

33 Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading. https://eur-lex.europa.eu/eli/dir/2003/87/oj

34 Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32006R1013

35 Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098

36 DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0075

37 Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001.

38 Directive 94/62/EC of the European Parliament and of the Council of 20 December 1994 on packaging and packaging waste. https://eur-lex.europa.eu/eli/dir/1994/62/oj

    - Provides certain guarantees regarding public opinion (environmental references set through a transparent process involving the public through NGOs).

- Renewable Energy Directive (RED II) and its revision proposal (RED III) were identified to have a positive impact on RDF uptake since it:
    - Envisages the use of RDF to produce, for example, recycled carbon fuels (RCFs)
- The Packaging and Packaging Waste Directive and its proposed revision (Regulation) have been identified to have a negative impact on RDF uptake due to:
    - Increasing packaging waste recycling targets (including plastics, paper and cardboard, and wood, which are NCV-valuable materials for RDF).

5.2 Conclusion

- Current and future (proposed) EU legislation relevant to RDF was identified to have an overall negative impact on the quantity of RDF generation and uptake in the future, because it will promote prevention, preparing for reuse, and recycling over energy recovery and may divert NCV-valuable waste flows (for example plastic, wood, etc.) from RDF production, which makes RDF less attractive for end users as replacement of current fossil fuels.
- Certain legislative texts may have a positive impact on the production and uptake of RDF, provided it is produced from non-recyclable materials; this is, for instance, the case for RED II/III.

6 Swot analysis

A SWOT analysis of both RDF uptake in cement plants and in WtE plants is provided below.

Table 7: SWOT analysis for the RDF uptake in cement plants

Strengths:	**Weaknesses:**
1. Reduces landfilling, supports MSs to meet the 10% landfill target by 2035. 2. Non-biogenic CO_2 emissions reduction in the cement production process. 3. Alternative energy source for cement plants, contributing to the reduction of fossil fuel consumption. 4. Cement factories have experience with RDF uptake. 5. RDF will continue to be required on a regular basis. 6. Leaves no residues that need to be landfilled. 7. Energy recovery efficiency between 70% and 80%.[39]	1. Changes in waste composition may affect RDF quality. 2. Challenging to meet cement fuel requirements in areas such as grain size, NCV, and moisture content. 3. Requires upgrades and investment in the cement plant reception, storage, dosing, and firing system. 4. Additional drying may be required to improve RDF quality, which increases the costs of producing RDF.
Opportunities:	**Threats:**
1. Stricter landfill regulations and bans are driving demand for alternative waste disposal methods, creating opportunities for RDF uptake. 2. The demand for RDF could increase, provided it aligns with regulatory requirements. 3. MBT plants can sign contracts with cement plants for continuous supply of RDF for a specific period to secure an alternative source of regular income. 4. Cement plants can achieve energy savings by using RDF. 5. Cement plants can reduce their (non-biogenic) CO_2 emissions and may generate carbon credits, allowing them to earn additional income.	1. Chlorine content is a critical concern due to its potential to cause blockages and damage in the ducts, as well as harm to cement kiln refractories. 2. Recycling targets: The EU's emphasis on waste recycling and circular economy goals could reduce the availability of materials for RDF production, thus impacting RDF quality. 3. Evolving power generation landscape: The shift towards renewable energy sources such as hydrogen may impact the demand for RDF uptake. 4. Reduced gate fees in cement plants may result in smaller economic incentives for cement plants to use RDF.

[39] https://www.giz.de/en/downloads/giz-2020_en_guidelines-pre-coprocessing.pdf

Table 8: SWOT analysis for the RDF uptake in WtE plants

Strengths:	Weaknesses:
1. WtE can provide an energy solution, especially in areas with limited energy resources. 2. WtE can accept all RDF classes, as the acceptance criteria of RDF for MW is not so strict, compared to other energy-intensive industries.	1. Bottom ash, accounting for 25%[40] of the weight of the input MW needs to be landfilled. 2. Public perception is negative (air quality and health concerns). 3. Regulatory compliance needed to meet strict emissions limits in the European Union.
Opportunities:	**Threats:**
1. Ongoing advancements in WtE conversion technologies promise cleaner emissions and more flexibility in terms of energy output.	1. With the EU-ETS, WtE plants may have to pay for their CO_2 emissions (from sources of non-biogenic origin), starting from 2024. 2. High initial investment. 3. Increased recycling will reduce quantity and decrease quality of residual waste inputs/feedstock.

[40] Šyc, M. et al. (2018). Material analysis of bottom ash from waste-to-energy plants. *Waste Management Journal*, 73, 360–366.

7 Overall conclusions

What are the technical standards and norms applicable to RDF and/or SRF?

RDF is produced through mechanical processing and recovery of combustible (NCV-valuable) waste from non-hazardous MW and C&I waste. In Europe, EN ISO 21640:2021-11 is the latest standard for the specification and classification of SRF, which is a subset of RDF. The EN ISO 21640 standard defines five classes of fuels based on their properties. The classes range from the high-quality class 1 to the lower quality class 5, based on the NCV and chlorine and mercury content.

What are the current RDF uses?

The main end users of RDF are:

- **Cement plants** – are well suited to use RDF on account of their clinker kilns, which ensure thorough combustion of organic matter and absorption of non-combustible materials. Energy-intensive cement production demands a substantial amount of heat energy. Typically, RDF class 1 and 2 RDF offer the necessary calorific value and other qualities required for kiln burner firing. Class 3 may also be used in specific installations. In the EU-27, the cement industry currently uptakes an estimated 5–6 million tonnes of RDF.

- **Lime plants** are currently able to utilise RDF to a smaller degree than cement plants. The quality limitations associated with quicklime quality and kiln technology differentiate lime plants from clinker-based operations. High-calorific RDF of class 1 or 2 with low ash, chlorine, and sulphur content is viable for lime facilities. Class 3 may also be used in specific installations. In the EU-27, the lime industry currently utilises RDF to cover an estimated ~8% of its energy needs.

- **WtE plants** use RDF as a fuel in generating electricity and heat. WtE facilities require fuel with calorific values surpassing 11 MJ/kg to maintain a minimum boiler temperature. Therefore, only class 5 RDF is typically unsuitable, even though there is experience of this being used in grate furnace MW incinerators. In the EU-27, the WtE industry currently utilises an estimated ~100 million tonnes of RDF.
- **Coal-fired power plants** can potentially utilise RDF of class 1, 2, or 3, depending on the furnace technology and operating permits. Even class 4 RDF may be used in the case of FBC hard coal plants. However, the trend towards decarbonisation could render many coal plants obsolete by 2030, diminishing the capacity for RDF co-incineration. In the EU-27, coal-fired power plants currently use RDF to cover an estimated 5–10% of their energy needs.

- **Paper mills** utilise RDF to produce steam for papermaking processes and pulp drying within dedicated boilers. Fuel selection is aligned with furnace technology and operational permits. Boilers effectively operate with NCVs ranging from about 12 to 17 MJ/kg, corresponding to class 3 and 4 SRF. In the EU-27, paper mills currently use RDF to cover an estimated <2% of their energy needs.

- **Steel plants** may utilise class 1 RDF, which is formed from pure plastics, as an alternative reducing agent in blast furnaces. Alternative reducing agents require strict adherence to requirements in terms of particle size, NCV, and moisture, ash, sulphur, chlorine, and mercury content. There are no precise data on RDF uptake in steel plants at the EU level.

- **Other industries:** RDF cannot be used in the food and beverage industry due to the specific fuel requirements of the boilers and engines used, as well as restrictions on product quality. Similarly, in the glass and ceramics industries, the use of RDF may negatively impact product quality.

What are the core technical, legal, and/or environmental constraints on increasing the uptake of RDF?

- Increased RDF uptake in the EU-27 can require investments from both RDF producers (typically MBTs and/or MTs), to acquire the technology to increase the quantity and quality of RDF, and from RDF end users to adapt their production lines, possibly also acquiring necessary technologies.
- The cement sector is limited by a maximum TSR of 85%, which represents an additional uptake estimated at ~10 million tonnes of RDF from current levels.
- Uptake of RDF by WtE plants is limited by the installed capacity. WtE plants will not have any further capacity to uptake RDF in the future – on the contrary, an estimated ~40 million tonnes capacity gap is identified if circular economy targets are met and waste generation and sorting follow current trends.
- EU legislation promotes the waste hierarchy principle, which prioritises waste prevention, preparing for reuse, and recycling over energy recovery. In addition, the current and upcoming recycling targets may negatively impact RDF quality in the future.
- Inclusion of MW incineration in the scope of the EU-ETS is expected to have a negative cost impact for RDF end users.
- The IED requires MSs to ensure that best available techniques (BAT) conclusions are the reference for setting the permit conditions. In the EU-27, RDF end users mostly operate under the scope of the IED.
- Control of mercury and metals is a limiting factor for the environmental aspects.

What are the available options to increase efficient RDF management?

Two main options were identified: further uptake in cement plants (installations) and in WtE installations – under condition of consistent and controlled RDF quality.

What additional investments and operational costs would be associated with such options?

The typical CAPEX required to enable the uptake of RDF in a typical cement plant is estimated to be in the range of €12 million to €32 million for a 70 000 t/y RDF-uptake capacity. The typical OPEX for such equipment is estimated at €2 to €3 per tonne of RDF.

The typical CAPEX required to produce higher-quality RDF in typical MBTs/MTs is estimated at €8 million for an RDF production line with 35 t/h of MW capacity.

Which actions should waste management plants and/or managing authorities/ministries take to improve use of RDF?

The current report can only point at typical areas of focus. Relevant parties should therefore explore case-by-case the plant/regional/national-specific possibilities and constraints and advance options for RDF long-term use. Typically, financial and environmental benefits should be expected from other RDF use than landfilling.

8 Annexes

8.1 SRF standards and other national quality requirements

8.1.1 Other relevant CEN standards, technical specifications, and reports

The following list provides an overview of the work of the CEN/TC 343 on SRF as downloaded from the CEN/CENELEC website (https://standards.cencenelec.eu/).

Table 9: List of relevant CEN standards, technical specifications, and reports published under the CEN/TC 343 work programme

Reference	Title	Status
prEN ISO 4349	Solid recovered fuels – Determination of the Recycling Index for co-processing (ISO/DIS 4349:2023)	Under approval
prEN ISO 3884	Solid recovered fuels – Methods for the determination of the content of elements (Al, Ca, Fe, K, Mg, Na, P, S, Si, Ti, As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Sn, Tl, V, Zn)	Being drafted
prEN ISO 18708	Solid recovered fuels – Determination of bulk density	Being drafted
EN ISO 22940:2021	Solid recovered fuels – Determination of elemental composition by X-ray fluorescence (ISO 22940:2021)	Published
EN ISO 22167:2021	Solid recovered fuels – Determination of content of volatile matter (ISO 22167:2021)	Published
EN ISO 21912:2021	Solid recovered fuels – Safe handling and storage of solid recovered fuels (ISO 21912:2021)	Published
EN ISO 21911-1:2023	Solid recovered fuels – Determination of self-heating – Part 1: Isothermal calorimetry (ISO 21911-1:2022)	Published
EN ISO 21663:2020	Solid recovered fuels – Methods for the determination of carbon I, hydrogen (H), nitrogen (N), and sulphur (S) by the instrumental method (ISO 21663:2020)	Published
EN ISO 21660-3:2021	Solid recovered fuels – Determination of moisture content using the oven dry method – Part 3: Moisture in general analysis sample (ISO 21660-3:2021)	Published
EN ISO 21656:2021	Solid recovered fuels – Determination of ash content (ISO 21656:2021)	Published
EN ISO 21654:2021	Solid recovered fuels – Determination of calorific value (ISO 21654:2021)	Published
EN ISO 21646:2022	Solid recovered fuels – Sample preparation (ISO 21646:2022)	Published
EN ISO 21645:2021	Solid recovered fuels – Methods for sampling (ISO 21645:2021)	Published

Reference	Title	Status
EN ISO 21644:2021	Solid recovered fuels – Methods for the determination of biomass content (ISO 21644:2021, Corrected version 2021-03)	Published
EN ISO 21640:2021	Solid recovered fuels – Specifications and classes (ISO 21640:2021)	Published
EN ISO 21637:2020	Solid recovered fuels – Vocabulary (ISO 21637:2020)	Published
EN 15590:2011	Solid recovered fuels – Determination of the current rate of aerobic microbial activity using the real dynamic respiration index	Published
EN 15415-3:2012	Solid recovered fuels – Determination of particle size distribution – Part 3: Method by image analysis for large dimension particles	Published
EN 15415-2:2012	Solid recovered fuels – Determination of particle size distribution – Part 2: Maximum projected length method (manual) for large dimension particles	Published
EN 15415-1:2011	Solid recovered fuels – Determination of particle size distribution – Part 1: Screen method for small dimension particles	Published
EN 15411:2011	Solid recovered fuels – Methods for the determination of the content of trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Tl, V, and Zn)	Published
EN 15410:2011	Solid recovered fuels – Methods for the determination of the content of major elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti)	Published
EN 15408:2011	Solid recovered fuels – Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F), and bromine (Br) content	Published
EN 15358:2011	Solid recovered fuels – Quality-management systems – Particular requirements for their application to the production of solid recovered fuels	Published
CEN/TS 15639:2010	Solid recovered fuels – Determination of mechanical durability of pellets	Published
CEN/TS 15414-2:2010	Solid recovered fuels – Determination of moisture content using the oven dry method – Part 2: Determination of total moisture content by a simplified method	Published
CEN/TS 15414-1:2010	Solid recovered fuels – Determination of moisture content using the oven dry method – Part 1: Determination of total moisture by a reference method	Published
CEN/TS 15412:2010	Solid recovered fuels – Methods for the determination of metallic aluminium	Published
CEN/TS 15406:2010	Solid recovered fuels – Determination of bridging properties of bulk material	Published

Reference	Title	Status
CEN/TS 15405:2010	Solid recovered fuels – Determination of density of pellets and briquettes	Published
CEN/TS 15401:2010	Solid recovered fuels – Determination of bulk density	Published
CEN/TR 15716:2008	Solid recovered fuels – Determination of combustion behaviour	Published
CEN/TR 15591:2007	Solid recovered fuels – Determination of the biomass content based on the ^{14}C method	Published
CEN/TR 15508:2006	Key properties on solid recovered fuels to be used for establishing a classification system	Published
CEN/TR 15441:2006	Solid recovered fuels – Guidelines on occupational health aspects	Published
CEN/TR 15404:2010	Solid recovered fuels – Methods for the determination of ash melting behaviour by using characteristic temperatures	Published
CEN/TR 14980:2004	Solid recovered fuels – Report on relative difference between biodegradable and biogenic fractions of SRF	Published
CEN ISO/TS 21911-2:2022	Solid recovered fuels – Determination of self-heating – Part 2: Basket heating tests (ISO/TS 21911-2:2022)	Published

8.1.2 EN ISO 21640:2021: Template for the specification

For each characteristic specified in Table 1, the compliance of a particular SRF is established by demonstrating that the results for the properties measured conform to the limit values defined for that class. Compliance is based on samples taken across a lot[41] of a maximum of 1 500 tonnes of SRF according to ISO 21645[42] and the subsequent statistical assessment of the laboratory test results.

EN ISO 21640 prescribes that SRF shall be specified according to the template presented below. The specification contains the mandatory characteristics (NCV and chlorine and mercury content), as well as voluntary physical and chemical parameters such as particle size, moisture, trace elements, and ash content.

According to EN ISO 21640, Annex A shall be used to specify SRF.

Template for the specification of solid recovered fuels

Class code and origin	
Class code:	
Origin: According to 7.2 and Table 1	
Physical parameters	
Traded Form:	
Particle size d_{95}(mm)	

Main fraction ᵇ (minimum 95 % in mass), mm							
☐ P8	$d_{95} \leq 8$ mm	☐ P12	$d_{95} \leq 12$ mm	☐ P25	$d_{95} \leq 25$ mm	☐ P50	$d_{95} \leq 50$ mm
☐ P90	$d_{95} \leq 90$ mm	☐ P140	$d_{95} \leq 140$ mm	☐ P200	$d_{95} \leq 200$ mm	☐ P300	$d_{95} \leq 300$ mm
☐ P500	$d_{95} \leq 500$ mm	☐ P1000	$d_{95} \leq 1000$ mm	☐ P1500+	$d_{95} > 1500$ mm		

		Typical value (mean)	**Limit value**		
			Min	Max	80th percentile
Ash Content, A ISO 21656	(% in mass (d))				
Moisture, M CEN/TS 15414-1, CEN/TS 15414-2, ISO 21660-3	(% in mass (ar))				
Net calorific value, NCV ISO 21654	(MJ/kg (ar))				
	(MJ/kg (d))				

Chemical properties					
	Standard method used		**Typical value (mean)**	**Limit value**	
				Max	80th percentile
Chlorine, Cl		(% in mass (d))			
			Typical value (median)	**Limit value**	
				Max	80th percentile
Antimony, Sb		(mg/kg (d))			
Arsenic, As		(mg/kg (d))			
Cadmium, Cd		(mg/kg (d))			
Chromium, Cr		(mg/kg (d))			
Cobalt, Co		(mg/kg (d))			
Copper, Cu		(mg/kg (d))			
Lead, Pb		(mg/kg (d))			
Manganese, Mn		(mg/kg (d))			
Mercury, Hg		(mg/MJ (d))			
Nickel, Ni		(mg/kg (d))			
Thallium, Tl		(mg/kg (d))			
Tin, Sn		(mg/kg (d))			
Vanadium, V		(mg/kg (d))			

White fields are normative while blue shaded fields are informative.

8.1.3 Other national quality classifications

For certain classes of SRF, MSs may have additional quality requirements. This is the case, for example, in Austria, France, Germany, and Italy.

- **Germany:** The "Bundesgütegemeinschaft Sekundärbrennstoffe e.V." sets additional quality requirements for SRF and establishes a quality label. The provisions are laid down in the "RAL GZ 724," which provides guidelines for an SRF quality control system and defines the rules for sampling and testing of SRF at the production site. These rules are in line with the European standard CEN/TC 343. The RAL defines threshold values for a range of 16 trace elements (that is, Cd, Hg, Tl, As, Co, Ni, Se, Te, Sb, Pb, Cr, Cu, Mn, V, Sn, Be). It does not prescribe limit values for chlorine content or NCV.[43]

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[41] A lot is a defined quantity of material (in this case, SRF) for which the quality is to be determined.

[42] ISO 21645:2021 – Solid recovered fuels — Methods for sampling.

[43] Solid recovered fuels – quality assurance RAL-GZ 724. German Institute for Quality Assurance and Certification. Edition June 2001.

- **Austria:** The national ordinance on waste incineration ("Abfallverbrennungsverordnung")[44] specifies limit values for secondary fuels ("Ersatzbrennstoffe"), which are used in co-incineration facilities such as cement factories and power stations. The ordinance only sets limit values for eight trace elements (that is, Sb, As, Pb, Cd, Cr, Co, Ni, Hg) and does not prescribe thresholds for chlorine content or NCV. The ordinance specifies the sampling procedures for secondary fuels and the frequencies at which they are to be sampled. If an SRF complies with the legally set mandatory requirements, then it can be declared End of Waste (EoW).
- **Italy:** Decree no. 22/2013 sets out a regulatory definition for RDF. Standardised RDF is named "CSS – Combustibile Solide Secondari." The decree includes the possibility that the waste status of RDF can be removed under specific preconditions. RDF must be produced either in EMAS-certified[45] waste treatment facilities or according to the quality control procedures that are laid down in the European standard EN 15359 (now EN ISO 21640). Threshold values are defined for 11 trace elements (Sb, As, Cd, Cr, Co, Mn, Ni, Pb, Cu, Tl, V). Decree no. 22/2013 introduces the possibility of declaring RDF EoW if the RDF complies with legally set mandatory requirements. This concerns SRF classes 1, 2, and 3 with respect to chlorine content and NCV and SRF classes 1 and 2 with respect to mercury content.[46]
- **France:** SRF is defined in article R. 541-8-1 of the national environmental code,[47] which prescribes that RDF is made from non-hazardous waste in authorised facilities. Compared to the European standard, the French definition of Combustible Solide de Récupération (CSR) enhances the set of required parameters and thresholds in the following respects:
  - by applying the principle of waste hierarchy
  - by stipulating a NCV above 12 MJ/kg
  - by making characterisation of certain chemical properties that are voluntary in the European standard mandatory
  - by setting limit values for Hg and for halogens (Cl, Br, I, F)

The preceding definitions of SRF as well as the standard EN ISO 21640 do not necessarily imply that SRF is always of better quality than RDF. However, the quality of SRF is known and defined according to a standard.[48] Even though SRF must comply with a certain standard, industrial consumers cannot use all types of SRF or RDF. The technical possibilities and constraints are explained in Section 2.4.

[44] Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft und des Bundesministers für Wirtschaft, Familie und Jugend über die Verbrennung von Abfällen (Abfallverbrennungsverordnung – AVV). https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20002239

[45] EMAS = eco management and audit scheme.

[46] RECORD, Utilisation des CSR et des RDF en Europe. Synthèse bibliographique et situations administratives rencontrées sur le terrain, 2018, 393 p, n°16-0250/1A.

[47] Légifrance – le service public de la diffusion du droit. Code de l'environnement, Partie réglementaire (Articles R121-1 à R714-2): Article R541-8-1. https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000032554270

[48] Martignon, G.P. (2020). Trends in the use of solid recovered fuels. IEA Bioenergy.

8.2 Types of waste considered suitable for RDF production in Germany

List of types of waste considered suitable for the production of RDF in Germany, taken from Solid Recovered Fuels – Quality Assurance RAL-GZ 724, German Institute for Quality Assurance and Certification (June 2001). The waste codes follow the European Waste Catalogue.

Table 10: List of types of waste considered suitable for the production of RDF in Germany – Group 1

Group 1 – wood, paper, cardboard		
Waste code	**Description**	**Origin**
02 01 03	plant tissue waste	primary production waste
02 01 07	waste from forestry exploitation	primary production waste
03 01 01	waste bark and cork	waste from wood processing and the production of panels and furniture
03 01 02	sawdust	waste from wood processing and the production of panels and furniture
03 01 03	shavings, cuttings, spoiled timber/particle board/veneer	waste from wood processing and the production of panels and furniture
03 03 01	bark	waste from pulp, paper, and cardboard production and processing
03 03 02	dregs and green liquor sludge (from black liquor treatment)	waste from pulp, paper, and cardboard production and processing
03 03 06	fibre and paper sludge	waste from pulp, paper, and cardboard production and processing
03 03 07	rejects from paper and cardboard recycling	waste from pulp, paper, and cardboard production and processing
15 01 01	paper and cardboard	packaging
15 01 03	wooden	packaging
17 02 01	wood	(construction and demolition waste) wood, glass, and plastic
20 01 01	paper and cardboard	(municipal waste) separately collected fractions
20 01 07	wood	(municipal waste) separately collected fractions

Table 11: List of types of wastes considered suitable for the production of RDF in Germany – Group 2

Group 2 – textiles, fibres		
Waste code	**Description**	**Origin**
04 02 01	waste from unprocessed textile fibres and other natural fibrous substances mainly of vegetable origin	waste from the textile industry
04 02 02	waste from unprocessed textile fibres mainly of animal origin	waste from the textile industry
04 02 03	waste from unprocessed textile fibres mainly artificial or synthetic	waste from the textile industry
04 02 04	waste from unprocessed mixed textile fibres before spinning and weaving	waste from the textile industry
04 02 05	waste from processed textile fibres mainly of vegetable origin	waste from the textile industry
04 02 06	waste from processed textile fibres mainly of animal origin	waste from the textile industry
04 02 07	waste from processed textile fibres mainly of artificial or synthetic origin	waste from the textile industry
04 02 08	waste from processed mixed textile fibres	waste from the textile industry
04 02 09	waste from composite materials (impregnated textile, elastomer, plastomer)	waste from the textile industry
04 02 10	organic matter from natural products (for example, grease, wax)	waste from the textile industry
04 02 12	non-halogenated waste from dressing and finishing	waste from the textile industry
20 01 10	clothes	(municipal wastes) separately collected fractions
20 01 11	textiles	(municipal wastes) separately collected fractions

Table 12: List of types of waste considered suitable for the production of RDF in Germany – Group 3

Group 3 – plastics		
Waste code	**Description**	**Origin**
02 01 04	waste plastics (excluding packaging)	primary production waste
08 03 09	waste printing toner (including cartridges)	waste from manufacture, formulation, supply and use of printing inks
12 01 05	plastic particles	wastes from shaping
12 01 13	welding wastes (1)	wastes from shaping
15 01 02	plastic	packaging
15 01 05	composite packaging	packaging
15 01 06	mixed materials	packaging
16 02 07	waste from the plastic convertor industry	discarded equipment and shredder residues
17 02 03	plastic	(construction and demolition waste) wood, glass, and plastic
17 06 02	other insulation materials	(construction and demolition waste) insulation materials
20 01 03	small plastics	(municipal wastes) separately collected fractions
20 01 06	other metals/other plastics	(municipal wastes) separately collected fractions

Table 13: List of types of waste considered suitable for the production of RDF in Germany – Group 4

Group 4 – other materials		
Waste code	**Description**	**Origin**
08 01 03	waste from water-based paints and varnishes	waste from the manufacture, formulation, supply and use (MFSU) of paint and varnish
08 01 04	powder paints	waste from MFSU of paint and varnish
08 01 05	hardened paints and varnishes	waste from MFSU of paint and varnish
08 01 09	waste from paint or varnish removal (except 08 01 05 and 08 01 06)	waste from MFSU of paint and varnish
08 03 03	waste from water-based ink	waste from MFSU of printing inks
08 03 04	dried ink	waste from MFSU of printing inks
08 04 03	wastes from water-based adhesives and sealants	waste from MFSU of adhesives and sealants (including waterproofing products)
08 04 04	hardened adhesives and sealants	waste from MFSU of adhesives and sealants (including waterproofing products)
09 01 07	photographic film and paper containing silver or silver compounds	waste from the photographic industry
09 01 08	photographic film and paper free of silver or silver compounds	waste from the photographic industry
09 01 10	single use cameras without batteries	waste from the photographic industry
15 02 01	absorbents, filter materials, wiping cloths, protective clothing	absorbents, filter materials, wiping cloths, and protective clothing
16 03 02	organic off-specification batches	off-specification batches
19 09 04	spent activated carbon	waste from the preparation of drinking water or water for industrial use
19 09 05	saturated or spent ion exchange resins	waste from the preparation of drinking water or water for industrial use

8.3 Potential end users of RDF

8.3.1 Cement

The EU-27 cement industry produced around 182.5 million tonnes of cement in 2021.[49] The main component of cement is clinker, which accounts for about 73.7%[50] of production in the cement industry. Clinker is produced in rotary kilns at temperatures of ~1 450° C.[51] Its production requires large quantities of thermal energy. In addition to fossil fuels such as coal or fuel oil, RDF may also be used as a source of energy. According to the European Cement Association (CEMBUREAU), so-called "circular waste fuels"[49] provided 52% of the thermal energy in 2020 and within the "circular waste fuels," the share of RDF was 45%. In terms of weight, fuels from waste accounted for 12.1 million tonnes. This sector has been estimated to have the potential to replace up to 60% of its traditional fuels (that is, coal) with RDF in the medium term.[52]

RDF corresponding to SRF classes 4 and 5 (Table 1) does not provide sufficient calorific power for the burning process. Moreover, the high chlorine content has deleterious effects on kiln operation. Class 3 with medium calorific power may be suitable for cement plants that are equipped with calciner technology. The "VDZ-Merkblatt" provides an overview of this technology.[53] Classes 1 and 2 provide sufficient calorific value for kiln burner firing.

8.3.2 Lime

Limestone is the raw material for a large range of lime-containing products. Quicklime is a key product that is produced by heating limestone in a kiln at temperatures above 1 000° C. Various technologies, such as annular shaft kilns (ASK), parallel flow regenerative kilns (PFRK), mixed feed shaft kilns (MFSK), rotary kilns (RK), and other kilns, are used to produce quicklime.[54] According to the latest report from the European Lime Association (EuLA),[55] 19.66 million tonnes of quicklime were produced in 2018.[56]

Traditionally, gaseous, liquid, and solid fossil fuels that are low in ash and sulphur and high in calorific value are utilised in lime kilns. RDF is used in some lime plants, but to a far lesser extent than in cement facilities. Since fuels influence the product quality, only a small range of fuels can be used. In contrast to the cement sector (see above), information on the utilisation of RDF in the lime sector is only sparsely available, for instance:

- In 2022, a lime factory in the north of France used around seven tonnes of pelletised RDF per day in one of its 12 annular shaft kilns. In this kiln, the TSR was roughly 20%.[57] The annual consumption was about 2 300 tonnes of RDF (class 1, see Table 1).
- In 2022, another lime factory in the north of France covered approximately 23–27% of the thermal heat in the rotary kiln with fluff RDF[58] (class 1, see Table 1).

These examples only refer to two individual kilns. The overall TSR in the lime industry, however, is quite low. A sustainability report published by one of the biggest European lime manufacturers[59] may serve as an indicator to corroborate this statement. According to this report, alternative fuels, that is, biomass and waste-derived fuels (without specifying the types), accounted for 2.1% of the thermal heat demand to produce 9 million tonnes of lime and lime-related products across the company's manufacturing sites in Europe and the United States in 2022.

Another big lime manufacturer stated that 6% of its fuel mix for lime and dolomitic lime production was covered by "recycled" fuel in 2021.[60] Recycled fuel consists of recycled waste streams from manufacturing industries,

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49 CEMBUREAU's key facts & figures, 2021. https://cembureau.eu/media/lfqjyve5/key-facts-figures-2021.pdf

50 CEMBUREAU – The European Cement Association: clinker substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/

51 Verein Deutscher Zementwerke e.V. (VDZ). (2008). Zement-Taschenbuch. 51. Düsseldorf: Verlag Bau+Technik GmbH.

52 CEMBUREAU – The European Cement Association. Waste-to-energy. https://www.cembureau.eu/policy-focus/environment/waste-to-energy/

53 Verein Deutscher Zementwerke e.V. (2005). Betriebsverhalten von Vorcalcinieranlagen. VDZ-Merkblatt Vt 14. Düsseldorf.

54 Oates, J.A.H. (1998). *Lime and Limestone. Chemistry and Technology, Production and Uses*. Weinheim: Wiley-VCH.

55 The European Lime Association EuLA. *2019-2020 Activity Report*. Brussels, Belgium.

56 This number has been reported by EuLA members for membership purposes. The EuLA membership represents about 95% of the European non-captive lime production.

57 Authors' expert knowledge.

58 Authors' expert knowledge.

59 Carmeuse Group, Belgium. (2023). Carmeuse – Sustainability – State of Play 2023.

60 Lhoist Group, Belgium. (2021). Lhoist – Sustainability 2021.

including certain plastics, paper, rubber, and textiles. The lime group has used recycled fuels for years in several countries, including France and the United Kingdom, most notably in rotary kilns.[61] This "recycled" fuel is, in fact, RDF. The low waste input (~8%) is also confirmed by the Technical Report of the European Lime Association from 2014.[62]

Usually, only class 1 and class 2 RDF are suitable for firing lime kilns (see Table 1).

