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Trends in the use of solid recovered fuels

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Abstract

The Report provides a background reference on terminology and origin (waste stream and treatment processes) of solid recovered fuels (SRF) and a brief analysis of the SRF market in a selection of countries in Europe, Asia and Africa. The focus is on the current role of SRF (production and final end uses) in the waste-to-energy value chains and the main drivers and barriers that affect the current situation and the future perspectives of the use of SRF for energy recovery.

Complementary to prepare the residual waste stream for material recovery and disposal in landfill, treatment processes that can produce waste derived fuels, more suitable for energy recovery than the incoming waste stream, have been widely implemented in some countries. Since the early 1990s, the production of secondary fuels has become a quite popular waste management option in different countries in response to a growing market demand.

SRF are a subset of the larger family of Refuse Derived Fuels (RDFs), produced from non-hazardous waste streams, differing from a "generic" RDF due to that it is a fuel that meets requirements (i.e. classification and specification) defined by a national or international standard. In other words, SRF is a regulated and RDF (generally) a non-regulated secondary fuel. A complementary assumption is that for the SRF production, preparation for re-use or efficient material recycling should be used. The added value of SRF lies in the fact that: it is well characterised and known for its properties, the technical and environmental needs related to the specific use for energy recovery; it can really be complementary to the waste recycling priority, based on the treatment technologies currently available for its production. The compliance with a standard does not hinder the fact that a further SRF compliance with other or more stringent quality requirements for fuel properties could be voluntary asked by fuel end-users (e.g. cement kilns, power plants, gasification plants) through a private commitment (specification) with the producer, so to receive a fuel that fits well with their own economic/technological needs. Examples of such agreed specifications are provided in the report.

SRFs are produced from individual or mixed streams of municipal (MSW), commercial (CW), industrial (IW) and construction and demolition (CDW) wastes. These streams include different shares of waste fractions and also show a different elemental composition. Different types and degrees of treatments are applied by producers that modify the properties of the incoming waste and determine the achievable yield in the outgoing waste fuels in both a quantitative and a qualitative term. These treatments are often some sort of mechanical treatment (MT) or a mechanical-biological treatment (MBT). It is important to note that SRFs put in the market (as well as RDFs) never identify a univocal fuel but fuels of which the properties (e.g. composition, physic-chemical properties) might differ from each other. The achieved degree of quality is consequent to fuel origin (waste stream), production processes and, of course - as main driving factor - the fuel quality requested by the market demand (the technological, economic and environmental requirements of its final end-user).

The market demand for SRF involves, in Europe and in other countries, facilities that fall into the waste management system (incineration: from a disposal to an energy recovery operation) and energy-intensive industrial sectors (e.g. cement and industry, thermal power plants), for which the use of secondary fuels as substitute of the fossil ones (e.g. coal, pet-coke) means a benefit in term of both less dependence on fossil fuels and lower environmental impact. Locally, other industrial energy from waste (EfW) plants exploit the potential of secondary fuels (e.g. in co-combustion with other waste streams or residues) ensuring an economic benefit (coverage of the

own energy need; sale of electricity to the national grid; access to economical supports). A quantitative figure of the SRF produced and sent to specific end uses is provided for most of the examined countries.

Energy-intensive industrial sectors such as cement and lime kiln or coal fired power plants are highlighted as the main expected end-users of SRF, at least in most of the European countries. Some now existing barriers have been pointed out such as waste management policies, availability of SRF of suitable quality, high local bureaucracy and lack of public acceptance. These barriers have been reviewed with respect to the European cement industry but are in many cases valid locally to other types of end uses, such as incineration, co-incineration and dedicated combustion plants.

Countries such as India and China that have to manage high annual