8.3.3 Waste-to-energy

Waste-to-energy (WtE) plants burn, among others, household and similar waste that could not be prevented or recycled. WtE recovers energy in the form of steam for industrial purposes, electricity for the grid, and/or hot water for heating nearby districts (co-generation).[63] WtE is widely used in various industrial subsectors, including waste incineration and the pulp and paper industry.

8.3.3.1 Waste incineration

In 2020, there were 402 WtE plants across the EU-27 that treated 80.9 million tonnes of waste[64]. The most common combustion technologies for the treatment of MW are the moving grate furnace and the fluidised bed furnace.[65] In Europe, about 95% of WtE facilities operate grate furnaces, while around 5% operate fluidised bed furnaces.[66] Grate furnaces enable the immediate combustion of MW without the need for preparation steps such as shredding. In contrast, fluidised bed furnaces require certain pre-treatments of the waste.

Usually, classes 3, 4, and 5 are suitable (Table 1).

8.3.3.2 Pulp and paper

Europe accounts for about 24% of world pulp production, with more than 60% of European production taking place just in Sweden and Finland. A total of 26% of world paper/board production takes place in Europe, led by Germany (25%), Finland and Sweden (11% each), and Italy (10%).[67] According to the latest report by the Confederation of European Paper Industries (CEPI) in 2022, there are 861 paper mills in Europe, producing 35.2 million tonnes of pulp and 85 million tonnes of paper and board.

There are several types of paper mills: non-integrated mills produce only pulp, without running a paper machine. Integrated mills produce pulp and paper in the same plant. Paper factories require steam for papermaking and the drying of pulp. Steam is produced in a broad range of boilers. Package boilers are typically fuelled by natural gas or oil. Powerhouse boilers are similar to WtE (grate furnaces, fluidised bed) and are fuelled by a broad range of fuels such as coal, wood waste, black liquor, oil, natural gas, sludge and rejects from the paper process, and RDF.

According to the latest report by CEPI, fuel consumption in the European paper industry was 1.2 million tonnes in 2021.[68,69] The major fuel in 2021 was biomass (60.6%), followed by gas (32.8%), coal (2.6%), "others" (2%), 1.4% fuel oil, and 0.6% "other fossil fuels." No information about which types of "others" or "other fossil fuels" were used is given.

However, according to the authors' experience, many paper facilities use their own reject material to fire the boilers. Some also use dewatered sludge (bio sludge, deinking sludge) from their own water treatment facilities. Several paper mills co-fire RDF to supply the thermal energy needed for their operations. Furnaces require NCVs in the range of approx. 12–17 MJ per kg of RDF, which corresponds to class 3 and 4 (Table 1).

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61 Lhoist Group, Belgium. (2021). Lhoist – Carbon Action 2030, Version 2021.

62 M. Stork et al. (2014). *A Competitive and Efficient Lime Industry, Cornerstone for a Sustainable Europe.* The European Lime Association (EuLA).https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Summary_0.pdf

63 Confederation of European Waste-to-Energy Plants (CEWEP). What is Waste-to-Energy? https://www.cewep.eu/what-is-waste-to-energy/

64 Confederation of European Waste-to-Energy Plants (CEWEP). Waste-to-Energy Plants in Europe in 2020. https://www.cewep.eu/waste-to-energy-plants-in-europe-in-2020/

65 Utilitalia: Water Environment Energy. (2020). White paper on municipal waste incineration. Part I - Technical and environmental impact aspects; Part II - Epidemiological surveys conducted in Italy and abroad in areas affected by the presence of incinerators and publications on the subject in scientific journals: annotated review.

66 Leckner, B., & Lind, F. (2020). Combustion of municipal waste in fluidized bed or on grate – A comparison. *Waste Management*, 109, 94–108.

67 EU Merci Project. (n.d.). Fact sheet on energy efficiency in the European industry: Pulp & paper sector.

68 Confederation of European Paper Industries (CEPI). (2022). Key statistics 2022 – European pulp & paper industry.

69 CEPI represents 91% of the European (excluding the Russian Federation) pulp and paper industry in terms of production.

8.3.3.3 Chemical industry

The chemical sector encompasses the manufacture of chemicals and chemical products. These are terms for a broad range of subsectors, such as pharmaceutical products and preparations, fertilisers, petrochemicals, and basic inorganic chemicals. In 2021, the total energy consumption by the EU chemical industry (manufacturing of chemicals, chemical products, and pharmaceuticals) was 1 988 PJ. Gas and electricity were the predominant sources of energy, accounting for 35.9% and 28.2% of total energy sources, respectively. The remaining sources were oil and petroleum-based fuels (13.6%), heat (15.4%), solid fossil fuels (5.5%), renewables and biofuels such as wind, solar, geothermal, biogas, biodiesel, and some others (0.7%), and 0.8% non-renewable waste.[70] The latter is defined as "non-renewable municipal waste."[71] This category may refer to WtE plants, which provide steam and/or electricity for chemical processes. For example, a WtE facility located within a big chemical park provides 70 MW of electrical power to the chemical plant. In 2022, this facility incinerated 379 258 tonnes of RDF with an average NCV of 13.4 MJ/kg (the NCV ranged between 10 and 23 MJ/kg).[72] This corresponds to RDF of class 3 and 4 (Table 1). Moreover, the chemical industry puts efforts into emerging techniques for the chemical recycling of waste plastics in gasification and pyrolysis processes. These emerging techniques are explained in Section 8.15.

8.3.4 Coal-fired power plants

Coal has historically been one of the main fuels of the European economy. According to the latest information available from the Joint Research Centre,[73] in 2016, there were 207 coal-fired power plants operating in 21 MSs. Eurostat reports that 86 million tonnes of hard coal were delivered to power plants in the EU producing electricity and heat in 2021. For brown coal, this amount was 256 million tonnes.[74] Various furnace technologies are in operation, such as fluidised bed, pulverised coal firing, and grate firing.[75]

Data on the use of RDF in coal-fired power plants is scarce. Co-firing of RDF at levels of 5–10% of thermal energy input has been demonstrated in Italy.[76] However, no information about the class or calorific value of RDF used is available. According to a 2018 research report,[77] German coal-fired power plants used 671 600 tonnes of RDF, corresponding to 11.4 PJ, or a NCV of about 17 GJ/t. This corresponds to class 3 (Table 1). In 2019, 560 000 tonnes of RDF was co-fired in German coal power plants.[78] A German lignite power plant has been using RDF since 2005 – its capacity is about 400 000 t/y.[79] RDF corresponding to classes 2, 3, and 4 (Table 1) is required for co-firing.

8.3.5 Metal industries

8.3.5.1 Steel

In 2021, the iron and steel sector accounted for 10.2% of energy consumption by industry within the European Union.[80] Steel is produced at 500 sites across the European Union, ranging from primary and secondary to downstream final production. The key product is crude steel or pig iron, from which a plethora of steel types is being manufactured. In 2021, European steel factories produced 152.6 million tonnes of crude steel.[81] In Europe

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70 Eurostat. Final energy consumption in industry – detailed statistics – Energy products used in the industry sector. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Energy_products_used_in_the_industry_sector

71 Eurostat. Energy data formulas for energy balances. https://ec.europa.eu/eurostat/documents/38154/4956218/Energy-Balance-Formulas.xlsx/cc2f9ade-5c0b-47b5-b83d-c05fe86eef6c

72 Thermal Conversion Compound Industriepark Höchst GmbH. (2023). Umwelterklärung 2023.

73 Alves Dias, P. et al. (2018). EU coal regions: opportunities and challenges ahead, EUR 29292 EN. Luxembourg: Publications Office of the European Union. doi:10.2760/064809, JRC112593.

74 Eurostat: Coal production and consumption statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Coal_production_and_consumption_statistics#Consumption_and_production_of_brown_coal

75 Lecomte, T. et al. (2017). Best Available Techniques (BAT) reference document for large combustion plants, EUR 28836 EN. Seville, Spain: European Commission Joint Research Centre. doi:10.2760/949.

76 Gasperetti, S. (2013). ENEL experience on refuse derived fuel co-combustion in a coal fired power plant. Workshop in Milan.

77 Flamme, S., Hanewinkel, J., Quicker, P., & Weber, K. (2018). Energieerzeugung aus Abfällen – Stand und Potenziale in Deutschland bis 2030. Dessau-Roßlau: Umweltbundesamt.

78 Flamme, S., & Hams, S. (2021). Perspektiven der Mitverbrennung von gütegesicherten Sekundärbrennstoffen nach dem Kohleausstieg. In: K. Wiemer, M. Kern, & T. Raussen (eds), Bioabfall- und stoffspezifische Verwertung III. Witzenhausen-Institut – Neues aus Forschung und Praxis. 301–310.

79 Geisler, A. Umwelt- und bedarfsgerecht – die EVA Jänschwalde. LEAG. 11.11.2020. https://www.leag.de/de/seitenblickblog/artikel/umwelt-und-bedarfsgerecht-die-eva-jaenschwalde/

80 Eurostat: Final energy consumption in industry – detailed statistics – Energy products used in the industry sector. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Energy_products_used_in_the_industry_sector

81 The European Steel Association EUROFER. (2022). European Steel in Figures 2022 – Data covering 2021.

steel is produced via two basic routes: the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace (EAF) route. BF-BOF accounts for 56.4% and EAF accounts for 43.6% of steel production.[82] While EAF operates with electrical energy, the blast furnace requires carbon-based materials to reduce the iron ore to pig iron. Although it burns with less air, the carbon in the coke transforms into carbon monoxide (CO). This CO reduces the iron oxide in the ore to metallic iron. Oil and plastics may act as alternative raw materials for coal or coke in a blast furnace, because under reducing burning conditions, the hydrocarbons of the plastics form CO as well as hydrogen. The basic chemical equations are as follows:[83]

$$C + O_2 \rightarrow CO_2 \text{ (coal, coke)}$$

$$C + CO_2 \rightarrow 2CO \text{ (coal, coke)}$$

$$\frac{1}{2}C_2H_4 + CO_2 \rightarrow 2\,CO + H_2 \quad \text{(hydrocarbons such as oil, plastics)}$$

$$Fe_2O_3 + 3CO \rightarrow 2\,Fe + 3CO_2 \text{ (reduction of iron ore with coke, pulverised coal)}$$

$$Fe_2O_3 + 2CO + H_2 \rightarrow 2\,Fe + 2CO_2 + H_2O \quad \text{(reduction of iron ore with hydrocarbons such as oil, plastics)}$$

The chemical reduction of iron ore is the predominant process in a blast furnace, rather than the mere combustion of carbon-based materials. This is the reason why the materials are called reducing agents.

The use of waste plastics in blast furnaces is well known. For many years, an Austrian-based steel manufacturer has been using around 220 000 tonnes of pelletised waste plastics annually.[84,85] This pelletised waste plastic is considered an alternative reducing agent to RDF. Nonetheless, coal-based materials and waste plastics also supply thermal energy to maintain the high temperatures of about 1 500° C in the blast furnace. The quality requirements for waste plastics are high: the minimum NCV must be 33 MJ/kg,[86] corresponding with class 1 (see Table 1).

8.3.5.2 Non-ferrous metals

This sector covers a broad range of light and heavy metals and their alloys, such as aluminium, copper, lead, tin, zinc, nickel, cobalt, precious metals (silver, gold), and ferro-alloys. According to latest data from the European Association of Metals (Eurometaux), Europe's non-ferrous metals industry produces 47 million tonnes of metals annually. In 2021, the total energy consumption of this sector amounted to 389.4 PJ, accounting for 3.87% of the EU's industrial energy consumption. No information about the amount of RDF used in the sector is available.

8.3.6 Other industries

The following industrial sectors are also energy-intensive industries. However, there is no information available about the use of RDF in these sectors.

Food and Beverage: The Food and Beverage (F&B) industry is the EU's biggest manufacturing sector in terms of jobs. As the sector is very diverse, it uses a large variety of processes. This sector accounts for 11.6% of EU industry energy consumption.[87] In terms of overall energy consumption, the key categories in food processing are process heat (29% of energy use) and refrigeration (16%). The main fuels used in boilers are fossil fuels, biomass, by-products from F&B, animal fat, and liquified petroleum gas (LPG).[88] No information is available about which types and volumes of waste fuels are used.

Ceramics: All sectors of the ceramics industry are energy intensive, as a key part of the process involves drying followed by firing to temperatures of between 800° C and 2 000° C. Natural gas, LPG, and fuel oil are mainly used

82 Ibid.

83 Ogaki, Y. Tomioka, K., Watanabe, A., Arita, K., Kuriyama, I., & Sugayoshi, T. (2001). Recycling of waste plastic packaging in a blast furnace system. NKK Technical Review, 84 1–7.

84 Voestalpine – Ersatzreduktionsmittel. https://www.voestalpine.com/stahl/Produkte/Huettennebenprodukte/Ersatzreduktionsmittel

85 Kieberger, N. (2016). The blast furnace process – experiences on alternative reducing agents. 3rd Alternative Fuels Symposium organised by MVW Lechtenberg & Partner, 12–13 October 2016, Landschaftspart Duisburg-Nord, Germany.

86 Voestalpine – Materialspezifikation Altkunststoffpellets. 01.09.2018.

87 Eurostat. Final energy consumption in industry – detailed statistics – Energy products used in the industry sector. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Energy_products_used_in_the_industry_sector

88 EU Merci Project (n.d.), Fact sheet on energy efficiency in the European industry: Pulp & paper sector.

for firing, while heavy fuel oil, liquefied natural gas (LNG), biogas/biomass, electricity, and solid fuels (for example, coal, petroleum coke) can also play a role as energy sources for burners. The use of heavy fuel oil, coal, and petroleum coke is mainly limited to brickworks.[89]

Glass: The European Union is the world's biggest producer of glass, with a market share of around one-third of total global production.[90] The glass industry is a very energy-intensive sector. In 2021, the European glass industry consumed 250.7 PJ of energy. Natural gas is the main energy source for glass making (73.7%), followed by electricity (24%). Natural gas is essential for efficient glass making nowadays and cannot yet be completely replaced in most glass sectors. Alternative energy sources are utilized to a much lesser extent. Oil-based fuels account for 1.6%, solid fossil fuels contribute 0.1%, and heat accounts for 0.4% of the energy in this sector.[91] The share of electricity use is increasing over the years as electric firing technology improves and companies turn to greater electric input to reduce CO_2 emissions.[92]

8.4 Technical and/or economic limitations on RDF uptake

8.4.1 Cement

Economic aspects: Thermal energy for the clinker-burning process accounts for around 90% of a cement plant's total energy demand. The remaining 10% can mainly be attributed to the grinding of cement. Fuels are the major cost factor in cement manufacturing. The trend of rising fossil fuel prices is the driver for seeking substitutes. Among other alternative fuels, such as animal meal, used tyres, and sewage sludge, RDF has gained financial attractiveness over fossil fuels. In the early 2000s, several German cement plants even achieved negative fuel costs meaning that the gate fees for alternative fuels compensated for the expense of the fossil fuels.

Given the current coal prices of around $144/t,[93] the pressure to reduce fuel costs increases. Moreover, the cement manufacturing process releases a great deal of fossil-derived CO_2. Around two-thirds of the total cement industry CO_2 emissions can be attributed to the decarbonisation of the raw material (limestone), and around one-third are caused by fuels. The cement sector is included in the EU Emissions Trading System (EU-ETS).

Given the increasing prices of CO_2 certificates (currently €91/t[94]), which represent an additional cost burden for the cement industry, manufacturers have been seeking alternative fuels with lower fossil CO_2 emission factors than fossil fuels. However, the latter aspect is very challenging: the RDF biogenic content can be increased by adding biomass (for example, wood or paper) and by reducing the share of waste plastics. One drawback is that biomass reduces the NCV of RDF. For example, the NCVs of waste wood range from around 6 (for a moisture content of 60%) to 18.8 MJ/kg (for a moisture content of 0%).[95] One the one hand, wastepaper from MW has an NCV of about 10.4 MJ/kg at 27% moisture. On the other hand, waste plastics have an average NCV of 25 MJ/kg at around 20% moisture.[96] Given the high requirements for kiln burner fuel (Table 15), it is obvious that only parts of the fuel mix can be covered by biomass.

Technical aspects: Clinker is produced in long rotary kilns where ground raw material (mainly limestone and clay) is burned. The rotary kiln is equipped with a main burner. The preheater tower is located in front of the rotary kiln. In older lines, only a preheater is present while modern lines feature a calciner in the preheater tower to ease the decarbonisation of the limestone in the raw meal. The basic feeding points in a kiln line are displayed in the following figure:

[89] European Commission. (2007). Reference document on best available techniques in the ceramic manufacturing industry.
[90] European Commission. Internal market, industry, entrepreneurship and SMEs – glass. https://single-market-economy.ec.europa.eu/sectors/raw-materials/related-industries/non-metallic-products-and-industries/glass_en
[91] Eurostat. Final energy consumption in industry – detailed statistics – energy products used in the industry sector. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Final_energy_consumption_in_industry_-_detailed_statistics#Energy_products_used_in_the_industry_sector
[92] Glass Alliance Europe. (2021). The European glass sector contribution to a climate neutral economy. Position paper V.2.
[93] Trading Economics. https://tradingeconomics.com/commodities (accessed 14.08.23).
[94] Trading Economics. https://tradingeconomics.com/commodity/carbon (accessed 14.08.23).
[95] Lechtenberg, D., & Diller, H. (2012). Alternative fuels and raw materials handbook for the cement and lime industry. Volume 2. Düsseldorf: Verlag Bau+Technik GmbH.
[96] MVW Lechtenberg & Partner Database Quality-Information-System (QIS).

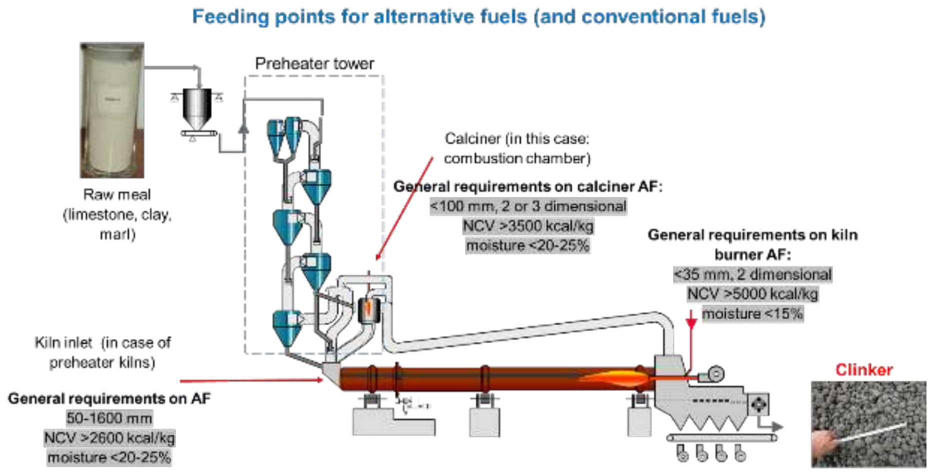

Figure 5: Typical clinker manufacturing line, highlighting the feeding points

The feeding point dictates the RDF's particle size and NCV:

- The main burner provides the high temperatures necessary to form the clinker minerals at around 1 450°C. This is the most critical step in producing clinker, and therefore RDF with a high NCV is required. To ensure rapid combustion, the particle size of the fuel must be as small as possible (Table 2).
- Compared to the main burner, calciner firing is less sensitive regarding low-calorific fuels and larger particle sizes. The temperature to be achieved must suffice to decarbonise the limestone, which takes place at roughly 950°C. Hence, the RDF may have a lower calorific value than kiln burner fuel. Since the retention time of particles in a calciner is much longer than in the main burner flame, particle sizes can be bigger.

Other issues are independent of the feeding points:

- Chlorine is the most critical chemical element in the clinker-burning process, as it can cause coating and blockages in the ducts, as well as damage to refractories.[97] It should be noted that chlorine is also present in raw materials and fuels.
- Trace elements (frequently called "heavy metals") are limited by the operating permit. From the technical point of view, most trace elements do not negatively impact the clinker quality or kiln operation, and do not have a direct impact on RDF quality. Nevertheless, they may affect the environmental performance and impact of the facility. Therefore, due to the environmental permit conditions, operators may limit or restrict RDF use when it does not meet the trace element requirements to achieve environmental performance.

It should be noted that only grey clinker plants are candidates for RDF. For quality reasons (ash contains colouring elements, particularly iron, but also manganese), white cement works cannot use RDF.

The following tables provide general requirements for RDF.

Table 14: General requirements for kiln burner RDF

Parameter	General requirements for RDF for the kiln burner
Grain size	<30 mm, two-dimensional material (2D), that is, flat and light particles
Bulk density	ca. 60–200 kg/m³
Moisture	max: 15%
Ash (dm)	<15%

97 Lechtenberg, D., & Diller, H. (2012). *Alternative Fuels and Raw Materials Handbook for the Cement and Lime Industry*. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH.

Parameter	General requirements for RDF for the kiln burner
Chlorine (dm)	depending on the chlorine input from raw materials and other fuels, in general chlorine from RDF should not exceed 0.8%
Net calorific value	at least 21 MJ/kg (at least 5 000 kcal/kg)
Class (Table 1)	at least 2

Note: dm = dry matter – Source: MVW

Requirements for calciner RDF: due to the wide range of calciner technologies, only approximate numbers are given.

Table 15: General requirements for calciner RDF

Parameter	Calciner type	General requirements for RDF for the calciner
Grain size	in-line calciner (ILC)	<50 mm, two- and three-dimensional material (2D and 3D), that is, flat and coarse particles
	combustion chamber	<50–80 mm, 2D, 3D
	Step Combustor, Pyrorotor	<300 mm, 2D, 3D
	HotDisc®	<300 mm, 2D, 3D
Moisture		Max: 25%
Ash (dm)		<20%
Chlorine (dm)		depending on chlorine input from raw materials and other fuels – in general, chlorine from RDF should not exceed 0.8%
Net calorific value		At least 14.7 MJ/kg (at least 3 500 kcal/kg)
Class (Table 1)		At least 3

Note: dm = dry matter – Source: MVW

Requirements for trace elements in RDF: RDF trace element content requirements are laid down in the cement factory's individual permits. The requirements are valid for both calciner and main burner RDF. The following table serves as an illustrative example: the numbers are valid for all alternative fuels that comply with the requirements of the environmental authorities in Germany. Such numbers have proven themselves as requirements on "fluffy" RDF, which is the "state-of-the-art" alternative fuel in German cement plants.[98,99]

Table 16: Requirements for trace elements in RDF in Germany (all classes)

Parameter	Unit	Median value	Maximum value
Cadmium (Cd)	mg/kg (dry)	4	9
Thallium (Tl)	mg/kg (dry)	1	2

98 Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen. (2000). Leitfaden zur energetischen Verwertung von Abfällen in Zement, Kalk-und Kraftwerken in Nordrhein-Westfalen. 2 Auflage.

99 German Institute for Quality Assurance and Certification. (2001). Solid recovered fuels – quality assurance RAL-GZ 724.

Parameter	Unit	Median value	Maximum value
Mercury (Hg)	mg/kg (dry)	0.6	1.2
Antimony (Sb)	mg/kg (dry)	50	120
Arsenic (As)	mg/kg (dry)	5	13
Lead (Pb)	mg/kg (dry)	70* / 190**	200
Chromium (Cr)	mg/kg (dry)	40* / 125**	120* / 250**
Cobalt (Co)	mg/kg (dry)	6	12
Copper (Cu)	mg/kg (dry)	120* / 350**	300–700#
Manganese (Mn)	mg/kg (dry)	50* / 250**	100* / 500**
Nickel (Ni)	mg/kg (dry)	25* / 80**	50* / 160**
Vanadium (V)	mg/kg (dry)	10	25
Tin (Sn)	mg/kg (dry)	30	70
Beryllium (Be)	mg/kg (dry)	0.5	2
Tellurium (Te)	mg/kg (dry)	3	5
Selenium (Se)	mg/kg (dry)	3	5

*Note: * means "solid recovered fuel from production-specific waste"; ** means "solid recovered fuel from the high-calorific fractions from MW"; # means that the values are from the "Leitfaden" (guidelines).* [100]

8.4.2 Lime

Economic aspects: The economic drivers for shifting from current fossil fuels (lignite, gas, and fuel oil) to RDF are the same as described above for cement manufacturers. Moreover, lime manufacturing releases significant amounts of CO_2. Per tonne of quicklime (CaO), around 751 kg of CO_2 come from the limestone, and about 330 kg comes from fuels.[101] As with cement, lime manufacturers will suffer from increasing prices for CO_2 emission certificates.

Technical aspects: Quicklime is produced from the calcination of natural limestone. Unlike clinker, several kiln types are employed. Quicklime is burned widely in annular shaft kilns (ASKs) and parallel flow regenerative kilns (PFRKs). Rotary kilns (RKs) and mixed feed shaft kilns (MFSKs) are employed to a lesser extent.

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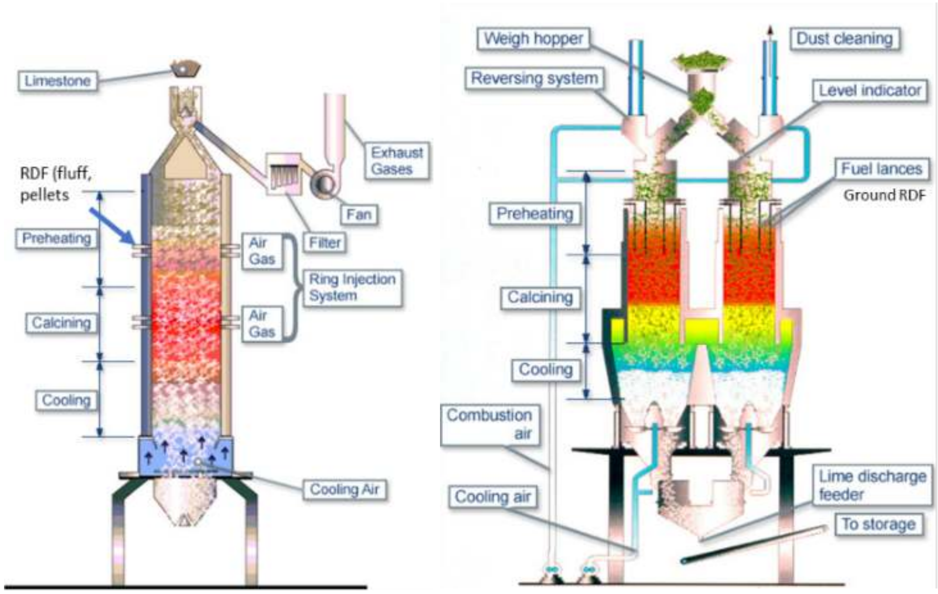
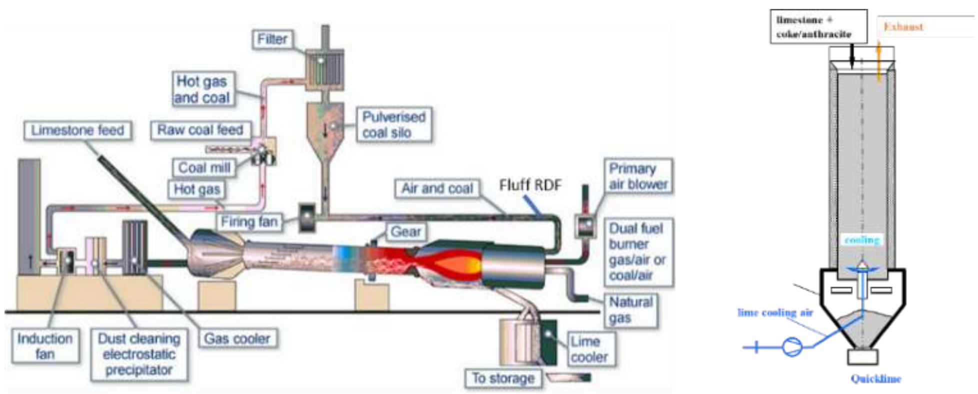
[100] Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen. (2000). *Leitfaden zur energetischen Verwertung von Abfällen in Zement, Kalk-und Kraftwerken in Nordrhein-Westfalen*. 2 Auflage.

[101] The European Lime Association EuLA. (2014). Technical report – a competitive and efficient lime industry – cornerstone for a sustainable Europe.



Source: adapted from EuLA.[102] Note: the feeding points for RDF are indicated.

Figure 6: Schematic presentations of annular shaft kiln (ASK) and parallel flow regenerative kiln (PFRK)



Sources: [103, 104]. Note: the feeding points for RDF are indicated.

Figure 7: Schematic presentations of a rotary kiln (RK) (left) and a mixed feed shaft kiln (MFSK) (right)

Like any fuel switch in lime production, the specific physical properties of the respective alternative fuel need to be considered. The selection of the appropriate alternative fuel depends on the lime product qualities desired and on the technical possibilities for injecting the fuels into the selected kiln.

Physical restrictions on fuels: Rotary lime kilns account for 7.2% of all lime kilns in Europe.[105] The main burners in lime rotary kilns have the same requirements regarding fuel as those in clinker rotary kilns. In Europe, ASKs account for 14.3% of all lime kilns. The physical requirements are for 2D material with a less than 30 mm particle size. However, the upper feeding point of the ASK can also take 3D RDF, that is, cylindrical pellets of about 8 × 6 mm. The major kiln type in Europe is the PFRK, which accounts for 39% of all kilns. Fuel is injected via lances into

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102 The European Lime Association EuLA. Kiln Types. (https://www.eula.eu/about-lime-and-applications/production/kiln-types/)

103 The European Lime Association EuLA. Kiln Types. (https://www.eula.eu/about-lime-and-applications/production/kiln-types/)

104 Ziad Habib. (2014). Kilns, combustion & fuels in the lime industry. 1st Alternative Fuels Symposium – MVW Lechtenberg & Partner, 29–30 October, 2014, Duisburg, Germany.

105 The European Lime Association EuLA. (2014). Technical report – a competitive and efficient lime industry – cornerstone for a sustainable Europe.

the kiln charge. The lances restrict the particle size to less than 2 mm, that is, pulverised fuel (coal, biomass, RDF). MFSKs account for around 18% of all kilns. These kilns are fed with a mixture of limestone and coke lumps, and they do not use RDF. There are ten other kiln types (21%), for example double-inclined shaft kilns, travelling grate kilns, and rotating hearth kilns. When solid fuels (fossil and waste-derived) are pulverised (i.e., to less than around 2 mm), they can be used in all of the above-mentioned types of kilns.[106]

Chemical restrictions on fuels: Gaseous fuels have few adverse effects on lime quality, while solid fuels generally have bigger impacts. The absorption of ashes by the quicklime causes some problems. The main components of fuel ashes (for example, silica, alumina, and iron oxide) are combined with CaO to form the respective calcium compounds that reduce the reactivity for the remaining CaO. Sulphur from fuels is absorbed by quicklime in the cooler part of the calcining zone as calcium sulphate, thus reducing the reactivity of the quicklime. Phosphorous decreases the reactive CaO by absorbing lime into calcium phosphates.[107]

Finally, each lime plant will impose its own individual restrictions on the use of any alternative fuels. This considers the lime factory's customers' requirements for quicklime or hydrated lime, as well as the restrictions laid down in the operating permit. This applies in particular to the RDF trace element contents.

The following table shows the approximate required ranges for RDF to be used in various kiln types:

Table 17: General requirements for RDF for lime kilns

Parameter	Rotary kiln (RK)	Annular shaft kiln (ASK)	Parallel flow regenerative kiln (PFRK)
Particle size	Fluff <30 mm, 2D particles	Pellets 6 × 8 mm Fluff <30 mm, 2D particles	<2 mm
Moisture	<10%	<7%	<12%
Net calorific value	>23 MJ/kg	>23 MJ/kg	>16 MJ/kg
Ash (dm)	<7%	<10%	<2%
S (dm)	<0.5%	<0.8%	<0.5%
Cl (dm)	<1%	<1%	n.a.
Class (Table 1*Note: dm = dry matter*)	at least 2	at least 2	at least 3

Note: dm = dry matter, n.a. = individual limit by the operator. Source: MVW

Burning lime requires high NCVs of above 23 MJ/kg, particularly when RDF is co-fired in RKs and ASKs. This corresponds to class 2 (see Table 1). Owing to its advantage in energy efficiency over other kiln types, and lower losses of enthalpy by exhaust gases, PFRKs can use RDF (or even 100% biomass fuels such as pulverised wood) with an NCV of more than 16 MJ/kg,[108] which corresponds to class 3 (see Table 1).

[106] European Commission. (2013). Best Available Techniques (BAT) reference document for the production of cement, lime and magnesium oxide. JRC Reference Reports.

[107] Lechtenberg, D., & Diller, H. (2012). Alternative fuels and raw materials handbook for the cement and lime industry. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH.

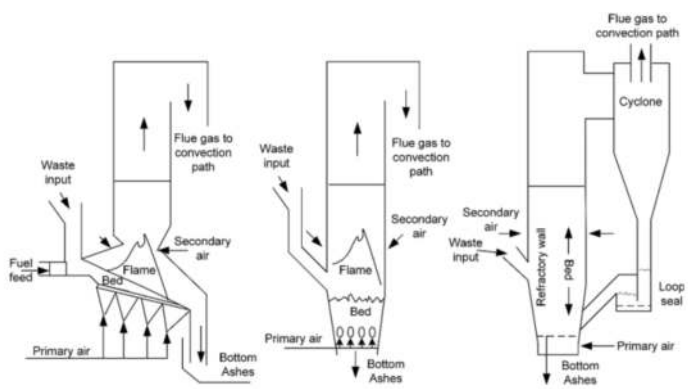
[108] Authors' expert knowledge.

8.4.3 Waste-to-energy – waste incineration, pulp and paper, chemical industry

Economic aspects: WtE is a proven technology and is considered an effective disposal system for non-recyclable waste. A WtE facility can incinerate large amounts of MW or RDF, reducing its volume and producing energy. Revenues are mostly generated by gate fees and electricity and/or heat sale. Electrical energy may account for 25% of total revenue in WtE plants in the European Union. The remainder is generated by environmental treatment fees (gate fees) and the sale of ancillary products including heat, bottom ash, and slag.[109] For instance, German waste incinerators received gate fees in the range of €65/t to €145/t of MW in 2022.[110]

Currently, MW incineration is excluded from the European Emissions Trading System. However, discussions have taken place about including waste incinerators in the ETS. Recent negotiations in the European Parliament and the Council of the European Union achieved a preliminary resolution that obliges the European Commission to issue a report by 2026 on including MW incinerators in the EU-ETS from 2028 onwards.[111] If incineration is included, waste companies will need to buy emissions credits for each tonne of CO_2 they emit when treating household and industrial waste. This additional cost of incineration can act as an incentive for waste prevention and recycling, which will then become more competitive (less costly) than incineration. The German legislation is ahead of that and pushing the national ETS. By 2024, MW incineration in German WtE plants will also be included in the carbon emissions trading system[112] (see also Section 8.16.1).

Technical aspects: Thermal waste treatment of non-hazardous waste is carried out via various types of installations, depending on the type of waste involved.[113] There are MW incineration plants and RDF power plants. Waste incineration plants were originally built for the purpose of minimising the amount of waste and destroying potential pollutants but have, by now, also become energy suppliers. RDF power plants, on the other hand, were originally built for the purpose of generating energy in the immediate vicinity of consumers,[114] for example in chemical parks or paper manufacturing plants. The combustion technologies used in RDF power plants and MW incineration plants are often identical, as grate firing (the most commonly used system for MW incineration plants) is generally used nowadays in RDF plants. Less than one-third of these plants use fluidised bed combustion systems (either bubbling or circulating fluidised bed). The following figure illustrates these technologies.



Source: [115]

Figure 8: Schematic presentation of grate furnace (left), bubbling fluidised bed (middle), and circulating fluidised bed technologies (right) in WtE facilities

The following table shows the approximate required ranges for RDF (and MW) to be used in various WtE furnaces.

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109 Asian Development Bank. (2020). *Waste to energy in the age of the circular economy: best practice handbook*.

110 EUWID – Recycling und Entsorgung. Jahrgang 33, Nr. 1/2.2023, p. 25.

111 EUWID – Recycling und Entsorgung. Jahrgang 32, Nr. 51/52.2022, p. 26.

112 Die Bundesregierung: Änderungen im Emissionshandelsgesetz – CO2-Preis für alle fossilen Brennstoffe (https://www.bundesregierung.de/breg-de/suche/co2-preis-kohle-abfallbrennstoffe-2061622).

113 Other types of incinerators – for example, for hazardous waste, sewage sludge, or biomass – are not within the scope of this elaboration.

114 Weber, K., Quicker, P., Hanewinkel, J., & Flamme, S. (2020). Status of waste-to-energy in Germany, Part I – Waste treatment facilities. *Waste Management & Research*, 38(1), S23–44.

115 Leckner, B., & Lind, F. (2020). Combustion of municipal waste in fluidized bed or on grate – A comparison. *Waste Management*, 109, 94–108.

Table 18: Approximate general requirements for RDF (and MW) in WtE

Parameter	Grate furnace RDF power plant	Grate furnace MW incinerator	Fluidised bed furnace RDF power plant
Particle size	max. 500 mm	max. 1000 × 1000 x 200 mm	max. 80 mm in 1 dimension length + width + height <250 mm
Moisture	max. 35%	not defined	max. 35%
Net calorific value	11–18 MJ/kg	at least 7.5 MJ/kg	11–20 MJ/kg
Ash (dm)	max. 30%	not defined	max. 25%
S (dm)	max. 1.2%	max. 1.2%	max. 1%
Cl (dm)	max. 2%	max. 1.7%	max. 2%
Class (Table 1)	3, 4	5	3, 4

Note: dm = dry matter (authors' experience). Classes refer to SRF classes (standardised)

These numbers are intended to serve as general guidelines. It should be noted that, from the authors' experience, it is evident that every facility has its own set of acceptance parameters and limit values that must be observed.

8.4.4 Coal-fired power plants

Economic aspects: In Europe, the standard fuels are either lignite or various qualities of hard coal. Hard coals are a world-wide traded commodity and are subject to global price developments. In Germany, lignite-fired power plants rely on their own lignite deposits, which are located close to the power plants. As a result, they are not subject to the volatility of the coal commodity market. In addition, the fuel price for pulverised lignite is significantly lower than the price for hard coal. From experience, the lignite cost is not disclosed by the operators of the power plants.[116] Co-firing RDF may be a means of reducing expenditure on coal or lignite.

Because all EU countries have either planned an end date for coal use in the power sector between now and 2040 or are considering one,[117] there has been a continuous downward trend in co-firing RDF, as observed by Flamme et al.[118] From 2016 until 2019, the volumes decreased from 0.73 million tonnes to 0.56 million tonnes, or by 23%. Flamme et al. conclude that due to the coal phase-out, the co-fired RDF volumes will fall to zero by 2038 at the latest.

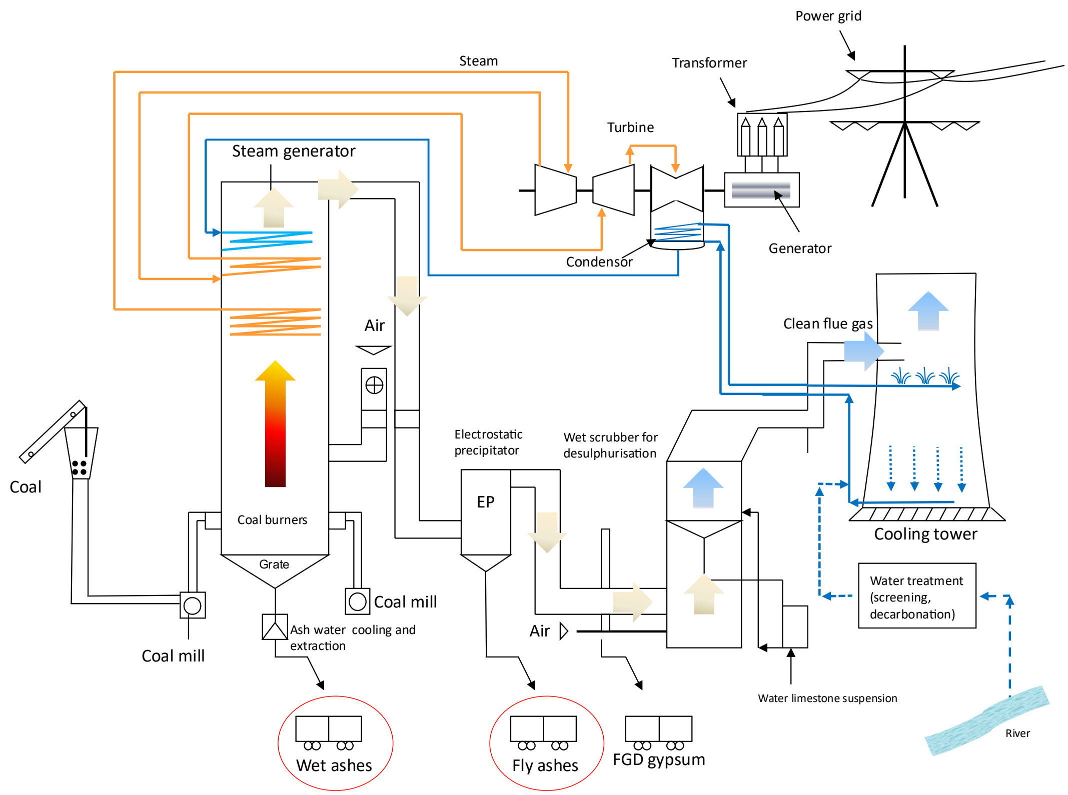
Technical aspects: In power plants, coal is combusted in dry-bottom boilers (DBB), wet-bottom boilers (WBB), or in fluidised bed combustion furnaces (FBC). Coal or lignite is subject to grinding before being injected via nozzles into the combustion chamber and burned with combustion air.[119] In Europe, the standard fuels are either lignite or hard coal. The following figure shows an example of the principle of a lignite-fired power plant with grate furnace (WBB):

[116] Sandau, F. et al., (2021). *Daten und Fakten zu Braun- und Steinkohlen. Stand und Perspektiven 2021*. Umweltbundesamt.

[117] Agora Energiewende and Enervis. (2021). *Phasing out coal in the EU's power system by 2030. A policy action plan.*

[118] Flamme, S., & Hams, S. (2021). Perspektiven der Mitverbrennung von gütegesicherten Sekundärbrennstoffen nach dem Kohleausstieg. In Wiemer, K., Kern, M., & Raussen, T. (eds.) *Bioabfall- und stoffspezifische Verwertung III*. Witzenhausen-Institut – Neues aus Forschung und Praxis, 301–310.

[119] Lecomte, T. et al. (2017). Best Available Techniques (BAT) reference document for large combustion plants. Seville, Spain: Joint Research Centre of the European Commission. EUR 28836 EN, doi:10.2760/949.



Source: [120]

Figure 9: Schematic presentation of lignite-fired power plant with grate furnace with wet-bottom boilers (WBB)

RDF is injected close to the coal burners into the furnace by means of a separate pneumatic injection system.

Coal-fired power plants impose high requirements on the RDF quality. The following table provides summarised quality data from 12 power plants according to Thiel:[121]

[120] Lechtenberg, D., & Diller, H. (2012). *Alternative fuels and raw materials handbook for the cement and lime industry*. Volume 2. Düsseldorf: Verlag Bau+Technik GmbH, 390.

[121] Thiel, S. (2006). Einsatz von Ersatzbrennstoffen aus aufbereiteten Siedlungs- und Gewerbeabfällen in Kohlekraftwerken – Stand, Erfahrungen und Problemfelder. In Thomé-Kozmiensky, K.J., & Beckmann, M. (eds), *Energie aus Abfall*, Band 1. Neuruppin, pp. 141–192.

Table 19: General requirements on co-firing RDF in hard coal and lignite power plants as specified by power plant operators

Parameter	Lignite power plants (DBB)	Lignite power plants (FBC)	Hard coal power plants (WBB)	Hard coal power plants (FBC)
Physical shape	Fluff or pellets or agglomerate	Fluff or agglomerate	Fluff	Fluff or agglomerates
Particle size (mm)	<10 to <25	<20 to <50	<10 to <20 (2D material only)	5–50
Moisture (%)	<25 to <50	<20 to <35	<12 to <20	<20 to <30
Net calorific value (MJ/kg)	>11 to 22	>11 to >13	>13	>11 to >17
Ash (%)	<30	<15 to 25	<15 to 25	<30
S (% dm)	<2 to <5	<0.8	<0.75 to <1	<0.3 to <2
Cl (% dm)	<0.6 to <1	<0.5	<1 to 2	<0.5 to <1.4
Sum of Cd, Tl, Hg, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn (mg/kg)	<1 960 to <96 724	<3 800	<2 260	<3 270
Class (Table 1)	2, 3 (NCV and Cl)	2 (Cl)	3 (Cl)	3, 4 (NCV and Cl)

Note: dm = dry matter.

The last row in this table shows which classes of RDF correspond to the requirements set by the power plant operators. The assignment considers the restrictions on chlorine content as well as the NCV.

Successful continuous operation with RDF has been demonstrated in various lignite and hard coal power plants. In lignite and hard coal DBB boilers, the share of RDF in the fuel mix is between 2.2% and 10% by weight. In the long run, it is estimated that RDF can cover 3–5% by weight of the fuel mix. In circulating fluidised bed (FBC) boilers, continuous operation with 15% of RDF by weight has been successful.

Besides these successful examples, many other power plants have carried out co-firing RDF trials. They have faced plenty of operational problems and ceased further processing. Experience has shown that the co-incineration of RDF entails several problems:

- incomplete burnout of RDF on the grate
- unburnt RDF ended up in the bottom ashes, thus reducing the marketability of the contaminated ashes as alternative raw materials in the cement industry
- increased chloride contamination of water used in the process in the desulphurisation scrubber
- mechanical problems triggered by disruptive metallic matter in the delivered RDF
- corrosion induced by chloride salts from RDF
- combustion breakdown
- slagging of boiler heating surfaces

Thiel concludes that the possible substitution rate while using RDF depends not only on its fuel properties, but also on the type and design of the firing systems, the other technical equipment, and the mode of operation of the power plant.

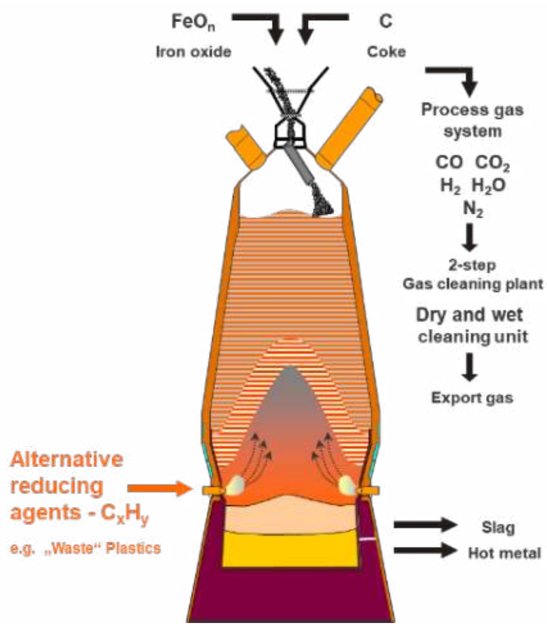
8.4.5 Metal industries

8.4.5.1 Steel

Economic aspects: Blast furnaces in the steel industry rely on coke and pulverised coal. Both materials are globally traded commodities and are subject to global price developments. The current price of coke from Eastern Europe is €416/t to €553/t free on board (May 2023).[122] Alternative materials such as plastics may represent an opportunity to reduce costs, since 1 tonne of plastics can be substituted for 0.75 tonnes of coke.[123]

The injection of waste plastics into blast furnaces started in the 1990s in Germany.[124] However, this practice was abandoned in 2010 for economic reasons.[125] The production of plastic pellets (for example, separated from RDF fractions such as packaging waste) as a reduction agent in blast furnaces is costly. According to the authors' experience, after separating plastics such as polyolefins and PET, these materials need to be pelletised into small-sized pellets of below 10 mm. This process consumes around 60 kWh of electrical energy per tonne of pellets. There are high overall operating costs of around €30/t. It would be preferable if the plastic feedstock were subject to recycling rather than thermal recovery.

Technical aspects: Plastics may act as an alternative raw material for pulverised coal or coke in a blast furnace, because, under reducing burning conditions, the hydrocarbons of the plastics form CO as well as hydrogen. Both compounds act as reducing agents for the iron ore. The following figure shows a simple scheme for a blast furnace, including the inlets for plastics.



Source: Kieberger.[126] Note: the feeding point for plastics is indicated

Figure 10: Schematic presentation of a blast furnace

[122] Steelonthernet.com – Steel Industry Knowledge. European Met Coke Prices - steelmaking input costs - blast furnace raw materials. https://www.steelonthenet.com/files/blast-furnace-coke.html

[123] Merkblatt über die Besten Verfügbare Techniken in der Eisen- und Stahlerzeugung nach der Industrie-Emissionen-Richtlinie 2010/75/EU. Umweltbundesamt, Dessau (Germany), March 2012.

[124] ArcelorMittal Bremen – Geschichte. https://bremen.arcelormittal.com/Ueber-uns/Geschichte/

[125] Merkblatt über die Besten Verfügbare Techniken in der Eisen- und Stahlerzeugung nach der Industrie-Emissionen-Richtlinie 2010/75/EU. Umweltbundesamt, Dessau (Germany), March 2012.

[126] Kieberger, N. (2016): The blast furnace process – experiences on alternative reducing agents. 3rd Alternative Fuels Symposium organised by MVW Lechtenberg & Partner, 12–13 October 2016, Landschaftspart Duisburg-Nord, Germany.

The following table shows the requirements for plastic pellets as an alternative reducing agent in a blast furnace:

Table 20: Requirements for plastic pellets as an alternative reducing agent in a blast furnace

Parameter	Limit values
Particle size	max. 6 × 10 mm (pellets)
Moisture	max. 1.5%
Net calorific value (dm)	min. 33 MJ/kg
Ash (dm)	max. 10%
S (dm)	max. 0.5%
Cl (dm)	max. 1.5%
Hg (dm)	max. 0.5 mg/kg
Class (Table 1)	1 (NCV)

Source: [127]. Note: dm = dry matter.

The last row in the table indicates that RDF class 1 corresponds to the requirement in terms of NCV. The NCV has to be above 33 MJ/kg and the material has to be virtually dry to enable stable operation of the blast furnace. The use of 220 000 tonnes of waste plastics per year means that 70 kg of plastics per tonne of hot metal are used in the blast furnace of the Austrian-based company Voestalpine. The overall coke consumption is about 498 kg/t of hot metal.[128] It is assumed that the maximum quantity of plastics that can be injected is about 70 kg/t of hot metal.[129]

Other furnaces in steel manufacturing cannot be fired with solid fuels such as RDF or coal. EAF is operated using electricity to obtain pig iron. Hot rolling mills shape blooms, billets, or slabs into profiles, strips, pipes, wire, and sheets. Hot rolling starts with heating the materials in reheating furnaces to around 1 200° C. The furnaces are fired with gas or oil, which do not contain ashes. Ashes from solid fuels would contaminate the surfaces of the materials to be reheated, thus impairing the steel quality.

8.4.5.2 Non-ferrous metals

A broad range of furnaces are used for a variety of purposes in this industry, such as roasting or calcining raw materials, melting and refining metals, and smelting ores and concentrates. Many processes rely on electric furnaces or electrolysis, while other processes need fuels. The Best Available Techniques Reference Documents (BREF)[130] lists 44 furnaces for ore processing and metal melting that use either electrical energy or various gaseous and liquid fuels. Conventional fuels and reducing agents can be replaced by waste materials. Different types of waste are used as fuels or reducing agents in the non-ferrous metals industry. Waste can often only be used after certain pre-treatment stages to provide tailor-made fuels for the burning process. Selected wastes with recoverable NCVs, such as waste oil, solvents, and plastics, can be used as fuels instead of conventional fossil fuels, provided that they meet certain specifications and characteristics. Different criteria play a decisive role in the selection of waste fuels, as they can have an impact on kiln operations and on emissions. Wastes that are used as fuel in the non-ferrous metals industry have a high NCV, for example, waste oil with an NCV of 37 MJ/kg and solvents with a NCV of 26 MJ/kg. In a rotary kiln at a nickel roasting plant in Austria, conventional

127 Voestalpine – Materialspezifikation Altkunststoffpellets. 01.09.2018.

128 Kieberger, N. (2016). The blast furnace process – experiences on alternative reducing agents. 3rd Alternative Fuels Symposium organised by MVW Lechtenberg & Partner, 12–13 October 2016, Landschaftspart Duisburg-Nord, Germany.

129 Merkblatt über die Besten Verfügbare Techniken in der Eisen- und Stahlerzeugung nach der Industrie-Emissionen-Richtlinie 2010/75/EU. Umweltbundesamt, Dessau (Germany), March 2012.

130 Cusano, G. et al. Best Available Techniques (BAT) reference document for the main non-ferrous metals industries (2017), EUR 28648, doi:10.2760/8224, pp. 1112–1114.

fuels were replaced by waste oil and solvents. From the latter numbers, it is suggested that waste plastics similar to those being used in blast furnaces and with an NCV of at least 33 MJ/kg may be used in selected furnaces (for instance, in rotary kilns for ore processing). Such waste plastics may correspond to RDF class 1 (Table 1).

8.4.6 Other industries

Food and Beverage: F&B manufacturing requires thermal energy for heating processing lines and buildings. The heat generated by the combustion of fossil fuels is transferred to the consumers by means of heat transfer media, which, depending on the requirements, are steam, hot water, air, or thermal oil.

The basic boiler/generator design generally consists of a combustion chamber in which the fuel combustion takes place. The hot gas and heat transfer media are separated from each other by a specially designed heat-exchange system. On-site combined heat and power (CHP) generation by high-pressure steam boilers/steam turbines, gas turbines, or gas- or diesel-fuelled engines is very common. Natural gas and fuel oil are the most convenient fuels. However, a few installations still burn solid fuels such as coal or waste from their own processes. Some products are heated up by means of direct radiation with open flames or convection with directly heated process air. In this particular case, natural gas or extra-light fuel oil is burned.[131]

RDF cannot be used in CHPs, as they are designed for specific fuels. For instance, reciprocating engines in CHPs can only use either gaseous or liquid but not solid fuels. Gas turbines can only operate with gas or oil. Direct heating of products with open flames can only be done with fuels that do not cause unwanted precipitation of ashes on the products, such as natural gas. In conclusion, the F&B industry is not a candidate for the uptake of RDF.

Ceramics: The term “ceramics” covers a broad range of products that are basically manufactured from clay by forming, drying, and firing. The products encompass bricks, tiles, sanitary ware, refractories, pipes, technical ceramics, expanded clay aggregates, and inorganic bonded abrasives. Natural gas, liquefied petroleum gas (propane and butane), and fuel oil are mainly used for firing, while heavy fuel oil, liquefied natural gas, biogas, electricity, and solid fuels (for example, coal, petroleum coke) can also play a role as energy sources for burners. The use of heavy fuel oil, coal, and petroleum coke is mainly limited to brickworks.[132]

According to the authors’ experiences with many fuel-switching projects, directly fired tunnel furnaces and dryers are designed for gaseous and liquid fuels. Moreover, many products, such as sanitary ware, bricks, and tiles, must not be contaminated with fuel ashes, as ashes settle on the surface, thus deteriorating the desired colour of the product. Hence, using RDF is not an option in the ceramics industry.

In some brick manufacturing, however, fuel can be provided as external and internal fuel. External fuel is the regular fuel which is fired in a tunnel furnace. Internal body fuel means that types of solid fuel such as coal, biomass, or even paper rejects from paper mills are mixed with the clay. While thermally treated in the furnace, the internal body fuel causes small voids within the brick body, thus acting as a porosifier to obtain lightweight bricks. Using RDF in such a specific application as internal fuel is supposed to be possible; however, whether this is really the case has still to be proven.

Glass: Glass is manufactured from a basic soda-lime mixture. This mixture is melted in fossil-fuel-fired furnaces or electrically heated furnaces. The energy sources for glass making are natural gas, fuel oil, and electricity.[133] The conventional and most common way of providing heat to melt glass is by burning fossil fuels above the batch blanket or batch piles above the molten glass. Fuels that produce ashes cannot be used for melting glass because ashes contaminate the glass surface and deteriorate the quality. Therefore, the glass industry is not a candidate for the use of RDF.

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[131] Santonja, G.G. et al. Best Available Techniques (BAT) reference document for the food, drink and milk industries (2019); EUR 29978 EN; doi:10.2760/243911.

[132] European Commission. (2007). Reference document on Best Available Techniques in the ceramic manufacturing industry.

[133] Scalet, B.M., Garcia Muñoz, M., Sissa, A.Q., Roudier, S., & Delgado Sancho, L. Best Available Techniques (BAT) reference document for the manufacture of glass, Industrial Emissions Directive 2010/75/EU Integrated Pollution Prevention and Control (2013). European Commission, Joint Research Centre, Institute for Prospective Technological Studies. EUR 25786 EN.

8.5 Landfill taxes and gate fees

The following table shows landfill taxes and gate fees in EU MSs. Unless specified, the tax rates refer to MW.[134] The "typical landfill gate fees" reflect the prices for accepting waste by the landfill's operator. The prices relate to the waste materials specified in the column "comment and sources."

Table 21: Typical landfill gate fees and taxes among EU Member States

Member State	Landfill restrictions (yes/no)	Landfill tax (€/tonne)	Typical landfill gate fee (€/tonne)	Comment and sources	Link
Austria	yes	9.2–29.8		European Commission: Ensuring that polluters pay – Austria (2020)	https://shorturl.at/xDFW4
		–	5.5–97	*Construction & demolition waste* (Rohrdorfer Preisliste 2021 Umwelttechnik / Sand & Kies)	https://shorturl.at/ajnsu
			13.50–95	*Construction & demolition waste* (Altlastensanierung und Abraumdeponie Langes Feld G.m.b.H, Preisliste 2023)	http://www.langesfeld.at/
Belgium	yes	40–267.55		*Wide range, depends on hazardousness and region* CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Bulgaria	no	50		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Croatia	yes	1.60		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
			26.25–49.90	*Household and commercial waste* (European Commission: 1.0 Fact–sheet – Croatia)	https://shorturl.at/hBELT
			59.73	ČISTOĆA d.o.o. SPLIT, UPRAVA DRUŠTVA, Split, 01.09.2022. CIJENA ODLAGANJA KOMUNALNOG OTPADA NA ODLAGALIŠTU KAREPOVAC ZA POTREBE SVIH JEDINICA LOKALNE SAMOUPRAVE I OSTALIH KORISNIKA *(Price of municipal waste disposal at Karepovac landfill for the needs of all units, local self-government and other users)*	https://shorturl.at/ksvX6

[134] Confederation of European Waste-to-Energy Plants (CEWEP). Landfill taxes and restrictions. https://www.cewep.eu/landfill-taxes-and-restrictions/

Member State	Landfill restrictions (yes/no)	Landfill tax (€/tonne)	Typical landfill gate fee (€/tonne)	Comment and sources	Link
Cyprus	no	No tax		CEWEP – Landfill Taxes and Restrictions (28.10.21)	https://shorturl.at/csBFV
Czech Republic	no	20–31.5		*Tax gradually increases to reach 72 €/t by 2029* CEWEP – Landfill Taxes and Restrictions	http://tinyurl.com/2p9yr98b
Denmark	yes	79		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Estonia	no	29.84		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Finland	yes	70		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
France	yes	47–152		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Germany	yes	–	56–950	*Wide range depends on hazard level* *Construction & demolition waste; soil, road construction waste* (AWN-Preisliste zur Anlieferung von Abfällen im Zentrum für Entsorgung und Umwelttechnologie Sansen-hecken, 01.04.2022)	http://tinyurl.com/5byrzkss
			72–416.50	*Broad range: mineral, agricultural, industrial waste* (Kreis Kleve Abfallwirtschaftsgesellschaft mbH Preisliste D 2023)	https://kkagmbh.de/
			4.20–262.40	*Broad range: bulky, industrial, mineral, construction & demolition waste* (Abfallarten und Gebühren der Deponie Lachengraben ab 01.01.2023)	http://tinyurl.com/2v465y84
Greece	no	20 (2022) 45 (2026) 55 (2027)		*From 2023: annual increments of €5/t to €35/t in 2025. From 2027: €55/t constant for 5 years.* ΕΔΣΝΑ: Η νέα “πράσινη” τιμολογιακή πολιτική του ΕΔΣΝΑ για το 2022 (29.04.2022)	http://tinyurl.com/yc6cf22p
Hungary	yes	19.35		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b

Member State	Landfill restric-tions (yes/no)	Landfill tax (€/tonne)	Typical landfill gate fee (€/tonne)	Comment and sources	Link
Ireland	no	75		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Italy	no	5.2–26		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Latvia	no	95–100		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Lithuania	yes	27.51–50		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Luxembourg	yes	no tax	200	*Household, bulky waste* SIGRE, région de Grevenmacher, Remich et Echternach: Dienstleistungen ab dem 01.01.2023	https://sigre.lu/
Malta	no	no tax		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
			30–40 (2023) up to 20–30 (2037)	*Broad range, dep. on waste types.* *Ranges for organic, household, mineral waste* (WasteServ Malta: Gate Fees 2023)	https://www.wsm.com.mt/en/gate-fees
Netherlands	yes	33.15		Rijkswaterstraat: Verhoging afvalstoffenbelasting per 1 januari 2022 Belastingdienst: Tabellen tarieven milieubelastingen	http://tinyurl.com/2et39ybc
Poland	yes	46		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
			13–322	*Broad range: mineral, industrial, household waste* Skladowisko Odpadow Komunalnych Sp. z.o.o. w O´swiecimiu: Cennik 01.01.2023 r.	https://www.sok-oswiecim.biz/
Portugal	no	22		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
Romania		17		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
			40.63–43.50	EcoSud, Bucaresti – Depozitarea deseurilor direct in celule	http://tinyurl.com/56zf4ccn

Member State	Landfill restric-tions (yes/no)	Landfill tax (€/tonne)	Typical landfill gate fee (€/tonne)	Comment and sources	Link
				Depozitului Ecologic Vidra (15.12.2021)	
	no		17.03–39.75	Composting 17.03; disposal MW, construction & demolition 39.75; disposal other 23.55 (ECO–IHOR - Depozitul Ecologic de Deseuri Nepericuoase – Lista de deseuri acceptate si preturi–2022 – 2022)	http://tinyurl.com/yckdw4wj
			23.55	Tarifele pentru depozitarea deşeurilor la groapa de gunoi a Oradiei se majorează cu 14%. (Tariffs for waste storage at the Oradea landfill increase by 14%). eBihoreanu, Dan Simai, 02.05.2022	http://tinyurl.com/3y8xmzte
Sweden	yes	51		CEWEP – Landfill Taxes and Restriction (28.10.21)	http://tinyurl.com/2p9yr98b
		97–113		*asbestos-containing waste; mineral wool* SYSAV – Prislistor 2023	https://www.sysav.se/foretag/priser/prislistor/
Slovakia	yes	11–33		CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
			76	Aká je cena za likvidáciu komunálneho odpadu pre mestá a domácnosti a aký vývoj môžeme očakávať? (What is the price for municipal waste disposal for cities and households and what development can we expect?) (04.04.2022)	http://tinyurl.com/5d65rwk2
Slovenia	yes	11–22		*Wide range, depends on hazardousness* CEWEP – Landfill Taxes and Restrictions (28.10.21)	http://tinyurl.com/2p9yr98b
		34–247		*Broad range: Construction & demolition, MW, asbestos waste* Komunala Ribnica: CENIK DEPONIRANJA GRADBENIH ODPADKOV. 2023	http://tinyurl.com/2tev6xa5

Member State	Landfill restric-tions (yes/no)	Landfill tax (€/tonne)	Typical landfill gate fee (€/tonne)	Comment and sources	Link
Spain	no	1.50–40		Cuatrecasas ESG: New Developments on Waste Tax April 2022	http://tinyurl.com/2m74z374

The landfill gate fees are levied by the operator of the landfill. These are laid down in the respective price lists ("comment and sources" and "link" columns).

8.6 Prices for waste incineration

The following table lists price ranges for the incineration of mostly household waste in several MSs. The column "price ranges" shows the net prices (without taxes) that need to be paid to the incinerator for one tonne of waste. They relate to the sources specified in the columns "source" and "link." The tariffs have mostly been retrieved from various operators of waste incinerators or MW management.

Table 22: Typical price ranges for incineration of waste in some EU Member Countries (net prices)

Country	Landfill restrictions (yes/no)	Price ranges (€/t)	Source	Link
Austria	yes	108–254	ABFALLWIRTSCHAFTSVERBAND SPITTAL /–DRAU – Preisliste gültig ab 01.01.23	http://tinyurl.com/a5ezmha2
Belgium	yes	101.86	OVAM: TARIEVEN EN CAPACITEITEN VOOR STORTEN EN VERBR–NDEN – Evolutie van de beschikbare stort- en verbrandingscapaciteit in functie van het huidige aanbod Actualisatie tot 2021 publicatiedatum / 5.11.2022	http://tinyurl.com/rckzas4v
Czech Republic	no	84 (RDF) 110 (household)	TE–MIZO – Ceník platný od 1. 1. 2023	http://tinyurl.com/mtemm5nb
Denmark	yes	90.60–241.30	Revas, Viborg Kommune: Affaldscenter 2023, Prisliste pr. 1. Januar 2023	http://tinyurl.com/5n8enjn9
France	yes	130	Seine & Oise Communauté Urbaine: Au 1er janvier 2023: tous les emballages et papiers se trient	http://tinyurl.com/37z32vvb
		208.80 (household) – 321 (industrial)	Sitcom Coté sud des Landes au service de son territoire – Tarifs valables du 1er avril 2023 au 31 mars 2024	https://www.sitcom40.fr/sitcom/tarifs
Germany	yes	65–145 (various regions)	EUWID – Recycling und Entsorgung. Jahrgang 33½r. 1/2.2023, p. 25	
Italy	no	112.56	ATO-R Associaz'one d'Ambito Torinese per il Governo dei Riffiuti – CORRISPETTIVO DI CONFERIMENTO ALL'INCENERITORE DEL GERBIDO 2021	http://tinyurl.com/55hxaxxe
Luxembourg	yes	200	Syndicat Intercommunal pour la gestion des déchets ménagers, encombrants et assimilés en provenance des communes de la région de Grevenmacher, Remich et Echternach (SIGRE): Dienstleistungen ab dem 01.01.2023	https://sigre.lu/

Country	Landfill restrictions (yes/no)	Price ranges (€/t)	Source	Link
Netherlands	yes	155	Pieter van den Brand: Ongekend hoge tarieven bij aanbestedingen afvalverwerking. 16.07.20	http://tinyurl.com/bdd4rrcb
Poland	yes	127–207	PGK SłupskPRZEDSIĘBIORSTWO GOSPODARKI KOMUNALNEJ SPÓŁKA Z O.O. W SŁ–PSKU – CENNIK 02.01.23	http://tinyurl.com/5n6jsphn
Slovakia	yes	144	Cenník zhodnotenia odpadu v ZEVO, 02.01.2023	http://tinyurl.com/63xax3xk
Slovenia	yes	84.78	Sklep o določitvi cene za sežig komunalnih odpadkov na območju občin Savinjske regije za obdobje 2020 do 2022	http://tinyurl.com/y4579d4p
Spain	no	123.97	SIRUSA – Servei d'Incineració de Residus Urbans, S.A. Pressupost Anual Exercici 2023	http://tinyurl.com/4ubsabt2
Sweden	yes	70.40–171 *to be added: 27.72 for emission right–*	NSR – Prislista Ängelholm	http://tinyurl.com/bdcpst2j
		74.78–238 (range depends on fossil carbon content)	Sysav: Prislistor 2023	https://www.sysav.se/foretag/priser/prislistor/

8.7 Example of CO_2 cost reduction potential

The EU-ETS price has significantly increased across recent years to reach a current price of about €90/t.[135]

Source: Trading economics [136]

Figure 11: Trend in carbon prices

135 Trading Economics. https://tradingeconomics.com/commodity/carbon (accessed 14.08.23)
136 Ember Carbon Price Tracker. https://ember-climate.org/data/data-tools/carbon-price-viewer/

To illustrate the RDF CO_2 reduction potential, the authors of this report have elaborated the following example. The table below shows the simulated quality values in terms of NCV, carbon content, and the CO_2 emission factor of an RDF (class 2) consisting of mixed plastics from separately collected household and commercial waste and a paper/cardboard fraction from waste-sorting facilities. Also, the calculation includes lignite and hard coal, which are being substituted for by RDF in industrial applications such as cement or lime kilns.

Table 23: Simulated RDF quality parameters and comparison of CO_2 emissions and costs for RDF and fossil fuels

Parameter	Unit	RDF components		RDF from these components	Lignite	Hard coal
		Non-recyclable mixed plastics from separately collected household and commercial waste	Non-recyclable paper/cardboard from waste-sorting facilities			
Proportion	%	75	25	**100**		
NCV	MJ/kg	23.7	12	**20.8**	22.1	28.1
C total	%	65	43	**59.5**		
C fossil		51	0	**38.3**	59.5	80
C biogenic	%	14	43	**21.3**		
Fossil CO_2 emission factor	t CO_2/t fuel			**1.4**	2.2	2.9
	t CO_2/TJ			**67.5**	99	104
CO_2 price	€91/t					
CO_2 cost	€/t fuel			**128**	198	267
	€/GJ			**6.1**	9.0	9.5

Source: MVW,[137] with CO_2 price retrieved from Trading Economics.[138]

As the table shows:

- The RDF quality data calculated show that the fossil carbon content accounts for 38.3/59.5 = 64.4% of the total carbon content. The remaining 35.6% of the total carbon is biogenic carbon, which is derived from the paper/cardboard fraction, as well as from some biogenic matter that is included in the mixed plastics from separately collected household and commercial waste.
- The emission factor of this RDF is 1.4 tonnes of fossil CO_2 per tonne of RDF, or 67.5 tonnes of fossil CO_2 per terajoule (TJ).
- Fossil fuels such as lignite and hard coal contain only fossil carbon. The emission factors calculated from the carbon contents are 2.2 and 2.9 tonnes of fossil CO_2 per tonne of fuel, respectively. The energy-related emission factors are 99 and 104 tonnes of CO_2 per TJ, respectively.

[137] MVW Lechtenberg & Partner, firm's own calculations. Chemical and physical data on RDF components, lignite, and hard coal are from MVW Lechtenberg's quality-information-system (QIS) database.

[138] Trading Economics. https://tradingeconomics.com/commodity/carbon (accessed 14.08.23).

- One gigajoule (GJ) of RDF substitutes for the same energy amount supplied by lignite or hard coal. Hence, the fossil CO_2 emissions from one GJ of RDF are around 100 − (100 × 67.5/99) = 31.8% less than those from one GJ of lignite and 35% less than those from one GJ of hard coal.
- In terms of CO_2 cost, one GJ of RDF would save €9 − €6.1 = €2.9 when compared to lignite, and €3.4 when compared to hard coal.
- One tonne of RDF can replace 20.8/22.1 = 0.9 tonnes of lignite. Hence, one tonne of RDF saves €0.9 × 198 per tonne – €128 per tonne = €50 per tonne of RDF compared to fossil CO_2 emissions. Applying the same rationale to hard coal, the resulting savings are €59 per tonne of RDF.

8.8 EEA residual waste forecast

The European Environment Agency recently explored different scenarios for meeting the legally binding target of recycling 60% of MW (set by the Waste Framework Directive) while also reaching the non-binding target of 56.5 million tonnes of residual waste (or refuse) by 2030 (set by the Circular Economy Action Plan and Zero Pollution Action Plan).[139] To accomplish this, three scenarios were considered:

- Scenario 1: only the legally binding 60% recycling target is met in 2030, and no residual waste reduction is considered.
- Scenario 2: both the legally binding 60% recycling target and the non-binding target of 56.5 million tonnes of residual waste are reached in 2030, without waste prevention (73% recycling and 0% waste prevention).
- Scenario 3: both the legally binding 60% recycling target and the non-binding target of 56.5 million tonnes of residual waste are reached in 2030, along with waste prevention (60% recycling and 34% waste prevention).

For these three scenarios, residual waste was estimated to reach 38%, 25%, and 38%, respectively.

Considering historical Eurostat[140] data on energy recovery and/or incineration in the EU-27, one can extrapolate the final potential share of RDF in MW:

- Based on Eurostat, the share of residual waste sent to energy recovery or incineration varied from 56% in 2012 to 47% in 2021, with an almost constant decrease.
- This means that the potential share of RDF in MW could be roughly estimated in a range of 18% to 12% of MW by 2030.

Furthermore – and without a detailed calculation methodology for reaching the different targets, including losses in the waste management chain – it is obvious that the scenario of meeting the 65% recycling target of MW by 2035, along with a 10% landfill target by 2035, would lead to a maximum share of RDF in MW of 25% in 2035.

Considering that MW may reach ~232 million tonnes in 2035[141] if no waste prevention/reduction measures are in place, this means that the RDF production in the EU-27, in the future, should not exceed 58 million t/y.

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139 Reaching 2030’s residual municipal waste target — why recycling is not enough, EEA 2022. https://www.eea.europa.eu/publications/reaching-2030s-residual-municipal-waste

140 Eurostat ENV_WASMUN database. https://ec.europa.eu/eurostat/databrowser//product/view/ENV_WASMUN

141 European Commission, Directorate-General for Environment, Karigl, B., Neubauer, C., Kral, U., et al. (2022). Scoping study to assess the feasibility of further EU measures on waste prevention: final report. https://data.europa.eu/doi/10.2779/21588

8.9 Ways to improve RDF uptake from MBT/MT plants

Increase sorting efficiency: By increasing the efficiency of their sorting and separating machines, mechanical treatment facilities can more effectively separate the desired waste fractions from the waste stream. This will increase the RDF consistency and quality, which would also increase the plant's output. An increase in sorting and separating efficiency can be achieved using various technologies:

- Near-infrared (NIR) devices, including pneumatic nozzle bars, for
  - diverting PVC (a chlorine-containing material that is undesirable as a component of RDF);
  - extracting other plastic materials (polypropylene, polystyrene compounds and others), which are desirable as components of RDF;
- Separation of metals (eddy current separators, magnetic separators). Metals are undesirable in RDF. Moreover, metal separation protects downstream comminution equipment.
- Air classifiers divert heavy particles such as glass, stones, and sand from the desired combustible matter.

Note: NIR devices can also be used for online quality control (see also Sections 4.3)

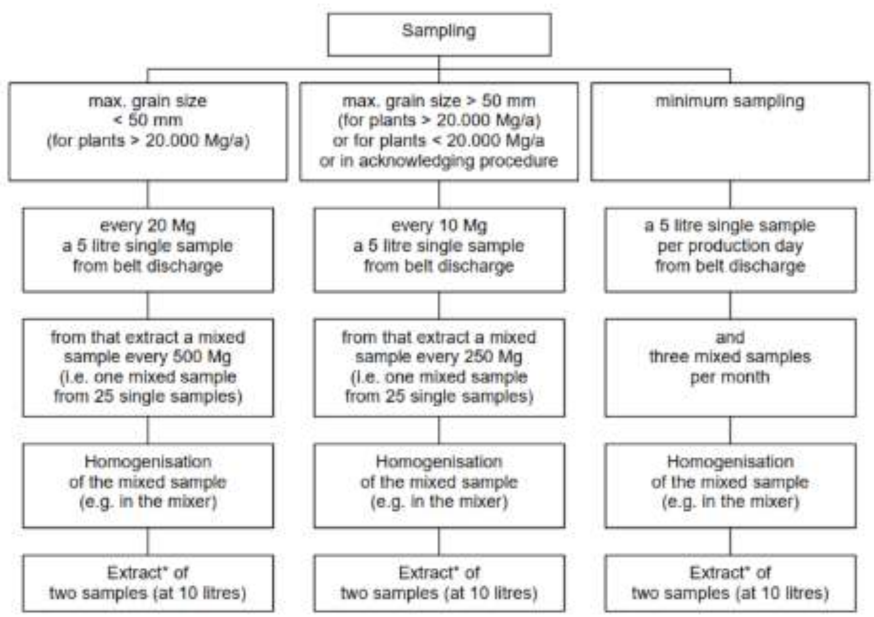
Improve quality control: The MBT shall implement a factory production control system featuring the following major elements:

Standard sampling and testing procedures:

To make sure that the RDF generated complies with specifications from clients, mechanical treatment facilities should implement a thorough quality control system. This encompasses primarily:

- regular sampling of RDF according to a sampling plan
- proper subsampling techniques (such as combined use of grab samples and composite samples)
- laboratory tests on samples collected
- proper recording of test results with statistical evaluation and the measures derived from the assessment.

Facilities can follow the sampling procedure set out in the German RAL-GZ 724:



Source: RAL-GZ 724[142]

Figure 12: Sampling procedure in production plants for quality-controlled SRF

[142] Solid Recovered Fuels. Quality Assurance RAL-GZ 724. June 2001.

This process aims to obtain samples from the RDF output for subsequent laboratory tests which check the entire range of relevant parameters, including calorific values, moisture levels, ash content, and other major and minor elements, according to the pertinent standards.

Online analysis:

The quality control procedure for producing quality-assured SRF can be enhanced by online analysis. Contrary to the sampling procedure described above, which relies on samples after every 10 or 20 tonnes of material produced, online analysis detects the material stream continuously and is carried out by NIR devices. They are placed above the conveyor to scan the material stream beneath. The device can monitor the chlorine content, moisture level, and calorific value parameters online. The operator will need to immediately launch countermeasures in case there are any deviations from the set points. It is important to bear in mind that the chlorine and NCV parameters are determined indirectly from the materials' infrared patterns using mathematical modelling and that the values derived from this procedure are not as exact as those obtained by standard laboratory test methods. However, for production control and immediate response in case something goes wrong, online analysis has been proven to be effective.

Drying of RDF: Drying of RDF reduces its moisture levels and thus improves its NCV. Reducing moisture in RDF improves the energy efficiency in technical kilns and furnaces, increasing the TSR. Drying of RDF can be carried out by a variety of drying processes. Drying at the RDF production facility requires additional thermal energy, mainly from natural gas or oil, resulting in a burden in terms of operating expenses. If the MBT/MT plant is equipped with a combined heat and power plant of sufficient thermal capacity, then the waste heat can be recovered in the dryers (see also Section 4.2.2) without any additional cost for fuels. Another option is a cooperation model between MBT and an RDF end user, such as a cement plant. Cement plants have a surplus of waste heat that can be used advantageously for drying purposes. The owner of a cement plant or the RDF producer can install a drying system (either flash, belt, or drum dryer) in the cement plant. Then the dried RDF would be conveyed by the usual feeding equipment into the kiln.

8.10 Poorly performing MBT/MT plants: causes and possible improvements

There are several factors that may cause MBT/MT plants to work poorly. The following sections give a non-exhaustive list of potential causes of underperformance in RDF production and possible ways to solve these problems, based on the authors' experience:

No input control: many observations have revealed no control or poor control of the waste input. For instance, an Irish-based MT plant produced RDF for cement factories, mainly from commercial waste. Within the input, there were many plasterboards that entered the mechanical treatment line without visual inspection. The plasterboards increased the desired performance of the line, in terms of tonnes of throughput per hour, but the quality of the resulting RDF was poor. The plasterboards increased the ash content and reduced the NCV of the RDF, resulting in complaints from cement factories when they received the material.

Carrying out at least a visual inspection of all waste deliveries is highly recommended. Dividing the input storage of the MT plant into different receiving areas is strongly advised – for instance, into four areas as follows:[143]

- **Area I / material A:** High-calorific value, uncontaminated materials for direct feeding (pre-sorted and clean, such as defined industrial waste)
- **Area II / material B:** MW materials for separation (such as mixed MW and mixed industrial/commercial waste for further separation)
- **Area III / material C:** Defined materials with low calorific value (such as paper rejects from the paper industry or clean industrial/commercial waste with low calorific value)
- **Area IV / material D:** Unsuitable materials (disallowed materials such as hazardous or contaminated waste, rejects from magnets, air classifier, screens). Deliveries with disallowed materials shall be rejected.

The feeding of the mechanical treatment line should be carried out according to a recipe. Such a recipe might look like this:

- The front loader takes three shovels from Area I, two shovels from Area II, and one shovel from Area III.
- The front loader feeds the input conveyor of the mechanical treatment plant line with this mixture.

The material from Area IV is for disposal purposes only and must not be used.

Unsuitable waste input: The quality of the waste input determines the quality of the RDF final product. This is because if there is no input control, waste with high chlorine content or low NCV for instance, will have a negative impact on the quality of the RDF. The next table gives a non-exhaustive list of materials considered impurities that are disallowed as input materials in RDF production facilities:[144]

[143] Lechtenberg, D., & Diller, H. (2012). *Alternative fuels and raw materials handbook for the cement and lime industry*. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH., 329–330.

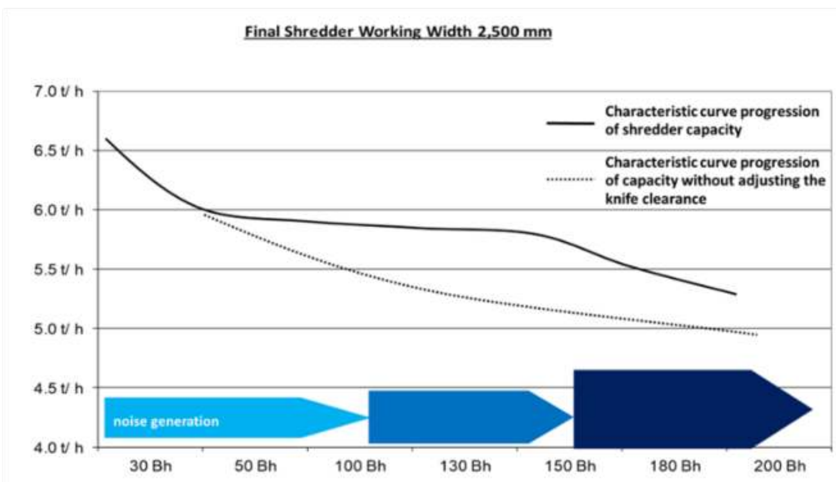
[144] Lechtenberg, D., & Diller, H. (2012). *Alternative fuels and raw materials handbook for the cement and lime industry*. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH., 347–348.

Table 24: Non-exhaustive list of waste materials not suitable for RDF production

Chlorine-containing materials	Materials/waste with low calorific value	Inert materials	Other impurities
• Shutters, blinds • PVC water and wastewater pipes (sewer pipes) • Window frames • PVC floor coverings or carpets • Garden furniture made of PVC • Pond films • Water hoses • Corrugated plastic boards (for example, from roof or façade construction) • Other PVC materials (for example, inflatable mattresses, pools, water toys)	• All kinds of organic waste, such as green matter and food • Soaked waste	• Gypsum and gypsum plaster boards • Stones • Demolition waste • Sand • Ashes • Insulation materials such as stone wool and glass wool	• Dangerous and hazardous waste • Roofing felts (made of tar or bitumen) • Asbestos materials (such as asbestos cement sheeting) • Explosive materials and containers with explosive contents • Hospital and medical practice waste, infectious waste • Liquid waste • Sludge and litter • Electronic scrap

A list of this type can be a handy tool for the banksman when checking waste deliveries arriving at the RDF production plant.

Insufficient attention paid to the final shredder: It is well known that the shredder throughput decreases as the knives increasingly become worn. This is acoustically recognisable through the level of noise generation by the shredder. However, this phenomenon is often neglected.



Source: Diller/Lechtenberg[145]). Note: Bh = operating hours

Figure 13: Relationship between throughput and noise generation by a final shredder

As this figure shows, as the operating hours increase, noise also increases, while the throughput decreases. Therefore, proper observation of the machine's performance and noise levels is recommended. The knives

145 Lechtenberg, D., & Diller, H. (2012). *Alternative fuels and raw materials handbook for the cement and lime industry*. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH., 108–109.

mounted on the rotor can be turned four times, as there are four cutting edges. This allows utilisation of the knives' whole cutting capacity. As a rule of thumb, the total lifetime of the knives is around 250 operating hours. However, the optimum time interval for maintenance or knife changes must be determined for each shredder individually.[146]

Unfavourable installation of metal separators: As a rule, magnetic metal separators are placed above a conveyor belt to extract ferrous metal pieces from the waste mass flow. Metals need to be extracted from the mass flow to prevent damage to the downstream final shredders and to feeding equipment at the customer's facility. Moreover, metals are destined for recycling, rather than being supposed to end up in RDF.

Magnetic separators are placed either parallel to or across the conveyor belt (see Figure 14). The authors of the current report have observed that the separation efficiency is lower when the magnet is placed across the conveyor belt, particularly when the material depth on the conveyor belt is high. The preferred direction of a magnetic separator is parallel to the conveying direction at the discharge of the conveyor, as the following figure shows.

Source: MVW

Figure 14: Left: A magnetic separator across the conveying direction in an RDF plant (less favourable position). Right: Favourable positioning of a magnetic separator parallel to the conveying direction and at the discharge point of the left conveyor belt

At this point, all materials are suspended in the air and the magnetic forces can easily pick up any ferrous materials.

Undesired high chlorine content: Chlorine is regarded as a RDF contaminant (see also Section 8.4), so the chlorine content should be kept as low as possible. Although visual inspection of delivered waste may detect and divert PVC-containing matter (see above), smaller chlorine-containing plastic parts may still be undetected. As a result, the chlorine content of RDF may exceed the limit values laid down in customers' specifications, thus provoking complaints. NIR devices for the extraction of chlorine-containing plastics are a means of producing RDF with low chlorine content.

Too much moisture in RDF: This is a frequently observed phenomenon. Moisture reduces the NCV, thus giving rise to complaints from the RDF end users. For example, an RDF with 33.5% moisture and an NCV of 13.8 MJ/kg (class 4) is dried to a residual moisture of 20%, which meets the general requirements imposed by cement plants.

[146] Ibid.

The NCV would increase to 17 MJ/kg (class 3).[147] The moisture comes from wet feedstock, particularly MW. Even if the wet organic fraction is separated at the beginning of the treatment line, the remaining fractions will still contain a great deal of moisture. If the moisture in RDF cannot be reduced by an appropriate feedstock, for example, by adding dry commercial waste to MW, then drying of RDF is advised. Drying of RDF can be carried out by means of a drum dryer (see Section 4.2.3) or belt dryer. However, drying is costly as it requires a heat generator, which is usually fuelled with natural gas or fuel oil. If the MBT/MT plant operates a combined heat and power plant that has sufficient thermal power, the enthalpy from the exhaust gases as well as from the cooling water can be used in the dryers. In this case, there is no need to install a hot gas generator, thus saving costs on fossil fuels. This kind of waste heat recovery has been successfully implemented in the authors' RDF pelletising facility in Germany.

Poor quality control: If the RDF quality is not monitored, it cannot be expected to match customers' specifications, resulting in many complaints addressed to the RDF producer. Quality control in RDF production facilities, either by online analysers and/or by classical sampling and laboratory tests, is essential. A factory production control system enables the RDF producer to manage the input recipe properly (see above).

However, even if there is already a factory production control system in place, one often underestimated potential pitfall is the frequently improperly carried out procedure for laboratory sampling of RDF. This means that only a grab sample is taken at some easily accessible place on the conveyor belt. This kind of grab sample is usually not representative, thus laboratory test results do not reflect the overall quality of the material. Observing the sampling procedures and the right sampling points, as laid down in the standards,[148,149] to obtain representative samples is of utmost importance. Sampling can also be carried out by means of automatic sampling stations with improved reproducibility. Neglecting the basic rules of sampling results in laboratory test values that do not reflect the quality of the material as a whole.

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147 The calculation is based on the formulae for the conversion of NCV from "as received" to "dry base" and vice versa. The formulae are explained in: Lechtenberg, D., & Diller, H. (2012). *Alternative fuels and raw materials handbook for the cement and lime industry*. Volume 1. Düsseldorf: Verlag Bau+Technik GmbH, 153.

148 EN ISO 21645:2021 Solid Recovered Fuels – Methods for Sampling.

149 Solid Recovered Fuels. Quality Assurance RAL-GZ 724. June 2001.

8.11 Case study – best current practice of an RDF-producing MBT

The **AWG Ennigerloh MBT** in Germany produces two classes of RDF. The whole process is shown in Figure 4.

The plant includes a RDF plant and a biological treatment facility. Two qualities of RDF are produced: class 2 and class 4. The waste feedstock used to produce RDF includes MW and industrial waste.

RDF plant

- Household and industrial waste are discharged in the reception hall. Larger parts of paper, wood and metal, coarse impurities, PVC-based matter, or other types of waste containing hazardous substances are already segregated here from the industrial waste.
    - An excavator takes the industrial waste to the comminution step (1);
    - A wheel loader moves the household waste to a shredder.
- The waste streams are separated into two fractions by means of vibration screens (2):
    - a fine fraction (screen passing), which contains a high proportion of organics;
    - and the screen overflow (retained by the screen).

RDF is obtained from the screen overflow.

- The fine fraction is conveyed for further treatment in the adjacent biological treatment plant (BT plant (4));
- In the reception hall and at further points in the process, over-belt magnetic separators and magnetic rollers (5) extract metals from the waste stream;
- The remaining wastes are segregated by means of air classifiers (4) into a light fraction, for example, foils or paper, and a heavy fraction like non-ferrous metals, glass, ceramics, stones, and rigid plastics;
- The light fraction is transported to the “fine particles control / preparation” for fuel production;
- Following a screening of the fine portion (6) and a comminution to a grain size of 80 mm (7), the still moist material is conveyed to a rotary drum dryer (8);
- PVC is diverted from the material flow using NIR (9);
- The remaining heavy materials/particles are discharged by a second air classifier downstream (10);
- RDF is transported into the storage area, from where it is automatically loaded on lorries (11);
- The negative pressure inside the building ensures that the air remains inside, even when the gates are open. The dusty exhaust air passes through dust filters and regenerative thermal oxidation (12), which destroys any odour.

Two qualities of RDF are obtained:

- A high-caloric material, which is a so-called quality-assured SRF (according to the German RAL GZ-724), with net calorific values of up to 22 000 kJ/kg. This SRF is highly suitable for main burner firing in the local cement industry. This material matches class 2;
- RDF in the medium calorific range (with NCV of up to 14 000 kJ/kg). Such RDF is used in mono-power stations (which use only medium calorific alternative fuels). This RDF corresponds to class 4.

BT plant:

- Circa 50% of the waste delivered to the facility is treated aerobically in the adjacent BT plant;
- The residual waste is stabilised biologically within three weeks;
- The material is transported from the reception hall (13) to the impurity segregation (14) and then via conveyor belts into the intensive decomposition tunnels (15);
- Encapsulated intensive degradation processes take place here, through microbial activity without any connection to the environment, under conditions of continuous control of temperature, humidity, and aeration. The material is turned once a week;
- After the intensive decomposition step, automatic transport to the post-decomposition area is provided (16), where the continuous degradation process is monitored and regulated in an enclosed system;
- The second phase of post decomposition takes place in a separate hall (post decomposition 2) (17). The residual organics are decomposed to a large extent in decomposition channels, and the humidity content of the material is adjusted. After a nine-week treatment period, the waste mass displays a soil-like property and can be landfilled according to legal requirements (18);

- Compared to the original input, the weight of the waste has been reduced by approximately 40% through treatment in the BT plant. The output can then be landfilled on the adjacent central landfill.

8.12 Current status, market considerations, and prospects for RDF production and uptake in selected countries – country reports

Among the EU-27 MSs, the RDF context of Romania, Croatia, Greece, Malta, and Slovenia based on desktop studies is presented in this report for illustration of the different situations and challenges that RDF producers and end users might face.

In the subsections to follow, the industrial sectors that use RDF, as well as the qualities and volumes are highlighted. The potential RDF quantities have been deduced from statistical data from the Eurostat database. The respective waste volumes were multiplied by the proportion of combustible matter derived from the waste composition.

The potential use is based on the thermal capacities of the end users, which are mainly in the cement industry. It should be noted that the cement industry already employs various types of alternative fuels (liquid and solid fuels), which will influence the RDF uptake. To determine the RDF uptake capacities of the target countries, the following methodology is adopted:

- Evaluation of the current thermal substitution rate (TSR) through publicly available sources such as cement group annual reports and calculation or recording of the associated volume of RDF (and/or other alternative fuels that an individual factory uses);
- Permits for a 100% substitution rate were granted to the cement plants. However, attaining this level of TSR by using solid RDF is not feasible. From experience, it is not possible to achieve 100% TSR – therefore, a maximum attainable limit of 85% TSR with solid alternative fuels has been set;[150]
- The theoretical volumes of RDF have been derived by means of a simulation model developed by the authors. This takes into account a standard NCV of 4 500 kcal/kg (class 3) for calciner RDF, as well as an NCV of 5 500 kcal/kg (class 2) for main burner RDF. The average specific thermal energy consumption of a clinker kiln is 800 kcal/kg of clinker.[151]

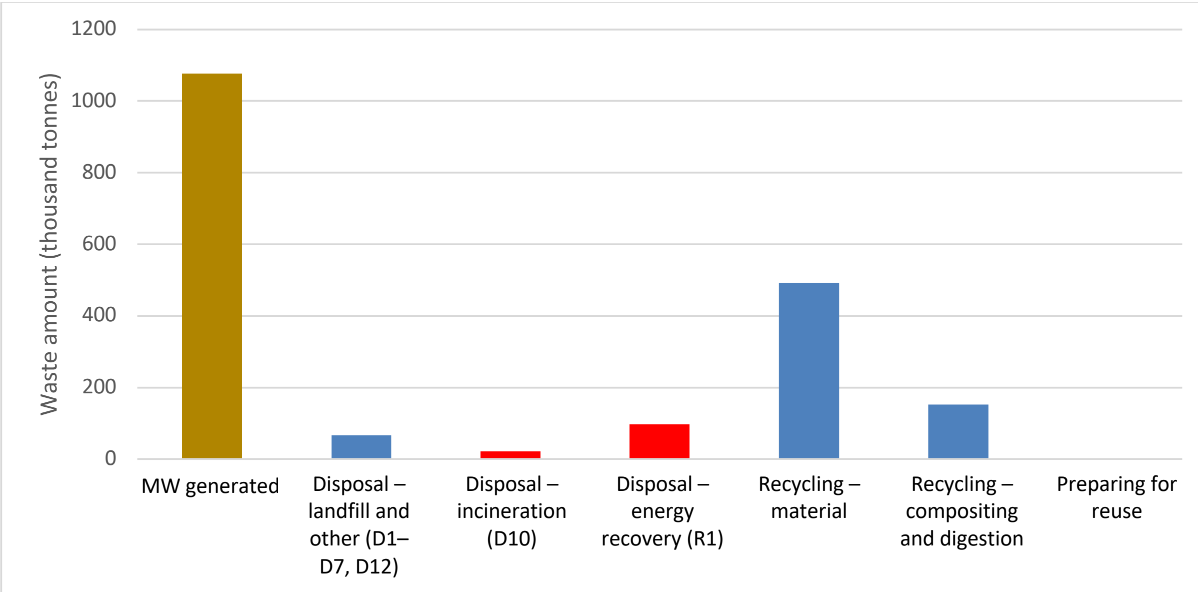
The resulting difference between the current and the calculated maximum TSR is the potential uptake capacity, or maximum quantity of RDF that can be used in the cement plants. The cement plants use RDF to substitute fossil fuels in the clinker production process. The WtE facilities use RDF based on their designed capacities.

[150] The assumptions have been set based on the authors' experience.
[151] The assumptions have been set based on the authors' experience.

8.12.1 Slovenia

8.12.1.1 Current volumes

The following chart illustrates the generation and distribution of MW across different types of waste treatment operations in Slovenia in 2021.



Source: data retrieved from Eurostat[152]

Figure 15: Generation and distribution of MW across different types of waste treatment operations in Slovenia in 2021

The leftmost column of the chart shows the total generated MW in 2021 of 1.077 million tonnes.

Of this, 21 000 tonnes were incinerated (D10) and 97 000 tonnes were energetically recovered (R1) (columns marked in red). The other waste treatment operations are indicated by the respective columns.

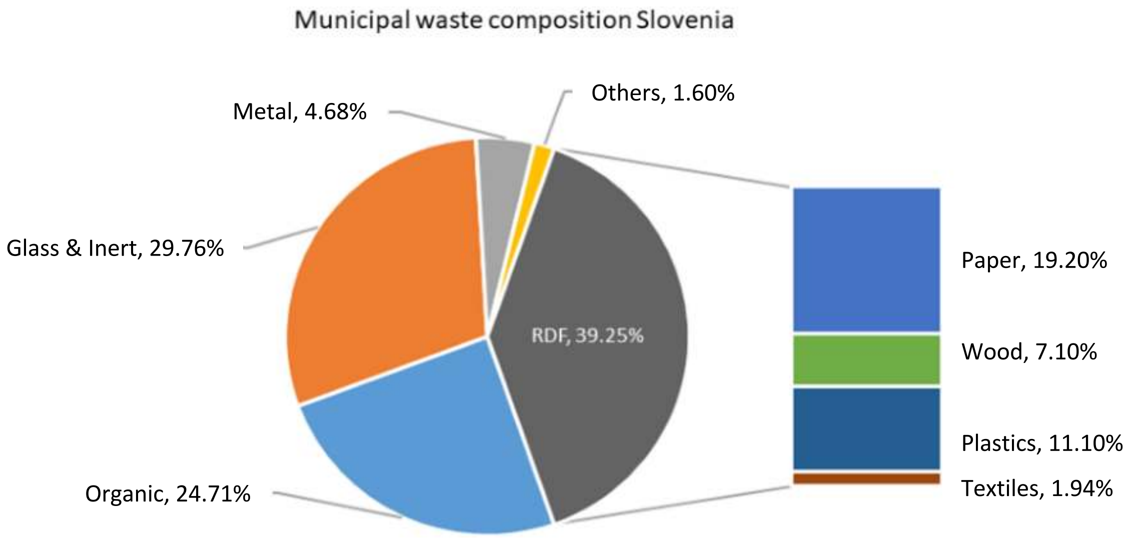
To validate the quantity, the calculations in Section 8.12.1.3 lead to the presumption that the Salonit Anhovo cement plant used 97 000 tonnes of RDF for the energy recovery.

It is suggested that the WtE facility in Celje, a municipality in the Savinja Region, incinerated a volume of 21 000 tonnes (D10) (Section 8.12.1.3).

8.12.1.2 RDF potential

The basis for obtaining the potential RDF volumes is the quantity of MW and the waste composition. For RDF, only the percentages of combustible matter (that is, paper, wood, plastics, and textiles) have been used in the calculation model.

[152] Eurostat – Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en



Source: EC factsheet[153]

Figure 16: Municipal waste composition in Slovenia (based on the Factsheet Slovenia)

The figure shows that 39.25% of the combustible fractions (that is, paper, wood, plastics, and textiles) can be used as raw material for RDF.

The in-house model considers that 20% of the RDF fraction is not used for RDF production.

This leads to 33.19% as the net yield of RDF.

Nevertheless, considering the Circular Economy Package (CEP) targets, a maximum share of RDF in MW of 25% should be aimed for, if the targets are to be met (see Section 3.3). Therefore, the **final long-term (2035) RDF potential is estimated at 269 000 t/y** (rounded to the nearest thousand).

To estimate the potential RDF quality and class, a simulation tool developed by the authors has been used. It takes into account the percentages of the combustible fractions from the figure above, as well as the respective NCVs. The quality data are listed in the next table:

Table 25: Average quality values of RDF components obtained from several waste-sorting campaigns carried out by the authors of this report

Waste fractions for RDF	NCV (as received) (MJ/kg)	Moisture (%)
Plastics	25.6	20.7
Paper, cardboard	13.1	21
Textile	16.4	13.6
Wood	14.7	15.2

Source: MVW[154]

The simulation tool needs the shares of combustible fractions and the corresponding quality values as input data. The table below shows the results.

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153 European Commission – Factsheet Slovenia – Waste Management. https://ec.europa.eu/environment/pdf/waste/framework/facsheets%20and%20roadmaps/Factsheet_Slovenia.pdf

154 Database Quality-Information-System (QIS) from MVW Lechtenberg & Partner.

Table 26: Simulated RDF quality

Slovenia	RDF total potential				
Waste fraction	**% in MW**	**% in RDF**	**Volumes (t)**	**NCV (MJ/kg)**	**Moisture (%)**
Plastics	11.1	28.3	100 961	25.6	20.7
Textiles	1.9	4.9	17 645	16.4	13.6
Wood	7.0	17.9	63 760	14.7	15.2
Paper and cardboard	19.2	48.9	174 634	13.1	21
Total	**39.3**	**100.0**	**357 000**	**17.1**	**19.5**
Class				**3**	

Source: MVW.

The resulting RDF would have an NCV of 17.1 MJ/kg (class 3) and a moisture content of 19.5%. If better quality is required, drying of this material is advised.

8.12.1.3 Uptake capacities

Waste-to-Energy: A WtE facility in the Celje municipality, which is located in the Savinja Statistical Region of Slovenia, has a capacity of **30 000 tonnes** of pre-treated MW per year. The government issued a decision that allowed Energetiki Celje to extend its concession to provide services for the incineration of communal waste in the municipalities of the Savinja Region for five years (valid until 29 August 2028). Moreover, the uptake capacity will be increased to **40 000 t/y**.[155] According to the operator, the WtE plant takes pre-treated MW belonging to the “light fractions,” which have the waste code 19 12 12.[156] It can be deduced that this fuel corresponds to RDF class 4.

The cement industry: There is only one cement plant in Slovenia: Salonita Anhovo. It has a 63% TSR owing to its use of a broad range of alternative fuels (Table 27). The alternative fuels are fed through the main burner of the kiln and calciners. Both feeding points can be simultaneously fed with different fuels, which are specially prepared and adapted for use in the cement plant. The use of alternative fuels takes place in accordance with the requirements and regulations of the environmental protection Integrated Pollution Prevention and Control (IPPC) permit.

The total cement and clinker capacity in Slovenia[157] is shown in the following table.

Table 27: Cement and clinker capacity of the Slovenian cement industry

Company	Plant	Clinker capacity	Cement capacity	№ of kilns	TSR (%)
Salonit Anhovo	Anhovo	0.96 Mt/y	1.30 Mt/y	1	63

Note: The clinker capacity is estimated based on the average clinker-to-cement ratio over all cement types in the EU-27[158]

[155] Skok, B. (2022). Vlada za pet let podaljšala koncesijo za sežiganje komunalnih odpadkov v Celju (The government extended the concession for incineration of communal waste in Celje for five years), 30 May 2022. https://www.celje.info/gospodarstvo/vlada-podaljsala-koncesijo-za-seziganje-komunalnih-odpadkov-v-celju/

[156] Energetika Celje – Technologija. https://www.energetika-ce.si/tehnologija

[157] Cemnet. https://www.cemnet.com/global-cement-report/country/Slovenia

[158] CEMBUREAU – The European Cement Association: Clinker Substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/

To estimate the potential RDF uptake, a simulation for the Salonit Anhovo cement plant has been carried out, based on the current clinker production, the heat required, and depending on the current RDF and other alternative fuels use.

Table 28: Thermal substitution scenario for the Salonit cement plant based on current RDF and other alternative fuels usage and potential for RDF uptake

Kiln data			
Total clinker production (t/y)	960 000	.	
Specific heat consumption (kcal/kg clinker)	800		
Heat consumption (Gcal/y)	768 000		
Thermal Substitution in the cement plant	**Substitution scenario**		
	Current	**85% TSR**	**Potential for RDF uptake**
Net calorific value (kcal/kg)	4 500	5 250	5 250
Thermal substitution rate (%)	63	85	22
Heat portions (Gcal/y)	483 840	652 800	168 960
RDF and other alternative fuel (t/y)	107 520	124 343	**32 183**

Source: MVW

As the table shows, with a clinker capacity of 0.96 million t/y, the Salonit cement plant currently has a high TSR of 63%. Increasing this to 85% TSR with RDF, meaning a difference of 22% TSR, would require an estimated additional uptake of 32 183 tonnes of class 2 RDF.

8.12.1.4 Qualities

The cement plant in Anhovo has the technical possibility of using RDF in both the main burner and the calciner, with the lower-quality RDF (class 3) being destined for the calciner and the higher-quality RDF (class 2) for the main burner. It can be assumed that the cement plant accepts RDF with properties matching at least class 2.

8.12.1.5 Implications of waste disposal costs/gate fees for RDF streams

There is a broad range of costs for disposal of waste in Slovenian landfills, depending on its hazardousness. The tariff for mixed MW is €78.39/t to €101.64/t (Table 21). Restrictions have been in place since 2011 for landfilling waste with specific chemical parameters. These restrictions also apply to mixed MW and separately collected waste. The price for waste incineration is €84.78/t (Table 22).

The disposal cost of RDF in Slovenia may be impacted in the following ways:

- **Higher RDF gate fees:** If the cost of landfilling RDF increases due to higher disposal costs, waste management facilities (MBT, RDF producers, incineration plants) and cement plants may choose to charge higher gate fees to accept and process RDF;
- **Increased competitiveness of waste incineration**: The price for waste incineration is slightly higher than the lower range of landfill tariffs for MW. If the landfilling costs continue to rise, waste incineration could become a more cost-competitive option for waste management facilities.

8.12.1.6 The influence of logistics

In terms of logistics, the main options in Slovenia are roads and railways. Most of the waste management centres (WMCs) are located in the North-Eastern part of the country, and the cement plant and WtE facility are located in the Western and central part of the country. However, Slovenia is small country, and the distances are acceptable for RDF transport.

Figure 17: Map of the WMC and uptake facility locations, with related distance ranges

Typically, the road transport costs for RDF for distances between 200 to 300 km are around €2/km for a lorry load of 20–23 tonnes[159] (see Section 8.13.2.2).

[159] Internal MVW Lechtenberg & Partner database.

8.12.1.7 Summary – Slovenia

The balance between potential RDF generation and uptake capacity is expressed in the next table.

Table 29: Potential RDF generation, current and potential uptake capacities available in Slovenia

RDF capacities	Amounts (t/y)	User type	RDF classes
Import[160]	23 000	cement plant – Salonit Anhovo	
Export[160]	192 000	incineration and energy recovery	
Current production capacity	–		
Current waste incineration (D10+R1)[161]	118 000	incineration and energy recovery	
Potential additional RDF uptake (WtE)	10 000	waste-to-energy	class 4 and class 5
Calculated current uptake of RDF + other alternative fuels (cement)	107 520		
Potential additional RDF uptake (cement)	32 183	one cement plant – Salonit Anhovo	100% class 2
Potential generation	269 000	–	

In 2020, Slovenia exported 192 000 tonnes of RDF and imported around 23 000 tonnes. This indicates that the country reached its RDF uptake capacity. It is possible that the RDF imports were of higher quality than locally produced RDF or were imported due to their being sold on more favourable economic terms.

The Toplarna Celje WtE plant has been granted permission to increase its capacity, which would result in an additional uptake of 10 000 tonnes.

If the cement plant in Anhovo increases its TSR to 85% (ca. 5 250 kcal/kg) by using RDF, this would result in additional RDF uptake of around 32 183 tonnes. The simulation of the average NCV of the total RDF resulted in 17.1 MJ/kg, which corresponds to class 3 (see Section 8.12.1.2). As mentioned above, the Anhovo cement plant requires at least 22 MJ/kg or class 2, which can be produced by eliminating more plastics from the total RDF potential (see Section 8.12.1.2). The remaining 324 817 tonnes of RDF will have a lower NCV of 16.6 MJ/kg (class 3). An improved approximation of the quality would require dedicated waste analysis.

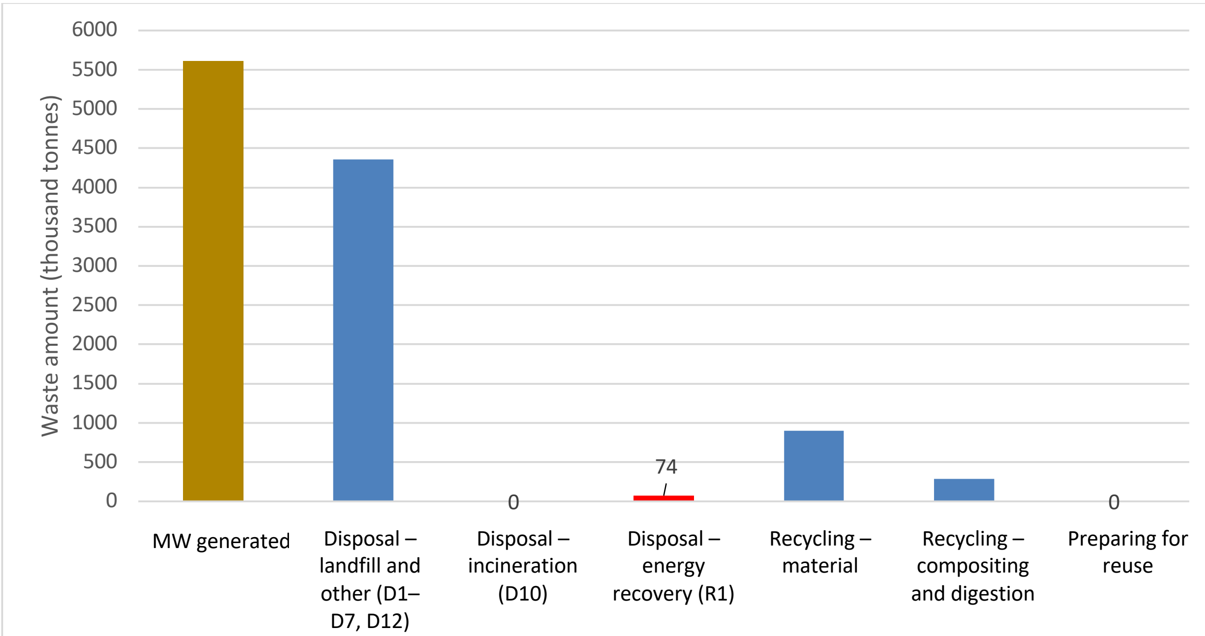
160 Eurostat: Waste shipment across border. https://ec.europa.eu/eurostat/documents/342366/351880/Waste_shipment_data_imports_exports/

161 Eurostat – Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

8.12.2 Greece

8.12.2.1 Volumes

The following chart illustrates the generation and distribution of MW across different types of waste treatment operations in Greece in 2019:



Source: data retrieved from Eurostat[162]

Figure 18: Generation and distribution of MW across different types of waste treatment operations in Greece in 2019

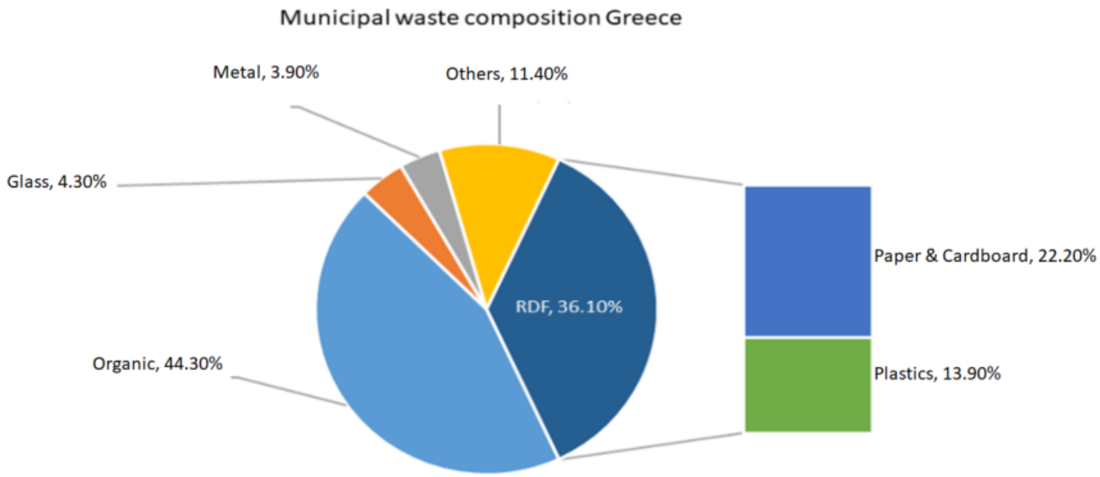
The leftmost column of the chart shows total arisings of 5.6 million tonnes in 2019. Of this, the major part was landfilled (77.7%). Only a minimal percentage – 1.3%, or 74 000 tonnes – was energetically recovered (R1) (column marked in red). The amounts of waste processed by the other types of waste treatment operations are indicated by the respective columns.

To validate the quantity, the calculations in Section 8.12.2.3 lead to the presumption that cement plants in Greece used these 74 000 tonnes of RDF for energy recovery.

[162] Eurostat – Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

8.12.2.2 RDF potential

The potential RDF volumes are based on the quantity of MW and on the waste composition. For RDF, only the percentages of combustible matter (paper, wood, plastics, and textiles) have been used in the calculation model.



Source: BlackForest Solutions[163].

Figure 19: MW waste composition in Greece

The column to the right of the chart highlights the combustible fractions that are suitable for RDF production, that is, 36.1%.

To obtain the net yield of RDF, the rationale for recyclables has been applied, as already described in Section 8.12.1.2.

The in-house model considers that 20% of the RDF fraction is not used for RDF production.

This leads to 28.9% as the net yield of RDF.

Nevertheless, considering the Circular Economy Package (CEP) targets, a maximum share of RDF of MW of 25% should be aimed for if the targets are to be met (see Section 3.3). Therefore, the **final long-term (2035) RDF potential is estimated at 1 403 000 t/y** (rounded to the nearest thousand).

To estimate the potential quality of this RDF, the same simulation method described in Section 8.12.1.2 has been applied. The average NCV of the RDF is 17.9 MJ/kg (class 3), and the moisture content is 20.9%.

[163] BlackForest Solutions GmbH. (2020). Guide for Greek municipalities with steps to be taken to introduce separate collection of bio-waste. https://www.giz.de/de/downloads/Biowaste%20Guide%20for%20municipalities%20EN.pdf

8.12.2.3 Uptake capacities

Waste-to-energy: WtE operations in Greece are not well developed. There is currently only one incineration plant for hazardous waste in operation, located at Ano Liossia. It is owned by the Association of Municipalities in the Attica Region, Solid Waste Management, operated by a subsidiary of the Greek-based ELLAKTOR Group, and is the first and only licensed incineration facility in Greece. The incinerator is used only for hospital waste, collected from 1 800 medical unit points around Greece (hospitals, clinics, clinical laboratories, doctors' private practices, dental clinics, veterinary clinics, and pharmaceutical warehouses). The total capacity of the facility is 4 000 t/y.[164] It is not intended for RDF. The Greek WtE Research and Technology Council developed three scenarios for overcoming all difficulties in waste management in the Attica region.[165] These scenarios examined various volumes of between 400 000 and 700 000 t/y of MW, as well as 300 000 t/y of RDF. However, nothing has materialised, and there has yet to be any actual uptake of RDF.

Cement industry: The total grey cement and clinker capacity in Greece[166] is shown in the next table. The clinker capacity is estimated based on the average clinker-to-cement ratio over all cement types in the EU-27.[167]

Table 30: Cement and clinker capacity of the Greek cement industry

Company	Plant	Clinker capacity (Mt/y)	Cement capacity (Mt/y)	№ of kilns	Current TSR (%)[168]
Halyps [Heidelberg]	Aspropyrgos	0.74	1.00	1	55
Heracles [Holcim]	Milaki	5.23	7.10	1	23
Heracles [Holcim]	Volos			3	
Titan	Patras	1.40	1.90	1	0
Titan	Kamari	2.14	2.90	2	43
Titan	Thessaloniki	1.22	1.65	1	32
Total		**10.72**	**14.55**	**10**	

The TSR of Titan Cement is 25%,[169] including various alternative fuels (RDF, biomass, and tyres). Titan Cement operates four plants in Greece, two of which use alternative fuels (the plants in Kamari and Thessaloniki) and two of which do not (the plants in Patra and Elefsina). The plant in Patra is not permitted to use waste-derived materials. The Elefsis White (Titan) plant is a white cement producer and, for quality reasons, RDF cannot be used (see Section 8.4).

The TSR of Heracles (Holcim's plants in Volos and Milaki) is 23% (2018) with various alternative fuels (RDF, biomass, and dried sewage sludge) in a total quantity of more than 200 000 tonnes. Halyps (HeidelbergCement's plant) has a TSR in the range of 55% (2023).

To estimate Greece's RDF potential uptake, a sample calculation has been carried out for Halyps Cement (Heidelberg) in Aspropyrgos. The potential for further RDF uptake has been calculated on the basis of the current clinker production, the heat required, and depending on the current RDF and other alternative fuels use.

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164 ΕΛΛΑΚΤΩΡ: Διαχείριση νοσοκομειακών αποβλήτων Covid-19 του Ν.Ι.Μ.Τ.Σ (ELLAKTOR: Management of hospital waste Covid-19 of N.I.M.T.S.). CSR index. 01.09.2021. https://csrindex.gr/ellaktor-diacheirisi-nosokomeiakon-a/

Kalogirou, E., and Sakalis, A. (2016). Overview of the Waste Management Situation and Planning in Greece, in: Thomé-Kozmiensky, K.J., & Thiel, S. (Eds.), Waste Management, Volume 6 – Waste-to-Energy.

166 Cemnet. https://www.cemnet.com/global-cement-report/country/greece

167 CEMBUREAU – The European Cement Association: Clinker Substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/

168 Internal MVW Lechtenberg & Partner database.

169 Internal MVW Lechtenberg & Partner database.

Table 31: Thermal substitution scenario for the Halyps Cement plant based on current RDF and other alternative fuels usage and potential for RDF uptake

Kiln data			
Total clinker production (t/y)	737 000		
Specific heat consumption (kcal/kg clinker)	800		
Heat consumption (Gcal/y)	589 600		
Thermal substitution in the Halyps Cement plant	**Substitution scenario**		
	Current	**85% TSR**	**Potential for RDF uptake**
Net calorific value (kcal/kg)	4 500	4 500	4 500
Thermal substitution rate (%)	55.0	85.0	30.0
Heat portions (Gcal/y)	324 280	501 160	176 880
RDF and other alternative fuels (t/y)	72 062	111 369	39 307

This calculation reveals that Halyps Cement could utilise around 39 307 tonnes of RDF per year.

The simulation has been applied to the other cement plants. The following table shows the summarised RDF potential uptakes based on the current TSR, as well as the maximum potential TSR.

Table 32: Cement companies in Greece and related TSR and RDF-uptake potential

Company	Plant	Clinker capacity (Mt/y)	Current TSR (%)	Current RDF and other alternative fuels usage (tonnes)	TSR limit (%)	TSR differenc e (%)	Potential RDF uptake in tonnes
Halyps [Heidelberg]	Aspropyrgos	0.74	55	72 062	85	30	39 307
Heracles [Holcim]	Milaki	5.23	23	216 750	85	62	573 969
Heracles [Holcim]	Volos						
Titan	Patras	1.40	-	-	-	-	-
Titan	Kamari	2.14	43	163 385	85	42	159 585
Titan	Thessaloniki	1.22	32	69 180	85	53	114 579
		10.72		**521 377**			**887 440**

As the table shows, with a clinker capacity of 10.72 million t/y, cement plants in Greece currently co-process around 521 377 tonnes of various alternative fuels, including RDF. There is the potential for co-processing of an additional 887 440 tonnes of RDF per year in the Greek cement industry.

8.12.2.4 Qualities

The cement kilns in Greece that employ alternative fuels currently have the technical possibility of using both higher-quality (main burner) and lower-quality (calciner) RDF.

It should be noted that the higher the TSR, the higher the RDF quality required. For TSR up to 60%, class 3 may be used, and for TSR up to 85%, class 2 is required. It is assumed that the Greek cement industry could utilise around 887 440 tonnes of RDF, of which around 43% would need to be class 2 and approximately 57% class 3.

8.12.2.5 Implications of waste disposal costs/gate fees on RDF streams

The current low landfill tax (in 2023, €25/t, see Table 21) is not a major hurdle to the disposal of the major portion of MW in landfills – that is, 77.7% (Section 8.12.2.1). In other words, it is cheaper to divert waste to landfills than to produce RDF. This statement can be corroborated by the following findings:

The current low rate of energy recovery of Greek MW (Section 8.12.2.1), in conjunction with the importing of RDF for thermal recovery (R1) in the Greek cement industry (46 737 tonnes from the United Kingdom and Italy, EWC 19 12 12, 19 12 10 in 2020),[170] may be a sign of the high gate fees for acceptance of imported RDF. Other factors, such as the low or unstable quality of locally produced RDF, may also play a role, but it can be assumed that the financial attractiveness of supposedly high gate fees will predominate. However, there is no information available about the range of gate fees.

8.12.2.6 The influence of logistics

In terms of logistics, the choices in Greece are transport by road, railway, and sea. The collection and handling of MW from the Greek islands is expected to be challenging. There are two WMCs located on islands, one on the island of Crete, which is in operation, and the other on the island of Corfu, which is not currently in operation.

Three of the WMCs and all of the cement plants are located close to or directly on the Aegean Sea coast, which gives some flexibility, as well an opportunity for the import and export of RDF by sea.

Three of the WMCs are located in the Attica region, positioned within a 100-km radius of the cement plants in Kamari (Titan) and Halyps (HeidelbergCement). The cement plant in Milaki (Holcim) is approximately 140 km from the WMC. The distance between Holcim's cement plants and the WMC in Volos is less than 50 km. In all cases, the preferable mode of transport is by road.

However, delivery of MW or RDF from the islands needs to be executed by ship.

[170] Eurostat. Waste shipments across borders. https://ec.europa.eu/eurostat/web/waste/data

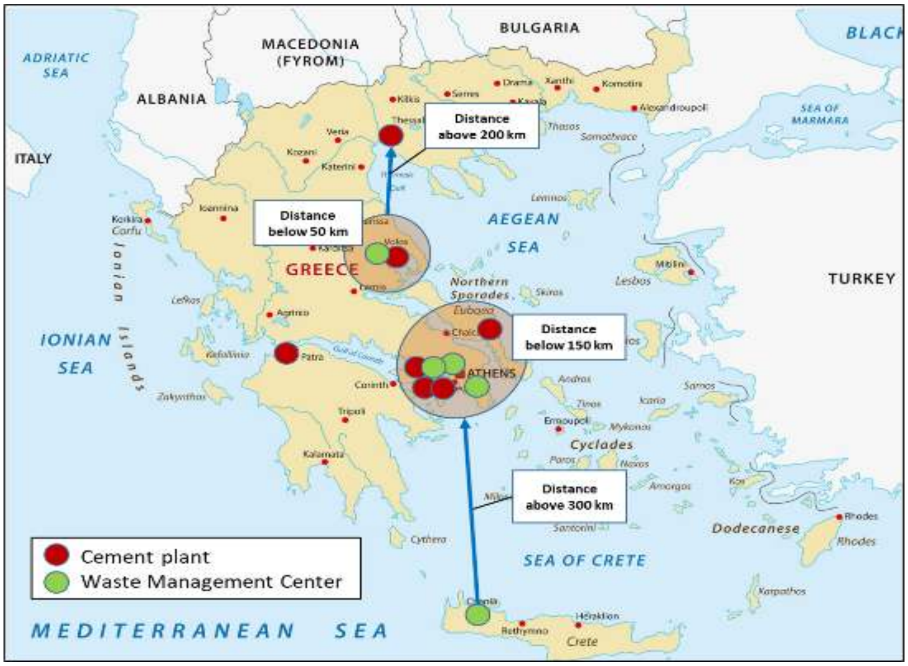

Figure 20: Map of the WMC and uptake facility locations with related distance ranges

Typically, the road transport costs for RDF vary between €2.3/km and €2.5/km for a lorry load of 20–23 tonnes.[171] It is expected that the transport costs up to a distance of 100 km would be about €2.5/km and that the costs for transport above 200 km would be around €2.3/km.

171 Internal MVW Lechtenberg & Partner database.

8.12.2.7 Summary – Greece

The balance between RDF generation, production, and uptake capacity is expressed in the next table.

Table 33: Potential RDF generation and current and potential uptake capacities in Greece

RDF capacities	Amounts (t/y)	User type	RDF classes
Import[172]	63 200		
Export	–		
Current production capacity	–		
Current waste incineration (D10+R1)[173]	74 000	energy recovery in cement plants	class 3
Potential additional RDF uptake (WtE)	–	waste-to-energy	
Calculated current uptake of RDF + other alternative fuels (cement)	521 377		
Potential additional RDF uptake (cement)	887 440	cement plants	~43% class 2 for main burner ~57% class 3 for calciner
Potential generation	1 403 000		class 3

If the local cement industry increases its TSR to 85%, based on the current cement demand, this would result in a potential RDF uptake of 887 440 t/y.

The simulation of the average NCV of the total RDF resulted in 17.9 MJ/kg, which corresponds to class 3 (see Section 8.12.2.2). As mentioned above, the cement industry in Greece requires at least 19 MJ/kg or class 3. The remaining 732 560 tonnes will have a lower NCV of 16.6 MJ/kg. This is also class 3.

As already mentioned, an improved approximation of the quality requires dedicated waste analysis in every country.

It seems Greece has the potential to produce 1.62 million tonnes of RDF per year from MW. The cement industry has the capability to co-process 55% of the potential RDF.

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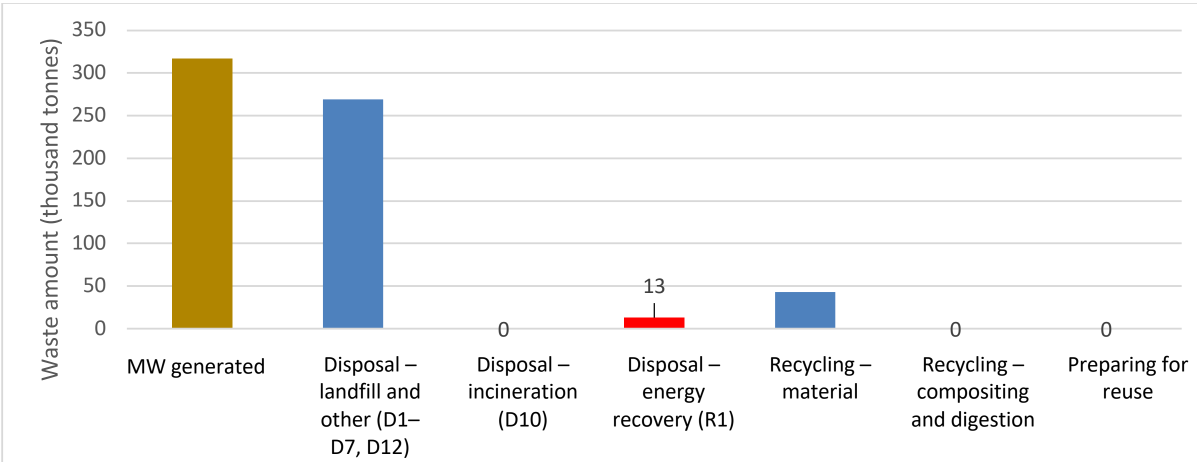
172 Eurostat. Waste shipment across borders. https://ec.europa.eu/eurostat/documents/342366/351880/Waste_shipment_data_imports_exports/

173 Eurostat. Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

8.12.3 Malta

8.12.3.1 Volumes

The following chart illustrates the generation and distribution of MW across different types of waste treatment operations in Malta in 2021:



Source: Eurostat[174]

Figure 21: Generation and distribution of MW across different types of waste treatment operations in Malta in 2021

The leftmost column of the chart shows the total arisings of 317 000 tonnes in 2021, of which the major part (84.9%) was landfilled. According to Eurostat, only a small volume of 13 000 tonnes was energetically recovered (R1) (column marked in red).

There are no cement or lime factories on the island that could serve as end user for the 13 000 tonnes. There is only an incinerator at the abattoir in Marsa. The Marsa Thermal Treatment Facility was designed not only for slaughterhouse waste, but also for a broad range of types of hazardous waste.[175] According to the European Commission's factsheet,[176] the incinerator has a capacity of 13 000 tonnes, however, there is no information available on whether it utilises that fully. However, the Wasteserv Malta North facility processes about 15 000 t/y of so-called "grey bags," in which mixed recyclables (cardboard, paper, plastic bags, metal bottles, cans, etc.) are collected by the inhabitants. The material can actually be considered RDF that is both landfilled and exported – depending on market demand.[177]

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174 Ibid.

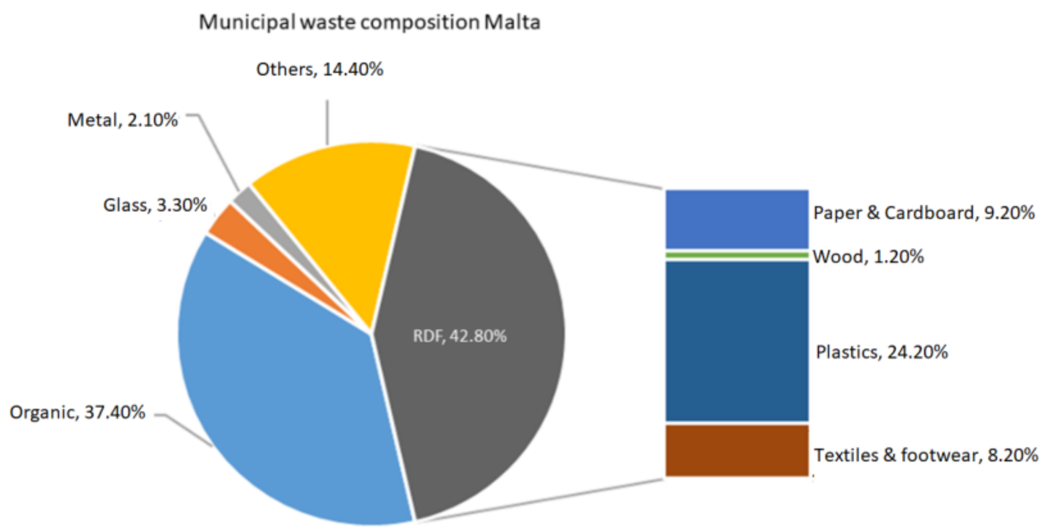
175 Marsa Thermal Treatment Facility: Operation of an incineration plant for hazardous wastes and animal by-products, and a rendering plant (Autoclave) – Application for Renewal of IPPC permit IP 0004/07/B. Wasteserv; @econsulting. Version 2.0; Febr. 2021.

176 European Commission. Factsheet – Malta (Waste Management plan). https://ec.europa.eu/environment/pdf/waste/framework/facsheets%20and%20roadmaps/Factshee_Malta.pdf

177 Andusia Holdings Limited UK, expert interview.

8.12.3.2 RDF potential

The RDF potential volumes have been obtained on the basis of the quantity of MW and the waste composition. For RDF, only the percentages of combustible matter (paper, wood, plastics, textile) have been used in the calculation model.



Source: The chart has been created based on the Waste Management Plan[178]

Figure 22: Municipal waste composition in Malta 2019

The column to the right of the chart highlights the combustible fractions that are basically suitable for RDF production, which account for 42.8% of MW.

To obtain the net yield of RDF, the rationale for recyclables has been applied, as described in Section 8.12.1.2.

The in-house model considers that 20% of the RDF fraction is not used for RDF production.

This leads to 36.1% as the net yield of RDF.

Nevertheless, considering the Circular Economy Package (CEP) targets, a maximum share of RDF of MW of 25% should be aimed for, if the CEP targets are to be met (see Section 3.3). Therefore, the **final long-term (2035) RDF potential is estimated at 79 000 t/y** (rounded to the nearest thousand).

To estimate the potential quality of this RDF, the same simulation method described in Section 8.12.1.2 has been applied. The average NCV of the RDF is 20.8 MJ/kg (class 2), and the moisture content is 19.3%.

8.12.3.3 Uptake capacities

In Malta, there are no cement plants or power plants that can serve as outlets for RDF. The material from Wasteserv's Malta North facility (see next section) is both landfilled and exported – depending on market demand.[179] The case of the small incinerator in Marsa has already been discussed in Section 8.12.3.1. However, there are plans to replace the Marsa incinerator with a WtE facility with a capacity of between 79 000 to 114 000 t/y.[180] Currently, a tender for this purpose is underway,[181,182] but its outcome is expected at least in three to four years.

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[178] Ministry for the Environment, Climate Change and Planning: Long Term Waste Management Plan 2021–2030, 216–7. https://era.org.mt/wp-content/uploads/2022/02/Long-Term-Waste-Management-Plan-v1.4.3-Spreads-Digital-Version.pdf

[179] Andusia Holdings Limited UK, expert interview.

[180] Ministry for the Environment, Sustainable Development and Climate Change, Malta. (2018). Technical report on the setting up of a waste-to-energy facility in Malta.

[181] Wasteserv: WasteServ's waste-to-energy tendering process attracts 11 bidders. 21.06.2022 (https://www.wsm.com.mt/en/article?id=effe4195-ecc5-447e-9e5a-b85848f2fcc5)

[182] European Union. TED – Tenders Electronic Daily. https://ted.europa.eu/udl?uri=TED:NOTICE:165878-2020:TEXT:EN:HTML

8.12.3.4 Quality

According to the authors' calculations (see Section 8.12.3.2), the average NCV of the total RDF is 20.8 MJ/kg, which corresponds to class 2. This result is close to the information provided by a waste trading stakeholder. As mentioned above, Wasteserv's Malta North facility processes about 15 000 t/y of so-called "grey bags" of mixed recyclables. The NCV of these materials is about 18.6 MJ/kg. The moisture content is about 27%, and it has low trace elements (many elements, including Hg, are below the detection limit).[183] This probably corresponds most closely to class 3.

8.12.3.5 Implications of waste disposal costs/gate fees for RDF streams

The company Wasteserv is responsible for organising, managing, and operating integrated systems for waste management[184] at Malta North MTP and Sant Antnin MBT. The company collects gate fees for acceptance of different types of waste. The gate fees for mixed MW to be paid to the company are €40/t for 2023, and are projected to increase by €20/t per year up to €120/t in 2027 (see Table 21). There is no landfill tax in Malta, and no restrictions on landfilling (see Table 21). MVW Lechtenberg was recently offered a high-calorific-value plastic film fraction that could be considered class 2 RDF material from Malta through a waste trading company. The gate fee offered for delivery to the MVW Lechtenberg processing facility in the north of Germany was €75/t.[185] Given the projected increase in gate fees and the lack of other local uptake opportunities (the planned WtE is still in the tendering phase), RDF exports are expected to increase.

8.12.3.6 The influence of logistics

The short inland distances within Malta are considered an advantage. Given the lack of industrial outlets for RDF on the islands, the material must either be landfilled or exported by sea vessels. Exports are subject to a notification according to the Waste Shipment Regulation.[186] For several years, Malta has been exporting waste (EWC 19 12 12; RDF; waste from mechanical treatment; RDF, paper, and plastics) to Portugal for landfilling (D1). According to Eurostat's latest numbers for 2020, 17 862 tonnes were exported that year.[187]

8.12.3.7 Summary – Malta

The balance between RDF generation, production, and uptake capacity is expressed in the next table.

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183 Andusia Holdings Limited UK, expert interview.

184 WasteServ Malta Ltd, ECOHIVE Complex, Tul il-Kosta, Naxxar NXR9030. https://www.wsm.com.mt/en/about-us

185 Andusia Holdings Limited UK, expert interview.

186 REGULATION (EC) No 1013/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 June 2006 on shipments of waste.

187 Eurostat. Transboundary shipments of notified waste by partner, hazardousness, and waste management operations (env_wasship). https://ec.europa.eu/eurostat/databrowser/view/env_wasship/default/table?lang=en

Table 34: Balance between RDF generation potential and production and uptake capacities in Malta

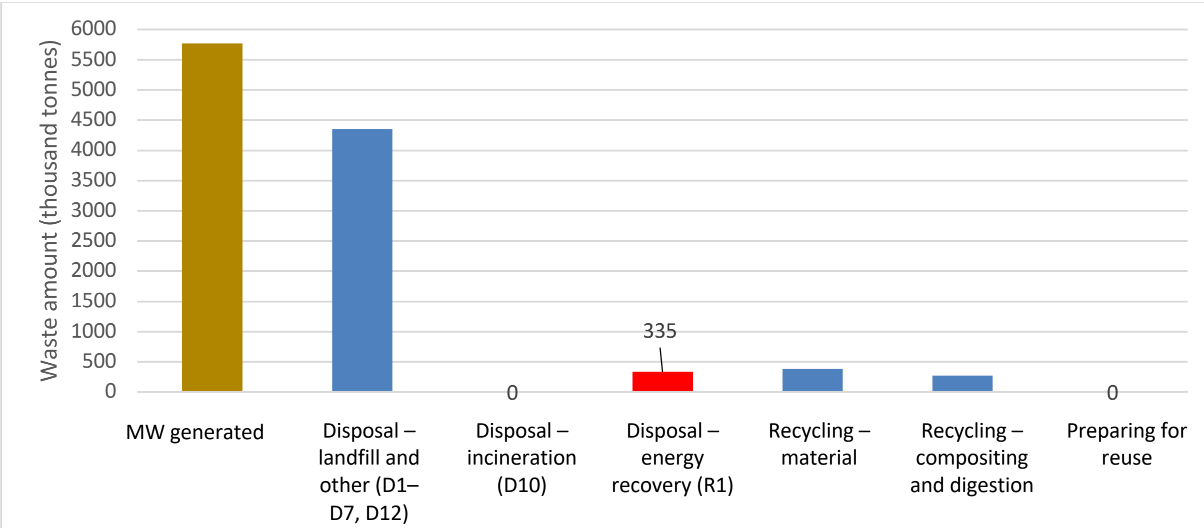
RDF capacities	Amounts (t/y)	User type	RDF classes
Import	-	-	
Export	17 900	incineration and energy recovery	class 3
Current production capacity	15 000		
Current waste incineration (D10+R1)	13 000	energy recovery	hazardous waste
Potential additional RDF uptake (WtE)	-	waste-to-energy	
Calculated current uptake of RDF + other alternative fuels (cement)	-		
Potential additional RDF uptake (cement)	-	-	
Potential RDF generation	79 000	-	class 2

In Malta, the RDF uptake is likely to be very low because the existing incinerator is dedicated to hazardous and animal waste. Because of the low landfill prices (Table 21), the major portion of RDF still ends up in the landfill. There is no market for RDF locally, therefore, RDF can currently only be exported.

8.12.4 Romania

8.12.4.1 Volumes

The following chart illustrates the generation and distribution of MW across different types of waste treatment operations in Romania in 2021:



Source: Eurostat[188]

Figure 23: Generation and distribution of MW across different types of waste treatment operations in Romania in 2021

The leftmost column of the chart shows the total MW arisings of 5.768 million tonnes in 2021. The major portion ended up in landfills (75.7%). Around 335 000 tonnes (5.8%) were energetically recovered (R1) (column marked in red). The volumes of the other waste operations are expressed by the respective columns.

It has been assumed that these 335 000 tonnes of RDF were produced locally and absorbed by the local cement industry, as there was no RDF import. To validate the quantities utilised in the local cement industry, please refer to Section 8.12.4.32.

The local **RDF production capacity is estimated at around 335 000 t/y** Table 35). The RDF is produced in an MBT plant with a capacity of 150 000 t/y that was implemented with the purpose of reducing the amount of waste before landfilling.[189] This plant was adapted and expanded for the production of RDF for use in cement factories through the introduction of cost-effective composting boxes with a semipermeable membrane roof in combination with a regular open biofilter. The waste input is sorted into fractions below and above 80 mm, then classified by a mobile ballistic separator. The average calorific value of the RDF is 17–18 MJ/kg. Geocycle (Holcim's subsidiary for providing alternative fuels) operates RDF production plants in Campulung and Alesd.

Table 35: Input capacities and related RDF production capacity per WMC

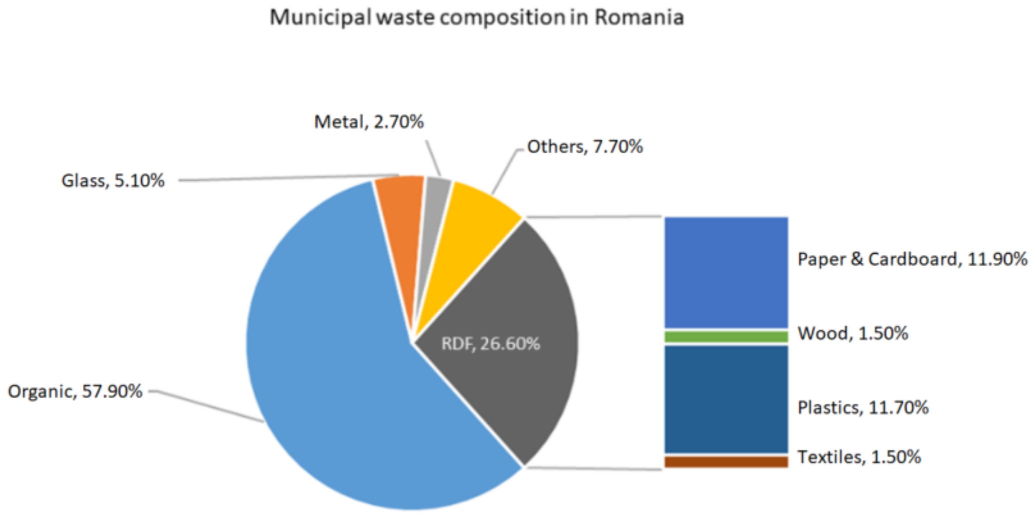
Waste management centre	RDF production (t/y)
Other facilities	117 560
Geocycle (in two cement plants)	217 440
Total	**335 000**

188 Eurostat – Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

189 8th International Symposium "Waste-To-Resources 2019", Hanover/Germany. Developments in waste management in synergy with the cement market. ZKG, 2019. https://www.zkg.de/en/artikel/zkg_Developments_in_waste_management_in_synergy_with_the_cement_market-3403585.html

8.12.4.2 RDF potential

The RDF potential volumes have been obtained on the basis of the quantity of MW and the waste composition. For RDF, only the percentages of combustible matter (paper, wood, plastics, and textiles) have been used in the calculation model.



Source: National Waste Management Plan[190]

Figure 24: MW composition in Romania

The column to the right of the chart highlights the combustible fractions that are suitable for RDF production, which account for 26.6% of total MW.

The in-house model considers that 20% of the RDF fraction is not used for RDF production.

This leads to 21.9% as the net yield of RDF.

This potential is below the maximum share of RDF of MW of 25% that needs to be aimed for, if the CEP targets are to be met (see Section 3.3).

Ultimately, **the potential RDF** that can be obtained from 5.768 million tonnes of MW **is estimated at 1.262 million t/y** (rounded to the nearest thousand).

To estimate the potential quality of this RDF, the same simulation method described in Section 8.12.1.2 has been applied. The average NCV of the RDF is 18.9 MJ/kg (class 3), and the moisture content is 20.1%.

Waste-to-Energy: There are no incineration facilities for MW in Romania.

Even though incineration is generally considered too expensive for the waste management market in Romania, future plans for an integrated waste management system within the Bucuresti-Ilfov Region include the construction of the first MW incinerator. The construction of a high-capacity waste incineration centre in Bucharest is also forseen, but this project was still in the planning phase in September 2020.[191] Interest in adopting such technology has been shown in the city of Brasov, as well.[192] A consortium consisting of Romelectro SA and Baumgarte Boiler Systems GmbH Germany has been assigned to develop the WtE project in Timişoara Municipality by erecting a plant and incorporating it in Timişoara Sud TPP. This would be the first WtE project in Romania with a planned capacity to process 78 750 t/y of MW and bio coal.[193]

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[190] Programul Operational Capacitate Administrava 2014–2020. Planul Național de Gestionare a Deșeurilor versiunea 5, 2 noiembrie 2017. http://mmediu.ro/app/webroot/uploads/files/PNGD_vers5.pdf

[191] European Environmental Bureau (EEB). (2020). NoTimeToWaste – Member States delay meeting the inevitable targets.

[192] Country fact sheet – Municipal waste management (Romania 2016). European Environment Agency, 2016.

[193] Romelectro Group – Consortium Leader for the first Waste-to-Energy Project in Romania. https://www.romelectro.ro/romelectro/en/news/romelectro-leader-first-waste-to-energy

The cement industry: The following table shows the total cement and clinker capacity in Romania.[194] The clinker capacity has been estimated based on the average clinker-to-cement ratio over all cement types in the EU-27.[195]

Table 36: Cement and clinker capacity of the Romanian cement industry

Company	Plant	Clinker capacity (Mt/y)	Cement capacity (Mt/y)	№ kilns	Current TSR (%)
Holcim	Campulung	2.21	3.00	1	40
Holcim	Alesd	1.70	2.30	1	
HeidelbergCement	Tasca	2.21	3.00	2	33.7
HeidelbergCement	Fieni	1.22	1.65	1	
HeidelbergCement	Chiscadaga	1.22	1.65	1	
CRH	Medgidia	1.95	2.64	2	37
CRH	Hoghiz	0.99	1.35	1	37
Total		**11.49**	**15.59**	**9**	

The TSR of Holcim is 40%, including different alternative fuels (waste oil, RDF, biomass, and waste tyres).[196] The TSR of HeidelbergCement is 33.7% with various alternative fuels.[197] The TSR of CRH is 37% with various types of alternative fuels.[198] The use of alternative fuels in the Romanian cement industry is well established, since all cement kilns have invested in specific technology and have been authorised for the co-incineration of a wide range of waste fractions and alternative fuels. It has been estimated that the co-incineration capacity in Romania and the potential RDF demand is ten times higher than the currently available RDF quantities.[199] This represents an incentive within the sector to invest in the selective collection and production of RDF. To estimate the RDF potential uptake in Romania, a sample calculation has been carried out for the Holcim Alsed cement plant.

Table 37: Thermal substitution scenario for the Holcim Alesd Cement plant based on current RDF and other alternative fuels usage and potential for RDF uptake

Kiln data			
Total clinker production (t/y)	1 695 100		
Specific heat consumption (kcal/kg clinker)	800		
Heat consumption (Gcal/y)	1 356 080		
Thermal substitution in the Holcim Alesd cement plant	**Substitution scenario**		
	Current	**85% TSR**	**Potential for RDF uptake**
Net calorific value (kcal/kg)	4 500	4 500	4 500

[194] Cemnet. https://www.cemnet.com/global-cement-report/country/romania
[195] CEMBUREAU – The European Cement Association: clinker substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/
[196] https://www.holcim.ro/ro/raportari-si-anunturi-publice-de-mediu
[197] https://www.heidelbergcement.ro/ro/raport-sustenabilitate
[198] https://www.romcim.ro/despre-noi/sustenabilitate/mediu-2/
[199] European Environment Agency. (2016). Country fact sheet – Municipal waste management (Romania 2016).

Thermal substitution rate (%)	40%	85%	45%
Heat portions (Gcal/y)	542 432	1 152 668	610 236
RDF and other alternative fuels (t/y)	120 540	256 148	135 608

The following table shows the potential RDF uptake in all Romanian cement plants based on the current TSR as well as the potential maximum TSR.

Table 38: Cement plants in Romania and related TSR and RDF potential uptake

Company	Clinker capacity (Mt/y)	Current TSR (%)	Current RDF and other alternative fuels usage (tonnes)	TSR limit (%)	TSR difference (%)	RDF potential uptake in tonnes
Holcim – Campulung	2.21	40%[200]	157 227	85	45	176,880
Holcim – Alesd	1.70		120 540	85	45	135 608
HeidelbergCement–Tasca	2.21	33.7%[201]	132 503	85	51	201 604
HeidelbergCement–Fieni	1.22		72 877	85	85	183 759
HeidelbergCement–Chiscadaga	1.22		72 877	85	85	183 759
CRH – Medgidia	1.95	37%[202]	127 983	85	48	166 031
CRH – Hoghiz	0.99	37%	65 446	85	48	84 902
Total	**11.49**		**749 451**			**986 790**

As the table shows, with a clinker capacity of 11.49 million t/y, the cement plants in Romania, currently co-process around 749 451 tonnes of various alternative fuels, including RDF. Considering the TSR difference, there is the potential for an additional 986 790 tonnes of RDF to be co-processed in the cement industry.

It should be noted that the higher the TSR, the higher the quality of RDF required. For TSR up to 60%, class 3 may be used, while for TSR up to 85%, class 2 is required. It is assumed that the Romanian cement industry can utilise 986 790 tonnes of RDF, of which around 48% is class 2 and approximately 52% is class 3.

8.12.4.3 Quality

The cement plants in Romania are already equipped to use both higher-quality (main burner) and lower-quality (calciner) RDF. This means they can take materials that match at least class 3 for use in the calciners and at least class 2 for use in the main burners (see also Section 8.4).

8.12.4.4 Implications of waste disposal costs/gate fees for RDF streams

The cost of disposing of MW in Romania is comparatively low. It is about €43/t (see Table 21). Therefore, it is not surprising that 75.5% of MW is disposed of in landfills (Section 8.12.4.1). However, there is no information available about prices or gate fees for RDF.

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200 Raportul Annual De Mediu- Geocycle / Holcim – Romania, 2022. https://www.holcim.ro/ro/raportari-si-anunturi-publice-de-mediu

201 Raport de sustenabilitate 2021 HeidelbergCement Romania. https://www.heidelbergcement.ro/sites/default/files/2023-01/Raport%20de%20sustenabilitate%202021.pdf

202 CRH – Extract from the 2022 Annual Environmental Report, Romania. https://www.romcim.ro/wp-content/uploads/2023/02/Raport_mediu_2022_extras-site.pdf

8.12.4.5 The influence of logistics

In terms of logistics, the only mode of transportation for RDF within Romania is road. The cement plants are spread equally across the country. Some of the largest cities in Romania are located within a 200-km radius of Bucharest, with a total population above 3.5 million citizens. This area is covered by four cement plants.

In the West, North-East, and North-West regions of Romania, the country is covered by one cement plant per region, with distances of less than 200 km between them. Most of the power plants are located in the South of Romania, close to the city of Craiova (that is, less than 100 km from the city).

It is expected that the road transport cost for RDF would be around €2/km to €2.5/km for loads of 20–23 tonnes.[203]

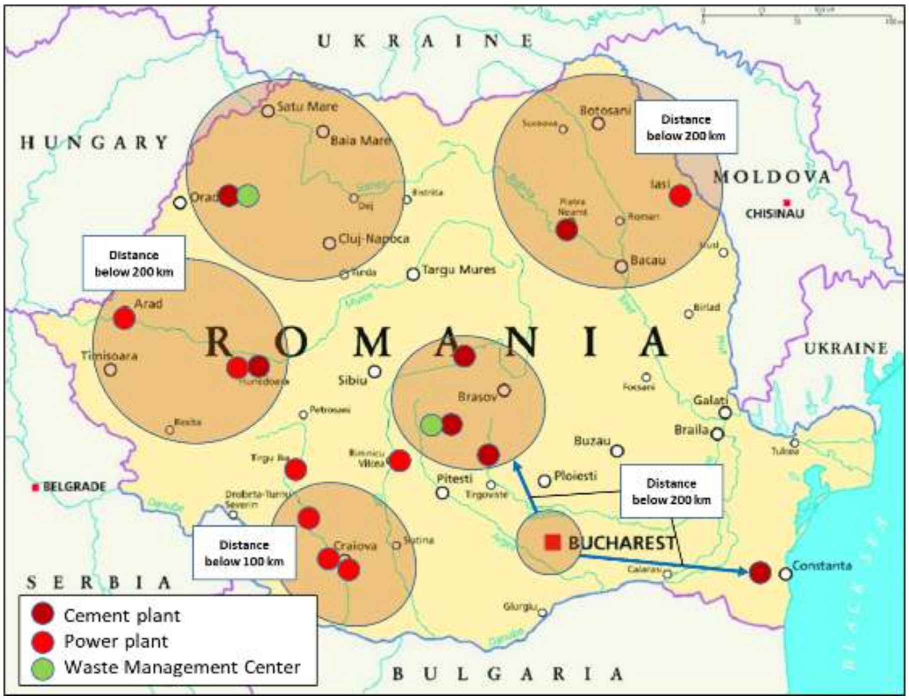


Figure 25: Map of the WMC and uptake facility locations with related distance ranges

[203] Internal MVW Lechtenberg & Partner database.

8.12.4.6 Summary – Romania

The balance between RDF generation, production, and uptake capacity is expressed in the following table.

Table 39: Balance between the RDF generation potential and the production and uptake capacities

RDF capacities	Amounts (t/y)	User type	RDF classes
Import[204]	-		
Export	-		
Current production capacity	335 000		
Current waste incineration (D10+R1)[205]	335 000	energy recovery in the cement plants	
Potential additional RDF uptake (WtE)	-	waste-to-energy	
Calculated current uptake of RDF + other alternative fuels (cement)	749 451		
Potential additional RDF uptake (cement)	986 790	cement plants	ca. 48% class 2 for the main burners ca. 52% class 3 for calciner
Potential RDF generation	1 262 000		

The current RDF uptake in Romania is 335 000 tonnes. If the cement industry can increase its TSR to 85%, then an additional 986 790 tonnes of RDF per year will be required.

The simulation of the average NCV of the total RDF resulted in 18.9 MJ/kg, which corresponds to class 3 (see Section 8.12.4.2). As mentioned above, the cement industry in Romania requires at least 19 MJ/kg or class 3, which can be covered by the potential RDF.

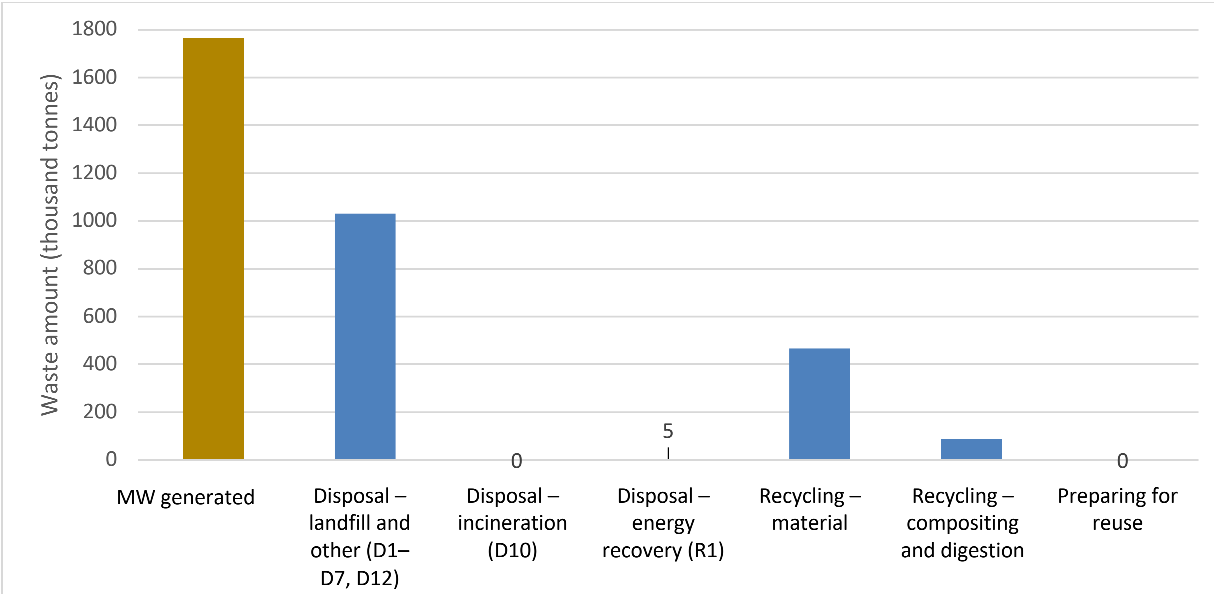
The cement industry's capacity is to co-process 78% of the entire potential RDF volumes.

[204] There are no reported quantities of RDF transboundary movements, as per Eurostat.
[205] Eurostat. Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

8.12.5 Croatia

8.12.5.1 Volumes

The following chart illustrates the generation and distribution of MW across different types of waste treatment operations in Croatia in 2021:



Source: Eurostat[206]

Figure 26: Generation and distribution of MW across different types of waste treatment operations in Croatia in 2021

The leftmost column of the chart shows total arisings of 1.767 million tonnes in 2021, slightly more than half of which has been landfilled. According to Eurostat, only a small volume of 5 000 tonnes has been energetically recovered (R1). The other recycling is as indicated.

According to the calculations in Section 8.12.5.3, it can be deduced that the cement plants in Croatia used 5 000 tonnes of RDF for energy recovery.

There are three MBT plants operating in Croatia. All of them are equipped to produce RDF with fine shredders (25–35 mm output).[207] In addition, Geocycle (Holcim's subsidiary for providing alternative fuels) is present in Koromačno's plant with RDF production capacity. The following table summarises the key performance parameters of these centres:

206 Ibid.

207 Waste Management Plan of the Republic of Croatia for the Period 2017–2022.

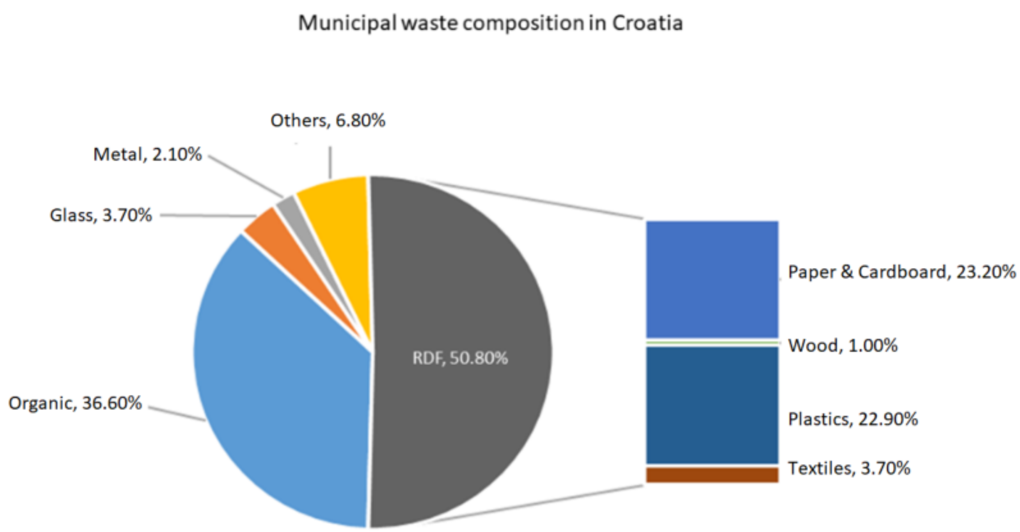
Table 40: Input capacities and related RDF production capacity per waste management centre

Waste management centre	Input capacity (t/y)	RDF production (t/y)	
Kastijun	90 000	33.3%	29 970
Mariscina	100 000	35.4%	35 400
Varazdin	95 000	34.0%	32 300
Geocycle (in one cement plant)			
		Total	**97 670**

Source: National Waste Management Plan [208]

8.12.5.2 RDF potential

The RDF potential volumes have been obtained on the basis of the quantity of MW and the waste composition.. For RDF, only the percentages of combustible matter (paper, wood, plastics, and textiles) have been used in the calculation model.



Source: National Waste Management Plan[209]

Figure 27: MW composition of Croatia

The column to the right of the chart highlights the combustible fractions that are suitable for RDF production. Just over half (50.8%) of MW might be suitable for RDF production.

The in-house model considers that 20% of the RDF fraction is not used for RDF production.

This leads to 41.6% as net yield of RDF.

Nevertheless, considering the Circular Economy Package (CEP) targets, a maximum share of RDF of MW of 25% should be considered if the CEP targets are to be met (see Section 3.3). Therefore, the **final RDF potential is estimated at 441 000 t/y** (rounded to the nearest thousand).

[208] Waste Management Plan of the Republic of Croatia for the Period 2017–2022.
[209] Waste management plan of the Republic of Croatia for the period 2017–2022.

To estimate the potential quality of this RDF, the same simulation method described in Section 8.12.1.2 has been applied. The average NCV of the potential RDF is 19 MJ/kg (class 3), and the moisture content is 20.2%.

8.12.5.3 Uptake capacities

Coal-fired power plants: Croatia has only one coal power plant left in operation (Plomin B), with a capacity of 199 MW. It uses only hard coal.[210] The country has decided to phase out coal by 2033, hence, it is surmised that there is no potential for RDF uptake in coal-fired power plants. Due to the phase-out of coal, a consortium of Kemokop VPC GmbH from Croatia and Goudini International Advisory from Germany was awarded a study to determine the best available techniques (BAT) for the use of alternative fuels – gas, biomass, and waste.[211] However, no further information about this study is available.

Waste-to-energy: According to Sarc et al.,[212] as of 2018, there were no WtE plants for MW in operation. In addition to this, Figure 26 shows that there was no disposal by incineration in 2021. Therefore, this finding corroborates the supposition that there is still no WtE in operation. There is only one private company (i.e., CIOS) that has a suitable location and a valid permit for construction of a WtE plant.[213] In 2021, a feasibility study for a WtE plant was carried out. This WtE shall take up to 96 500 t/y of waste-derived fuel and biomass, as well as up to 50 000 t/y of sludge from wastewater treatment.[214] No further information about the status of WtE plants in Croatia is given. The first WtE plant in Croatia is expected to be several years away.

Cement industry: The total cement and clinker capacity in Croatia[215] is shown in the next table. The clinker capacity is estimated based on the average clinker-to-cement ratio over all cement types in the EU-27.[216]

Table 41: Clinker and cement capacity of the Croatian cement industry

Company	Plant	Clinker capacity (Mt/y)	Cement capacity (Mt/y)	№ of kilns
Cemex Hrvatska	Sveti Juraj	0.94	1.28	1
Cemex Hrvatska	Sveti Kajo	0.41	0.56	1
Cemex Hrvatska-	Kolovoz	0.41	0.56	1
Holcim	Koromačno	0.66	0.90	1
Nexe	Našice	0.77	1.05	1
Total		**3.24**	**4.40**	**5**

However, the current cement demand and production will influence and determine the RDF consumption. The TSR of Cemex Hrvatska is 3%, including various alternative fuels (waste oil, SRF, waste biomass, and wood

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210 HEP Grupa: IZVJEŠĆE O POSLOVANJU I ODRŽIVOSTI 2021 (Business and Sustainability Report 2021).

211 Igor Todorović: Croatia examining alternative fuels for its retired coal plant Plomin 1. Balkan Green Energy News, 07.02.2022. https://balkangreenenergynews.com/croatia-examining-alternative-fuels-for-its-retired-coal-plant-plomin-1/

212 Sarc, R., Perovic, K., Relic, I., & Lorber, K. (2018). Mechanical-biological waste treatment plants in Croatia. In: Thiel, S., Thomé-Kozmiensky, E., Winter, F., & Juchelková, D. (Eds.), *Waste Management, Volume 8 – Waste-to-Energy*. Thomé-Kozmiensky Verlag GmbH.

213 Ibid.

214 STUDIJA O UTJECAJU ZAHVATA NA OKOLIŠ ENERGANA NA NEOPASNI OTPAD I BIOMASU – netehnički sažetak- (Study on Environmental Impact from Energy Recovery of No-hazardous Waste and Biomass). IPZ Uniprojekt Terra d.o.o., Zagreb. Client: CIOS Energy d.o.o., Sisak. June 2021.

215 Cemnet. https://www.cemnet.com/global-cement-report/country/croatia

216 CEMBUREAU – The European Cement Association: clinker substitution. https://lowcarboneconomy.cembureau.eu/5-parallel-routes/resource-efficiency/clinker-substitution/

chips).[217] The TSR of NEXE is 16% (2018), with various alternative fuels (SRF, waste tyres, and waste oils) with a total quantity of 23 000 tonnes[218].

To estimate the potential uptake of RDF in Croatia, a sample calculation has been carried out for Cemex Juraj Cement.

Table 42: Thermal substitution scenario for the Cemex Juraj Cement plant, based on current RDF and other alternative fuels usage and potential RDF uptake

Kiln data			
Total clinker production (t/y)	943 360		
Specific heat consumption (kcal/kg clinker)	800		
Heat consumption (Gcal/yr)	754 688		
Thermal substitution in the Cemex Juraj Cement plant	**Substitution scenario**		
	Current	**85% TSR**	**Potential for RDF uptake**
Net calorific value (kcal/kg)	4 500	4 500	4 500
Thermal substitution rate (%)	3.0	85.0	82.0
Heat portions (Gcal/yr)	22 641	641 485	618 844
RDF and other alternative fuels (t/y)	5 031	142 552	137 521

Cemex's kiln is not equipped with a secondary firing system. To achieve higher TSR (up to 85%), the pyrosystem of the cement plant would need to be upgraded.

The simulation has been applied to the other cement plants. The following table shows the summarised potential RDF uptake, based on the current TSR as well as the potential maximum TSR.

217 Saunders, A. (2015). Global Cement: Cemex's most energy-efficient plant in the world and Croatia's only well cement producer – Sv Juraj. https://www.globalcement.com/magazine/articles/910-cemexs-most-energy-efficient-plant-in-the-world-and-croatias-only-well-cement-producer-sv-juraj

218 Nexe – Report on the environment impact of Nasicecement – 2018. https://www.nexe.hr/wp-content/uploads/2022/02/Na_icecement-d.d.-Izvje_taj-o-utjecajima-na-okoli_-u-2018.-godini.docx

Table 43: Cement companies in Croatia and related TSR and RDF-uptake capacity

Company	Clinker Capacity (Mt/y)	Current TSR (%)[219]	Current RDF and other alternative fuels usage (tonnes)	TSR Limit (%)	TSR Difference (%)	Potential RDF Uptake in tonnes
Cemex Hrvatska – Sveti Juraj	0.94	3	4 528	85	82	137 521
Cemex Hrvatska – Sveti Kajo	0.41	0.4	264	85	84.6	62 073
Cemex Hrvatska – Kolovoz	0.41	0.4	293	85	85	62 073
Holcim – Koromačno	0.66	16	18 867	85	69	81 365
Nexe – Našice	0.81	16	23 060	85	69	99 446
	3.24		**42 791**			**442 478**

The table reads: With a clinker capacity of 3.24 million t/y, cement plants in Croatia currently co-process around 43 000 tonnes of various alternative fuels, including RDF. Taking into account the max. TSR of 85% and the difference from the current TSR, there is the potential for co-processing of an additional 442,478 tonnes of RDF.

It should be noted that the higher the TSR, the higher the quality of RDF required. For TSR up to 60%, class 3 may be used, and for TSR up to 85%, class 2 is required. It is assumed that the Croatian cement industry can utilise 442 478 tonnes of RDF, of which around 29% is class 2 and approximately 71% is class 3.

8.12.5.4 Qualities

Currently, all cement kilns in Croatia are technically able to use RDF with an NCV of above 4 500 kcal/kg (>19 MJ/kg) and particle size of 30–35 mm. This may correspond to class 3.

The Cemex cement plant[220] is only equipped with a main burner; therefore, only RDF class 2 can be used (see also Section 8.4). On the other hand, the Nexe cement plant is also equipped with a calciner,[221] allowing for class 3 to be used in the calciner and class 2 in the main burner (see also Section 8.4).

8.12.5.5 Implications of waste disposal costs/gate fees for RDF streams

Given the low landfill costs (between €26.25/t and €59.73/t, see also Table 21), it is not surprising that more than 50% of MW ends up in landfills (see Section 8.12.5.1).

The current low energy recovery of Croatian MW (Section 8.12.5.1) and the import of RDF (33,774 tonnes from Italy, Austria, and Slovenia, EWC: 191212, 191210 in 2020),[222] may be a sign of:

- High gate fees for acceptance of imported RDF
- Low or unstable quality of RDF produced locally by the WMC
- Better quality of imported RDF

8.12.5.6 The influence of logistics

In terms of logistics, the transport options in Croatia are road, railway, and sea. The collection and handling of MW from the Croatian islands is expected to be challenging. However, two of the WMC, three of the cement

219 Internal MVW Lechtenberg & Partner database.

220 Saunder, A. (2015). Global Cement Magazine: Cemex's most energy-efficient plant in the world and Croatia's only well cement producer – Sv Juraj. https://www.globalcement.com/magazine/articles/910-cemexs-most-energy-efficient-plant-in-the-world-and-croatias-only-well-cement-producer-sv-juraj

221 CE Industries: successful commissioning of a process line for the transportation and dosing of solid alternative fuels to the second largest cement plant in Croatia, 2020. https://www.ce.industries/news-article/65-successful-commissioning-of-a-process-line-for-the-transportation-and-dosing-of-solid-alternative-fuels-to-the-second-largest-cement-plant-in-croatia

222 Eurostat. Waste shipments across borders. https://ec.europa.eu/eurostat/web/waste/data

plants, and the Plomin power plant are located on the Adriatic Sea coast, which gives some flexibility, as well an opportunity for import and export of RDF by vessel.

The fourth cement plant and the third WMC are located on the mainland in a radius of 200 km from Zagreb. The distance between the WMC (Varazdin) and the NEXE cement plant is more than 200 km. In this case, the preferable means of transportation is by road.

Two of the WMCs (Mariscina and Kastijun) are very well positioned, within a 100-km radius of the cement plant in Koromačno (Holcim) and the Plomin power plant. Also, in this case the preferable means of transportation is by road.

The two cement plants (Cemex Hrvatska) are located nearby the city of Split, which is quite far from the WMC – more than 400 km. The preferable means of logistics will be by railway or sea (see Figure 28).

Figure 28: Map of WMCs and uptake facility locations with related distance ranges

The road transport costs for RDF typically vary between €1.9/km and €2.4/km for loads of 20–23 tonnes.[223] It is expected that transport of up to 100 km would cost about €2.4/km and that the cost of transport above 400 km would be about €1.9/km (see Section 8.13.2.2).

[223] Internal MVW Lechtenberg & Partner database.

8.12.5.7 Summary – Croatia

The balance between RDF generation, production, and uptake capacity is expressed in the next table.

Table 44: Balance between RDF generation potential and production and uptake capacities in Croatia

RDF capacities	Amounts (t/y)	User type	RDF classes
Import[224]	95 987		
Export[224]	8 045	incineration and energy recovery	
Current production capacity	97 670		
Current waste incineration (D10+R1)[225]	5 000	energy recovery in cement plants	class 2 and 3
Potential additional RDF uptake (WtE)	–	–	–
Calculated current uptake of RDF + other alternative fuels (cement)	42 791		
Potential additional RDF uptake (cement)	442 478	cement plants	c. 29% class 2 for main burners c. 71% class 3 for calciners
Potential RDF generation	441 000		class 3

The current RDF uptake is considered low compared to that of other alternative fuels used in the cement industry. The total potential RDF generation in Croatia is around 735 000 t/y. If all cement kilns in Croatia could increase their TSR to 85%, this would result in a potential RDF uptake of 442 478 tonnes.

The simulation of the average NCV of the total RDF resulted in 19 MJ/kg, corresponding to class 3. This would satisfy the quality requirements of the cement industry for calciner RDF. To obtain kiln burner RDF of class 2, drying of the material is needed.

[224] Eurostat: Waste shipment across borders. https://ec.europa.eu/eurostat/documents/342366/351880/Waste_shipment_data_imports_exports/

[225] Eurostat – Municipal waste by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

8.13 Transport considerations

8.13.1 Transport and technical requirements in MBT plants

In MBTs, there are several requirements for the storage of the RDF produced in connection with those imposed by logistics.

First, the space and size of storage required depends on the distance of the facility from the final user.

Second, the required space and type of the RDF produced depends on the necessities of the final RDF user. The usual questions to be considered are:

- How much RDF needs to be delivered per day?
- How often per day, per week, per month?
- On a regular basis or only seasonally?
- What is the storage capacity for this type of material at the final user?
- Does the final user accept RDF continuously, on a 24/7 basis, or only 3–4 days a week?

In the best case, the final user of the RDF will be located in the vicinity of the production facility – that is, within a meaningful distance of approximately 150–200 km, such that lorries can deliver the RDF directly to the final user. Typically, the storage size in an RDF production plant should cover at least three days' production capacity. Considering the low density of RDF, the storage capacity at the production facility should be as follows:

Table 45: Recommended storage capacities

Calculation of fuel storage volume (recommendations)		
Production volume RDF (t/h)	Storage volume	
	(t)	(m^3)
3	200	600
5	360	1 200
10	720	2 400

There are various storage technologies:

- Storage in the form of bulk material in an enclosed hall;
- Storage in a moving floor system;
- Storage in a deep bunker with overhead crane discharge systems;
- Storage in bunker systems (standing on the floor) with belt or chain discharge systems.

Also, the rule "first in – first out" needs to be applied. This is critical for safety and fire-protection reasons, to avoid possible self-ignition of RDF in long-term storage.

For transport over longer distances, for instance by rail or waterway, or if the RDF needs to be stored for a longer period, baling and wrapping is necessary. The production and storage of bales is always a challenge, as the required capital expenditures and operating cost are quite high. Typical balers require an investment of approximately €500 000. The operational costs of baling and wrapping are in the range of €12/t to €14/t.

Baled RDF has the considerable advantage that it can be stored in outside areas. Weathering does not affect the quality of the material if it is wrapped properly with stretch film, even over longer periods. Bales need to be stored according to local regulations and fire-protection requirements.

8.13.2 Cost considerations

8.13.2.1 Independence

RDF production is typically a local or regional business, as local waste sources are processed into RDF for local consumers. To maintain their independence, RDF manufacturers tend to produce for several customers. Moreover, they supply different qualities of RDF for different applications or end users. Similarly, RDF end users typically purchase their fuel from various suppliers to maintain their independence. Independence is an important concern for both parties – the producer and the consumer of RDF – as it allows some room for manoeuvre in case of technical issues or emergencies (technical interruptions, fire incidents, force majeure).

8.13.2.2 Road transport

Road transport is the universal transportation mode, as every shipper and consignee can load and receive materials by lorry. Walking floor trailer lorries are typical means for transporting loose or baled RDF. The advantage of these trailers is their high volume and fast unloading. RDF have a very low bulk density of around 100–250 kg/m³. A typical walking floor trailer with 90–100 m³ volume can load max. 23–24 tonnes of loose RDF.

The transport cost of RDF (or any other goods) depends on loading and unloading time as well as the transport distance. The transport costs are mostly calculated by the time that is needed for loading and unloading, road distance, fuel consumption, and maintenance. Therefore, the cost per km is lower for longer distances compared to shorter ones. The following table shows typical cost figures for the transport of RDF by lorry over different distances:

Table 46: Typical road transport costs

Distance in km	Loading time (€/h)	Price per km (€)	Unloading time (€/h)	Total transport costs (€ per transport)	Total transport costs (€ per tonne)
20	100	2.5	100	250	10.6
50	100	2.5	100	325	13.8
100	100	2.3	100	430	18.3
200	100	2	100	600	25.5
300	100	2	100	800	34.0
500	100	1.9	100	1 150	48.9

Source: MVW Lechtenberg's internal database, updated by interviewing forwarders.
Note: Total cost per tonne was calculated on the basis of a 23.5 tonne load.

8.13.2.3 Railway transport

Transport by railway may be more financially attractive than road transport when long distances need to be covered and bigger volumes are to be moved. Standard 40-foot sea containers may be the preferred containment for RDF because they are available everywhere and can be handled easily. Ideally, transport by railway requires that both the shipper and consignee have the ability to load and unload rail directly. However, rail transport very often needs to be combined with road transport if the shippers and/or consignees are not connected to a railway station. If consistent loads need to be transported over longer periods (for instance, one year), it is advisable to take transportation by rail into consideration, as it may have advantages, especially for bigger quantities and long distances.

The cost of railway transport of standard containers within Germany can serve as an indication of the costs involved. Standard containers can be loaded with baled RDF, and the loading capacity of a standard 40-foot container is about 19 tonnes of baled RDF.

Railway transport of a 40-foot container from Munich to Hamburg (about 770 km) costs €460. Another €137 per 40-foot container needs to be added to cover energy costs for electricity and diesel. This adds up to €597 per 40-

foot container,[226] or €31.3/t. Further optional costs may be imposed by the terminal or station, such as for storage and movement of the container. For instance, the optional movement of a 40-foot container costs €155,[227] adding another €8.1/t to the transport costs.

To the best of the authors' knowledge, railway transport of RDF in the European Union is not the common transport mode. The only known examples of transport of baled RDF by railway are as follows:

- from Italy to Germany, for use in waste incineration plants;
- from Italy to Bulgaria, for further processing or use as fuel in cement plants;
- from Italy to Denmark, for use as RDF in unspecified facilities.

Based on the authors' knowledge, railway transport over such long distances is economical because Italian-based RDF plants are able to pay the high gate fees in the region of €130/t to €150/t of RDF. However, transport costs cannot be stated in a reasonable way because there are too many individual factors that influence the total transport cost. The transportation prices always depend on the volumes, frequency, movement of a consignment within a station, shunting, and availability of suitable train connections to the destination. Additional road transport also needs to be included.

Transport costs must be requested from forwarders and assessed in every individual case.

8.13.2.4 Sea transport

It became common practice to transport RDF bales within the European Union by vessels (especially short-sea vessels). Typical volumes of a short-sea vessel are between 1 500 and 3 000 tonnes.

Large volumes of RDF are exported by vessel from the United Kingdom and Ireland to various European countries. However, the organisation of vessels requires logistical and legal background. The shipping terms, in particular, depend on many variables that need to be taken into consideration. According to the authors' experience of shipments of RDF by vessels, the following volatile factors contribute to sea transport costs:

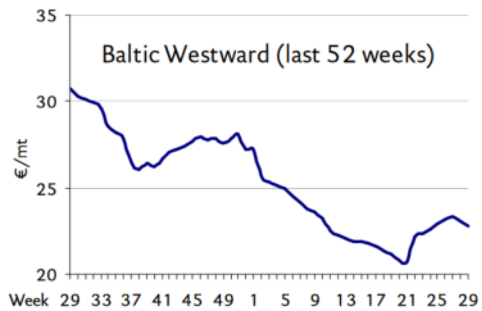
- The availability of suitable vessels (with regard to volume, draught, freeboard) is subject to seasonality and supply and demand;
- Demurrage is a fee levied on a consignee by the vessel owner. Demurrage applies in the event that the loading or unloading of the vessel takes longer than the agreed laytime;
- Possibility of backhauls;
- Prices of marine fuel oil.

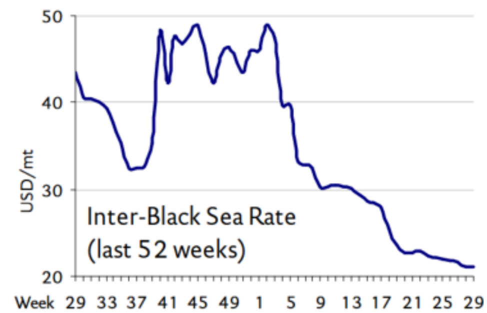
These factors contribute to highly volatile freight rates. The volatility is demonstrated by the "BMTI Short Sea Report."[228] The figure below shows that freight from the Baltic states to Amsterdam-Rotterdam–Antwerp-Gent (ARAG) fell from more than €30/t to between €21/t and €23/t over a 52-week period in mid-2023. Short-sea rates in the Black Sea have been subject to a high degree of fluctuation, ranging between nearly $50/t and $21/t within the same period.

226 Preisliste IGS Intermodal Container Logistics GmbH. Geltungsbereich 2023, gültig bis 30.06.2023. https://igs-intermodal.de/files/pdf/geltungsbereich-fahrplaene/geltungsbereich-1hj-20231.pdf

227 Ibid.

228 BMTI Short Sea Report – Brokers Market & Trend Information. No. 29, 13 to 19 July, 2023. BMTI Technik & Informations GmbH, Berlin (Germany).





Source: "BMTI Short Sea Report"

Figure 29: Average freight rates for a general short-sea cargo of 3 000 metric tonnes from the Baltic states to the ARAG region (top). Average freight rates for a general short-sea cargo of 3 000 metric tonnes from the Odessa area to the Sea of Marmara (bottom).

Additionally, the costs for required baling and wrapping (around €14 to €17 per tonne), storage of large quantities (depends on the port, around €2 to €8 per tonne per month), loading and unloading operations (~€8 to €12 per tonne) need to be taken into account. As for railway transport, additional road transport to and from the port needs to be included.

8.14 MBT/MT plants in the EU

In recent years, there has been a growing focus on the need to separate and collect bio-waste and other materials from MW. As a result, MBT/MT plants are increasingly being designed and configured to adapt to this changing waste composition. This section addresses the state-of-the-art MBT plants' technologies, processes, and effectiveness in processing the waste.

The next table depicts a non-exhaustive list of well-designed and best-performing integrated MBT/MT plants in the European Union as an example of current best practices in the industry.

Table 47: Non-exhaustive list of Best Practices MBT/MT plants in Europe

Country	City	Name of facility	Year of commissioning and operating status	Design capacity (t/y)
Austria	Linz	Linz Strom	2011	225 000
Bulgaria	Sofia	Consortium Aktor-Helektor	2015, in operation	410 000
Greece	Kozani	Waste Management of Western Macedonia (Diayma SA)	2017, in operation	120 000
Germany	Ennigerloh	AWG Ennigerloh	2006, in operation	125 000
Germany	Osnabrück	Herhof Recyclingcenter Osnabrück GmbH	2006, in operation	90 000
Germany	Kahlenberg	Kahlenberg (ZAK) MBT plant	2006	100 000
Norway	Stavanger	IVAR	2018	66 000
Poland	Radom	PPUH Radkom Sp. Zo.o.	modernisation 2019, in operation	sorting plant 210 000 composting plant 42 000
Poland	Bielskio-Biała	Zakład Gospodarki Odpadami S.A.	modernisation 2019	75 000 t/y
Poland	Tychy	MBT plant Tychy	2014	sorting 93 500 biological treatment 26 000
Romania	Ploiesti	MBT Plant Ploiesti	2018, in operation	mechanical sorting 150 000 composting 113 000
Spain	San Sebastián	Gipuzkoako GHK MBT plant	2019, in operation	200 000
Sweden	Stockholm	Brista Waste-Sorting Plant	2020, in operation	140 000

Source: MVW[229]

229 MVW Lechtenberg & Partner desktop research.

8.15 Emerging techniques

With increasing regulatory and legal requirements in areas such as CO_2 emissions reduction, producer responsibility has expanded and, therefore, the costs of fossil fuels have increased. The industry has developed some emerging techniques in response to these developments. This section indicates emerging techniques adopted by different end users/industries to use RDF in their plants. It also covers chemical recycling and its potential impact on MBT plants and RDF production/quality.

8.15.1 Sorting systems

Sorting robots: The German-based company Interzero has installed sorting robots in mechanical treatment plants. These robots use a deep learning system (artificial intelligence) that removes, for example, disruptive silicone cartridges from the waste plastics material flow.[230,231] These high-tech devices drastically increase the sorting efficiency to obtain pure plastics for recycling. Robots can perform this activity (as opposed to humans) without fatigue and with high precision and reproducibility.

Source: MVW

Figure 30: Sorting robots in action

Sorting robots controlled by artificial intelligence have already been installed in material recycling facilities in the United Kingdom, France, and Italy.[232] This kind of self-learning system can also be used for the extraction of recyclable matter from a waste stream ("positive sorting") before it is used for RDF production.

Real-time analytics: Smart facilities will make sorting decisions independently, divert various foreign matter, or direct the material flow (RDF, recyclables) to the dedicated storage. Special detection devices are needed for this.

- NIR – detection and separation units. NIR technology caters to two tasks: It enables the tracking and permanent recording of the quality of the material flow, in terms of calorific value and chlorine and moisture content and, therefore, of the RDF quality. Using a nozzle bar and compressed air, it can divert various materials, particularly recyclables. NIR devices have proven themselves in many waste treatment facilities and RDF production plants. They can be considered a key technology, with further great potential in future smart waste treatment plants (see above).

There is also a manufacturer of an NIR system who claims that the device can also determine the biogenic carbon content of RDF[233] online. Given the increased importance of recording and reporting the CO_2 emissions, this capability is an extremely interesting feature. However, the reliability of this characteristics still needs to be

[230] Recycling News – Das Branchenmagazin: Starke Technik für einen stabilen Kunststoff-Kreislauf. 20.09.2022. https://www.recyclingnews.de/recycling/starke-technik-fuer-einen-stabilen-kunststoff-kreislauf/

[231] INTERZERO: Hightech für hochwertige Recyclingkunststoffe. https://www.interzero.de/leistungen/kunststoffrecycling/recycling-und-sortierung/

[232] RecyclingPortal – Das Fachportal für Abfall, Entsorgung, Recycling, Kreislaufwirtschaft und Märkte: Recycleye bringt KI-gesteuerte Abfallsortierroboter nach Deutschland (18.05.2022). https://recyclingportal.eu/Archive/73020

[233] Recycling Inside: Separation and Sorting Technology – QC+: Quality Control. (24.01.2023). https://recyclinginside.com/recycling-technology/separation-and-sorting-technology/qc-quality-control/

proven in terms of reproducibility and comparability with the standard method (EN ISO 21644 Solid recovered fuels – Methods for the determination of biomass content).

Figure 31: Online NIR analysing unit

In general, NIR detectors have one drawback: They can only detect materials on the surface of the material flow. The NIR rays do not penetrate the material to detect materials in deeper layers.

- Prompt Gamma Neutron Activation analysis (PGNAA): PGNAA overcomes this drawback of NIR. The device is a single enclosure designed to be installed directly on production conveyor belts.

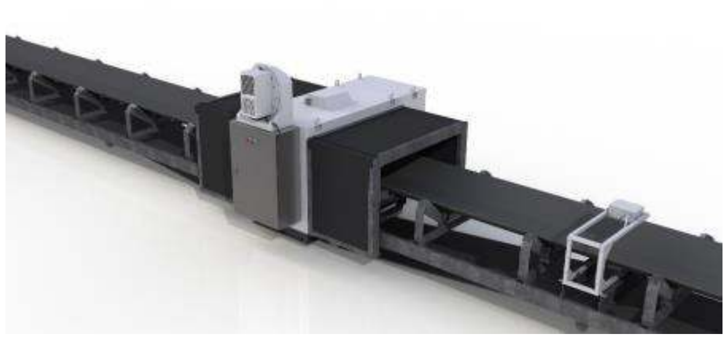


Figure 32: Online PGNAA analysing unit on a conveyor belt

The analyser uses a dual gamma ray beam that passes through the entire bed of material. It can determine the contents of nearly all chemical elements, directly and indirectly, using specific algorithms, as well as the ash content and NCV. This is an advantage over NIR systems. However, unlike NIR, PGNAA cannot detect or distinguish between the various types of plastics. Since such devices have been used in coal mining for several years, they certainly have potential for quality control applications in RDF production plants. However, the hurdles to operate PGNAA are high, as it uses a radioactive neutron source. A special operating permit, as well as specific measures for occupational health and safety, are required to operate PGNAA.

With each new technological advance, sorting robots become more competent and smarter. The likelihood is that they will advance to higher Technological Readiness Levels (TRL levels) and eventually turn into crucial elements of contemporary waste management systems.

As shown above, the use of NIRs is well established in RDF production facilities, and this technology has reached a high level of maturity for application in this field. However, there are ongoing research and development efforts that continue to improve the accuracy and capabilities of these sorting systems. This may lead to further advances and refinements in the future.

PGNAA is still at a very early development stage in RDF production facilities. In the authors' RDF production facility in Germany, initial tests on a laboratory scale have been executed with PGNAA.

8.15.2 Cement industry

When the cement industry started using RDF, the majority of the cement kilns were preheater kilns in which all fuels were introduced through the main burner. As already mentioned, for main burner firing, RDF with small, two-dimensional parts with a high-calorific value of at least 21 MJ/kg is required, which limits the sources for the production of RDF (see Section 8.4).

For later calciner kilns (for instance in-line calciner, separate line calciner, combustion chamber), a larger grain size of up to 80 mm with a lower calorific value can be used.

Separate combustion chambers: For a few years, separate combustion chambers have been under development, for example, the “Step Combustor” produced by Thyssen Krupp Industrial Solution (formerly Polysius) from Germany, the “Pyrorotor” produced by KHD from Germany, and the “Hot Disc” produced by FLSmidth from Denmark.

In this kind of separate combustion chamber, which is connected to the preheater of the kiln, a much longer retention time can be achieved than in conventional calciners. This allows the complete combustion of coarse RDF (even up to around 300 mm) with lower calorific values (see also Section 8.4). It may be feasible to generate up to 100% of the thermal heat demand at the calciner with RDF (equal to 60% of the overall thermal heat demand of the kiln).

The next figure shows a 3D view of separate combustion chamber technology.

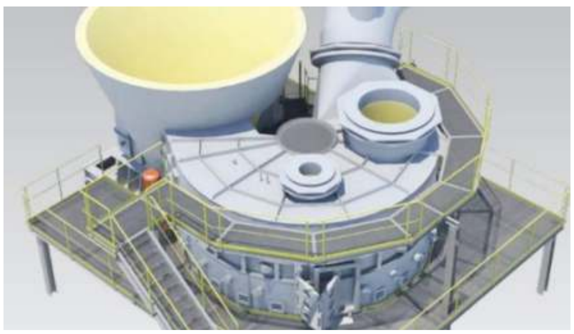


Figure 33: HotDisc by FLSmidth (left); Pyrorotor by KHD (right)

In the last seven years, some cement plants have built industrial-scale versions of these technologies to boost the rate of thermal substitution and use RDF with larger particle sizes.[234] A rising number of cement plants are working on installing such systems, as the cement industry moves towards greater consumption of RDF.

[234] Trela, F., & Zühlsdorf, S. (2017). The PREPOL SC to utilize low quality alternative fuels in cement plants. 4th Alternative Fuels Symposium organised by MVW Lechtenberg & Partner, 27–28 September 2017, Hotel Wyndham Duisburger Hof Duisburg, Germany.

The next figure shows actual installations of Prepol SC by Thyssenkrupp Germany in a cement plant in Germany and of Pyrorotor by KHD Germany in a cement plant in South Korea.

Source: Thyssenkrupp and KHD

Figure 34: Left: Installation of Prepol SC by Thyssenkrupp in a cement plant in Germany. Right: Installation of Pyrorotor by KHD in a cement plant in South Korea

This kind of technology necessitates an investment of €3 million to €10 million, depending on the capacity requirement and the additional civil and structural work needed.

Another emerging technique for the use of RDF in the cement industry is special comminution, whereby RDF is first pelletised and then milled to less than 3 mm for main burner feeding. As this technology is predominantly intended for use in the lime industry, it is described in the following section.

8.15.3 The lime industry

As already discussed in Section 8.4, the use of RDF in the lime industry is very limited. The restrictions on RDF quality are detailed in Section 8.4.2. One emerging technique for the use of RDF in the lime industry, and particularly in PFRKs, is special comminution. PFRKs are equipped with burner lances with small orifices. Hence, the kilns can be fed only with RDF smaller than 2 mm. RDF is first pelletised and then milled to less than 2 mm. Drying of the RDF is necessary to pelletise RDF properly.

Source: MVW

Figure 35: Pellets (left); milled pellets (right)

Fine milling of these pellets can be carried out by special comminution machines, to yield a "powder-like" material that can be fed through existing coal-firing systems in lime kilns, as well as in cement kilns.

Fine milling is only possible by either using liquid nitrogen to cool down the material and prevent it from melting, or after compacting the feedstock into pellets.

As lime plants can only use pelletised RDF for milling, it is anticipated that demand will increase in the coming years in the whole European lime industry. RDF pellets with a high biogenic content (where wood is added to the recipe) or pure wood pellets are the preferred materials. The limiting factor is the ash content, so MBTs will need to separate biogenic materials such as paper/cardboard, wood, tree cuttings, etc. for separate production of biogenic RDF with low ash content. It should be borne in mind that any substitution of high-calorific plastics with biogenic matter reduces the NCV of the resulting fuel.

The fine milling technique for RDF in lime plants is still being tested on a pilot scale, and it is predicted that additional industrial-scale projects will be undertaken following the successful testing of these pilot projects.

8.15.4 Waste-to-energy

Gasification, plasma gasification, and pyrolysis are emerging technologies to obtain energy from waste. These are conversion technologies to produce syngas (i.e., a mixture of hydrogen and carbon monoxide). The syngas produced can then be burned in a boiler system to generate electricity. It can also be processed into fuel for an efficient, low-emission natural gas generator, or refined into other valuable products. These conversion technologies promise cleaner emissions and more flexibility in terms of energy output. However, none of these technologies have yet been proven on a commercial scale, at least in the US.[235] A similar conclusion has been stated by Quicker et al. for Germany. Classical waste incineration is still the state of the art for the treatment of MW. None of the alternative conversion technologies has demonstrated similar performance and flexibility. There are still no alternative thermal processes that can compete with the usual WtE technology (see Section 8.4) in terms of ecology and economy. Owing to the higher complexity of the alternative conversion processes, such developments are not to be expected in the future from the current point of view.[236]

Another technical development concerns the waste that is incinerated in WtE facilities. It is connected with the upcoming pricing of CO_2 emissions (see Section 8.16.1). The main source of such fossil fuel emissions is plastic waste. Together with the petrochemical industry, which is forced to recycle more plastics, a few pilot projects to separate plastics before incineration have already been announced.

The separated plastic is further processed through sorting, drying, pelletising, and chemical recycling into oil or other liquid materials (see next section).

Currently, in Organisation for Economic Co-operation and Development (OECD) EU countries, plastic type wastes account for 44% of incinerated waste.[237] If all of these plastics were to be separated, the incineration capacity (in Europe) would be too high. In this case, the incineration plants would either need to shut down or use more organic waste. There is an ongoing discussion on separate collection within European waste management companies. If the WtE facilities separate any type of waste with modern, fully automated, self-learning technologies, the waste management industry in Germany for instance, will fear that the costly separate collection will stop. In this country, most cities collect packaging waste, paper/cardboard, and organic waste separately; other recyclables are brought to collection centres. At the same time, in many European countries, there is still no separate collection, even of wet (organic) and dry (recyclable) waste. Separate collection at the source reduces overall costs and offers the opportunity to obtain a clean organic fraction, for example, for the production of biogas and dry matter for recycling and producing RDF.

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235 Seltenrich, N. (2016). Emerging waste-to-energy technologies – solid waste solution or dead end? Environmental Health Perspectives, 124(6), A106–A111.

236 Quicker, P., Neuerburg, F., Noël, Y., & Huras, A. (2017). Sachstand zu den alternativen Verfahren für die thermische Entsorgung von Abfällen. Umweltbundesamt Dessau-Roßlau.

237 OECD Global Plastics Outlook Database, 2019. https://www.oecd.org/environment/plastic-pollution-is-growing-relentlessly-as-waste-management-and-recycling-fall-short.htm#:~:text=Another%2019%25%20is%20incinerated%2C%2050,environments%2C%20especially%20in%20poorer%20countries

8.15.5 Chemical recycling

Chemical recycling is the process of converting polymeric waste by changing its chemical structure and turning it back into substances that can be used as feedstock for the manufacturing of plastics or other products. There are various types of chemical recycling technologies: pyrolysis, gasification, hydro-cracking, and depolymerisation. Because chemical recycling breaks down polymers into their building blocks, it also allows to produce recycled plastic ("recyclate") with virgin plastic properties that can be used in critical applications such as food packaging.

There has been a substantial increase in investment in chemical recycling.[238] Currently, there are 44 planned projects for chemical recycling in 13 EU countries. More details and a list of "low-carbon technologies projects" are available on the CEFIC website.[239] It mentions a variety of so-called "plastic-to-oil" or other plastic recycling technology projects.

These projects include chemical recycling of plastics into new plastics, especially food-related, as well as renewable fuels of non-biological origin.

These regulation-driven technologies will have a significant impact on MBT facilities, RDF producers, and the current end users of RDF in terms of:

- Increased demand for low-quality plastics (which are currently mainly incinerated);
- Increased investments in technologies to separate polyolefins and other plastic fractions and biomass;
- Higher prices for such separated fractions;
- High competition for waste streams such as MW from new players in the waste management industry as the petrochemical industry develops new value chains.

Some chemical companies have set up pilot facilities to test the recycling of chemicals. It is anticipated that, with significant investments in chemical recycling projects, around 1.2 million tonnes of recovered plastics will be generated in 2025 and 3.4 million tonnes in 2030. The European Commission's Circular Plastic Alliance goal of using 10 million tonnes of recycled plastic in European products by 2025 will be significantly aided by the 1.2 million tonnes of recovered plastics from chemical recycling.[240]

8.15.6 Assessment of future potential

Overall, the future potential of these emerging technologies will depend on various factors, including significant investment, regulatory and legal frameworks and RDF market demand.

Technologies such as separate combustion chambers for cement plants and using pelletised or milled fuel in the lime industry, provide room for manoeuvre to achieve higher thermal substitution rates, and thus to co-process more RDF. Chemical recycling is supposed to boost the recycling economy in Europe – in parallel, chemical recycling poses a challenge to energy-intensive industries such as the cement and lime industries, in terms of the availability and quality of waste feedstock in the future.

238 Plastics Europe. Chemical recycling. https://plasticseurope.org/sustainability/circularity/recycling/chemical-recycling/
239 The European Chemical Industry Council (Cefic) – Low-Carbon Technologies Projects. https://cefic.org/low-carbon-projects-map/
240 Chemical recycling in brief. https://plasticseurope.org/wp-content/uploads/2022/12/OnePager_-P-E_Chemical-Recycling_221222.pdf

8.16 RDF-relevant EU legislation

8.16.1 The EU-ETS Directive

The EU-ETS aims to reduce fossil CO_2 emissions in the energy intensive industry. Its legal framework is provided by Directive 2003/87/EC, as last amended by Regulation 2023/435. Operating on the "cap and trade" principle, it sets a limit on greenhouse gas emissions. This limit is gradually lowered, prompting overall emissions reduction. Operators within the cap can buy and trade emissions allowances, which hold value due to the limited supply. This system encourages emissions reductions, fosters investment in low-carbon technologies, and ensures cost-effective emissions cuts.

Each year, operators must surrender enough allowances to cover their emissions; otherwise, heavy fines are imposed. Reduced emissions can be kept or sold to another operator that is short of allowances.[241] The prices have already been described in Section 3.

Besides the EU-ETS, several MSs have implemented national greenhouse gas emissions legislation, such as the "Bundesemissionshandelsgesetz" (BEHG) in Germany.[242] From January 2024, WtE facilities (including MW incinerators) in Germany need to pay for their fossil CO_2 emissions (for example, from incinerated mixed plastics), starting with €35/t of fossil CO_2 emissions and increasing incrementally over the following years.[243, 244] Pohl et al. analysed the impact of the national emissions trading system on waste management:[245] on the basis of €35/t of fossil CO_2 emissions, one tonne of typical input to MW incinerators will entail a cost of nearly €16, and one tonne of typical input to RDF power plants will entail a cost of €22.63 because the share of plastics is higher.

In June 2022, the European Parliament approved the addition of MW incinerators in the revised EU Emission Trading System to the EU-ETS Directive, starting in January 2026.[246] This forces the waste management companies to separate more recyclable plastics, for example, for mechanical or chemical recycling.

Update on the EU Emission trading system: The European Commission agreed on new emission reduction goals within the "Fit for 55" package. The "Fit for 55" package is a set of proposals to revise and update EU legislation and to put in place new initiatives, with the aim to insure that EU policies are in line with the climate goals agreed by the Council and the European Parliament.[247] The European Union agreed to cut overall CO_2 emissions by at least 55% by 2030 compared to 1990. It was further agreed to reduce the free CO_2 allocations for the industry gradually from 2026 and to stop free allocations by 2034. It was further agreed that several other sectors (building, transportation, shipping, etc.) will participate in newly set up emission trading systems. It is assumed that this will boost the need for more RDF with a high biogenic content, to enable the industry to reduce fossil CO_2 emissions, particularly in the cement and lime industries.

8.16.2 The Landfill Directive

The Landfill Directive, implemented on 16 July 2001, regulates waste management in EU landfills.[248] From 2010 to 2020, the landfill rate in the EU-27 decreased from 23% to 16% despite an increase in total waste generation. By 2035, MSs are required to decrease the proportion of MW sent to landfills to 10% or less of the total MW generated. As of 2020, eleven countries, including nine EU MSs (Austria, Belgium, Denmark, Finland, Germany, Luxembourg, Netherlands, Slovenia, and Sweden) and two non-EU countries (Norway and Switzerland), reached

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241 European Commission. EU Emissions Trading System (EU ETS). https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

242 Gesetz über einen nationalen Zertifikatehandel für Brennstoffemissionen (Brennstoffemissionshandelsgesetz – BEHG). 12.12.2019.

243 Bundesministerium für Wirtschaft und Klimaschutz: Nationaler Brennstoffemissionshandel: Ausnahmen für Kohle- und Abfall-Verbrennung entfallen. Pressemitteilung 13.07.2022 https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2022/07/20220713-nationaler-brennstoffemissionshandel-ausnahmen-fur-kohle-und-abfall-verbrennung-entfallen.html

244 Die Bundesregierung: CO2-Preis für alle fossilen Brennstoffe. 16.11.2022. https://www.bundesregierung.de/breg-de/aktuelles/co2-preis-kohle-abfallbrennstoffe-2061622

245 Martin Pohl, Gabriele Becker, Niklas Heller, Bärbel Birnstengel, Ferdinand Zotz: Auswirkungen des nationalen Brennstoff-emissionshandels auf die Abfallwirtschaft. Studie beauftragt vom Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV), erstellt für Bundesministerium für Wirtschaft und Klimaschutz (BMWK). März 2022.

246 Revision of the EU Emissions Trading System, 22 June 2022. https://www.europarl.europa.eu/doceo/document/TA-9-2022-06-22_EN.html

247 European Council. Fit for 55. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

248 Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste.

this target. Most of these countries achieved this goal by adopting MW incineration practices to a significant extent.[249]

One driver to accelerate the development of this kind of waste infrastructure and recycling industry is either to give clear targets for reduced landfill rates, or to implement a landfill tax or levy, which is collected by the MSs for each tonne of waste landfilled. These taxes can then be allocated to develop this type of waste management and recycling infrastructure.

European-based cement groups are mostly unwilling to invest in the necessary infrastructure for the reception, dosing, and feeding of RDF if they don't receive a gate fee that covers at least the depreciation and operating costs of such installations. Cement plants, especially from international groups, have created dedicated business units (such as "Geocycle" from Holcim) for the vertical integration of waste management or RDF production.

8.16.3 Intra- and extra-EU shipment of waste

The Waste Shipment Regulation[250] lays down provisions for transboundary shipments of waste. RDF falls under waste code 19 12 10 (fuel from wastes) or 19 12 12 (other wastes, including mixtures of materials, from mechanical treatment of wastes). Waste shipments between MSs, as well as imports from and exports to third countries are allowed under certain preconditions, and require the consent of all competent authorities involved. This enables RDF producers to export to RDF consumers within the European Union and to third countries.

RDF is mainly produced in countries with higher incineration or landfill costs and exported to countries with lower waste disposal costs, where RDF end users do not have sufficient material from local producers. RDF producers in countries with high gate fees for landfill or incineration, or with insufficient incineration capacities and high landfill rates, have been exporting their material for decades.

According to Eurostat,[251] the quantities of RDF that were exported within European countries within the last five years have always been in the range of 4–6 million t/y. A further and steady growth in the cross-border shipment of RDF within the European Union is expected, as this type of shipment supports the avoidance of seasonal or regional shortages for waste-derived fuels, for example, in WtE plants with district heating systems or for electricity production. It is also anticipated that a more detailed specification of RDF will be developed.

In 2017, China banned 24 types of solid waste, including paper, plastics, and textiles. The action, called "Operation National Sword," aimed to prevent foreign inflows of waste products. Up to then, China had been the world's largest importer of plastic waste and processed hard-to-recycle plastics from other countries, especially in the West (the European Union, the United States, and the United Kingdom).[252] The ban has greatly affected recycling industries worldwide.

Besides the intra-EU shipment of RDF, it is acknowledged that unknown quantities of RDF (and mixed plastic wastes) from European countries have been exported out of the European Union to Turkey, North Africa, and even Asia to save on disposal and recovery costs. European waste declared "for recycling" has been found at illegal dumpsites, especially in North African and Asian countries.[253]

As a result, in 2021, the European Commission made a proposal for a "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on shipments of waste and amending Regulations (EU) No 1257/2013 and (EU) No 2020/1056." By then, "the EU exported in 2020 to non-EU countries around 32.7 million tonnes of waste, an increase of 75% since 2004, with a value of EUR 13 billion. Ferrous and non-ferrous metal scrap, paper waste, plastic waste, textile waste, and glass waste represent the majority of waste exported from the EU." The proposal continues: "Waste shipped across borders can generate risks for human health and the environment, especially when not properly controlled. At the same time, these wastes often have a positive economic value, notably as

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249 European Environment Agency. (2022). Diversion of waste from landfill in Europe. https://www.eea.europa.eu/ims/diversion-of-waste-from-landfill

250 REGULATION (EC) No 1013/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 June 2006 on shipments of waste.

251 Eurostat. Transboundary shipments of notified waste by partner, hazardousness and waste management operations (env_wasship). https://ec.europa.eu/eurostat/databrowser/view/env_wasship/default/table?lang=en

252 Qua, S., Guo, Y., Ma, Z., Chen, W.-Q., Liu, J., Liu, G., Wang, Y., & Xu, M. (2019). Implications of China's foreign waste ban on the global circular economy. Resources, Conservation and Recycling, May 2019, 252–255.

253 Executive Director of Europol: Environmental Crime in the age of climate change. Threat assessment 2022. ISBN 978-92-95220-41-6. https://www.europol.europa.eu/cms/sites/default/files/documents/Environmental_Crime_in_the_Age_of_Climate_Change_threat_assessment_2022.pdf

secondary raw materials that can replace and reduce dependence on primary materials and thereby contribute to a more circular economy."[254]

As this proposal is for the avoidance and control of waste flows out of the EU MSs, it should not have any impact on the RDF market.

8.16.4 The Waste Framework Directive

The Waste Framework Directive lays down some basic waste management principles. It requires waste to be managed without endangering human health or harming the environment. The foundation of EU waste management is the five-step "waste hierarchy." It establishes an order of preference for managing and disposing of waste.

- to comply with the objectives of this Directive, EU countries shall take the necessary measures to achieve the following targets by 2020: the preparation for reuse and the recycling of waste materials (such as paper, metal, plastic, and glass) from households shall be increased to a minimum of 50% of overall weight;
- by 2020, preparation for reuse, recycling, and other material recovery, including backfilling operations using waste as a substitute for other materials, of non-hazardous construction and demolition waste shall be increased to a minimum of 70% by weight;
- by 2025, the preparation for reuse and recycling of MW shall be increased to a minimum of 55%, 60%, and 65% by weight by 2025, 2030, and 2035, respectively.

As described earlier in this report, RDF consists of mostly non-recyclable combustible matter. As defined by the Commission, "non-recyclable" refers to packaging waste that cannot be collected separately or poses challenges for a state-of-the-art sorting and recycling process.[255] However, as long as a landfill (or co-incineration) is cheaper than recycling, some types of difficult-to-recycle plastics or paper and cardboard will still be used as feedstock for RDF.

The packaging industry is affected by the Extended Producer Responsibility (EPR) approach. According to the European Organisation for Packaging and Environment, approximately €3.1 billion of estimated annual fees are paid by producers to industry- and non-industry-owned packaging EPR schemes in Europe. This reflects the financial aspect of EPR programmes, whereby producers contribute to the funding of waste management and recycling activities.[256] Also under an EPR scheme, producer responsibility organisations such as the "Green Dot System" or others that organise the collection, separation, and recycling of waste are financed through the producers' licence fees, especially in the field of packaging waste.

As recycling quotas are increasing and the use of RDF is not acknowledged as recycling (only thermal recovery R1), it is anticipated that the available quantities of mixed plastics and corrugated or laminated paper and cardboard, which represent the high-calorific components of RDF, may decline gradually in the medium term and significantly in the long term (around 10 years).

8.16.5 The Industrial Emissions Directive

The Industrial Emissions Directive[257] (IED) is the main EU instrument regulating pollutant emissions from industrial installations. The IED is based on several pillars, as described below.[258]

Integrated approach: Permits must take the whole environmental performance of the plant into account. This covers emissions to air, water, and land; generation of waste; use of raw materials; energy efficiency; noise; prevention of accidents; and restoration of the site upon closure.

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254 European Commission: Proposal for a Regulation of The European Parliament and of the Council on shipments of waste and amending Regulations (EU) No 1257/2013 and (EU) No 2020/1056 (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021PC0709)

255 European Commission: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022PC0677)

256 EUROPEN (European Organization for Packaging and Environment): Factsheet – Extended Producer Responsibility (EPR) for Used Packaging (2021). (https://www.europen-packaging.eu/wp-content/uploads/2021/03/EUROPEN-factsheet-on-EPR-for-used-packaging.pdf)

257 DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

258 European Commission. Industrial Emissions Directive. https://environment.ec.europa.eu/topics/industrial-emissions-and-accidents/industrial-emissions-directive_en

Best Available Technique: The permit conditions, including emission limit values, must be based on the Best Available Techniques (BAT). BAT is described in BAT Reference Documents (BREFs). The IED requires that these BAT conclusions are used as a reference for setting permit conditions.

Flexibility: The IED allows competent authorities some flexibility to set less strict emission limit values. This is possible only in very limited and specific cases where "an assessment shows that achieving the emission levels associated with BAT, described in the BAT conclusions, would lead to disproportionately higher costs compared to the environmental benefits due to the geographical location or the local environmental conditions or the technical characteristics of the installation." The competent authority shall always document its justification for granting such derogations.

Environmental inspections: The IED contains mandatory requirements for environmental inspections. MSs shall set up a system of environmental inspections and draw up inspection plans accordingly. The IED requires a site visit to take place at least every one to three years, using risk-based criteria.

Participation of the public: The IED ensures that the public has a right to participate in the decision-making process and to be informed of its consequences, by having access to permit applications, permits, and the results of monitoring of releases.

All RDF end users are so-called "IED plants" and need to comply with the provisions/requirements of the Industrial Emission Directive, which is implemented in the national legislation of the MSs. BREFs are available for various sectors of energy-intensive industries. Based on that, the RDF end users must meet the environmental performance standards set by these BREFs. For instance, the BREF for the cement and lime industry[259] describes BAT-associated environmental performance and emissions levels for the co-incineration of RDF.

To increase the substitution rate, for example, in cement plants, by co-processing RDF, additional investments are needed to comply with the strict emission limit values. Especially for the reduction of NO_x and ammonia in exhaust gas, dedicated selective non-catalytic reduction or selective catalytic reduction systems must be installed.

8.16.6 Renewable Energy Directive RED II/III

Since the introduction of the Renewable Energy Directive (2009/28/EC) in 2009, the deployment of renewables has kept growing annually, reaching 21.8% in 2021. In July 2021, the Commission proposed another revision to accelerate the take-up of renewables in the European Union and help achieve the 2030 energy and climate objectives (RED II).[260]

In March 2023, the Council and the Parliament negotiators reached a provisional political agreement to raise the share of renewable energy of the EU's overall energy consumption to 42.5% by 2030 with an additional 2.5% indicative top-up that would enable the share to be raised to 45% (RED III).[261] The agreement sets clear goals for the use of renewable energy in various sectors. In understanding the binding targets that impact MBT plants, as well as RDF end users, it is necessary to examine the main sectors outlined in the provisional agreement.

The definition of recycled carbon fuels (RCF) may be of importance for RDF. RCF are "liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin that are not suitable for material recovery, in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin that are produced as an unavoidable and unintentional consequence of the production process in industrial installations."[262]

In brief: RCF can be derived from waste streams of non-renewable origin, such as mixed plastics, and manmade fibres such as textiles, carpets, and rugs, which are also among the main components of RDF. These materials are not suitable for material recovery. They can serve as feedstock to produce RCF, like methanol or other liquid fuels.

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259 European Commission - JRC Reference Reports: Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide. May 2013.

260 European Commission. Renewable energy directive. https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

261 European Council – Council of the European Union: Council and Parliament reach provisional deal on renewable energy directive. Press release 30.03.2023. https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/

262 DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources.

For RDF producers, this revised RED results in an opportunity to sell the RDF produced to specialised companies for further treatment into RCF. The organic fraction from MW can be processed directly into biogas.

As industry and the transport sector are forced to use renewable fuels, they are currently investing significantly in the development of the infrastructure for such fuels and are interested in signing long-term agreements with producers of RDF and other biomass-containing fuels.

8.16.7 The Packaging and Packaging Waste Directive

The Packaging Directive aims to harmonise national measures on packaging and the management of packaging waste. The latest amendment to the Directive contains updated measures to prevent the production of packaging waste and promote the reuse, recycling, and other forms of recovery of packaging waste, instead of its final disposal. Among other rules, by end of 2024, EU countries should ensure that producer responsibility schemes are established for all packaging. The Directive also sets the following specific targets for recycling:[263]

Table 48: Specific packaging recycling targets

Material	Current targets (%)	By 2025 (%)	By 2030 (%)
All packaging	55	65	70
Plastic	25	50	55
Wood	15	25	30
Ferrous metals	50 (incl. Al)	70	80
Aluminium	-	50	60
Glass	60	70	75
Paper and cardboard	60	75	85

The proposed revision (Proposal for a Regulation on packaging and packaging waste) dated 30 November 2022 in Article 6 on recyclable packaging states the following:[264]

Point 1: “All packaging shall be recyclable”.
Point 2: “Packaging shall be considered recyclable where it complies with the following:
(a) it is designed for recycling;
(b) it is effectively and efficiently separately collected in accordance with Article 43(1) and (2);
(c) it is sorted into defined waste streams without affecting the recyclability of other waste streams;
(d) it can be recycled so that the resulting secondary raw materials are of sufficient quality to substitute the primary raw materials;
(e) it can be recycled at scale.

Letter (a) shall apply from 1 January 2030 and point (e) shall apply from 1 January 2035.

In addition to the points above, Article 6 proposal includes the following:

- Financial contributions from producers would be based on the packaging’s recyclability performance grades;
- Innovative packaging would have a five-year grace period for documenting recyclability;

[263] European Commission. Packaging waste. https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en

[264] European Commission: Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677

- Certain packaging types would be exempt from recyclability requirements until 2034, due to health and safety concerns.

The increase in the use of recycled plastics in packaging (closed loop) in particular, will have a significant influence on the available quantities and quantities of so-called “non-recyclable” plastics. With increasing regulatory demand for recycling, the plastic producers will be forced to use recycled plastics in their virgin products, so they may invest in new technologies such as “chemical recycling” and “plastic-to-oil” processes on a large scale (see also Section 8.15.5). According to Plastics Europe, significant increases in chemical recycling investment are planned: from €2.6 billion in 2025 to €7.2 billion in 2030. It is estimated that the production of recycled plastics will increase to 1.2 million tonnes in 2025 and to 3.4 million tonnes in 2030. With this planned contribution of 1.2 million tonnes of recycled plastics produced through chemical recycling by 2025, Plastics Europe plays a leading role in delivering on the Circular Plastics Alliance target of 10 million tonnes of recycled plastics in the European Union by 2025. Conversion to feedstock technologies (pyrolysis, gasification) represents 80% of the planned capacities.[265]

In 2020, an estimated 29.5 million metric tonnes of poster-consumer plastic waste was collected across the European Union (EU-27), Norway, Switzerland, and the United Kingdom.[266] Therefore, the European Commission’s goal of recycling 10 million tonnes within the European Union in 2025 would represent a recycling rate of 33%. According to a study by SYSTEMIQ,[267] “by 2050, the plastics system could achieve 78% circularity, with 30% of waste avoided through reduction and substitution and 48% being recycled, leaving 9% in landfills and incinerators.” This will force the petrochemical industry to invest in the separation and processing of mixed plastics, which are currently mainly used as RDF not only in the cement industry but also in WtE plants and the steel industry. Therefore, it is suggested that there will be a significant change in the waste treatment industry. In particular, MBT/MT plants will need to put more effort into the separation of better qualities of clean separated polyolefins for chemical recycling.

265 Plastics Europe: Chemical Recycling in Brief. 21.12.2022. https://plasticseurope.org/wp-content/uploads/2022/12/OnePager_-P-E_Chemical-Recycling_221222.pdf

266 Statista. (2023). Plastics post-consumer waste treatment in Europe (EU27+3)* in 2020, by method. https://www.statista.com/statistics/869617/plastics-post-consumer-treatment-european-union/

267 SYSTEMIQ (2022). ReShaping Plastics: Pathways to a Circular, Climate Neutral Plastics System in Europe.

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European Investment Bank
98-100, boulevard Konrad Adenauer
L-2950 Luxembourg
+352 4379-1
www.eib.org – info@eib.org

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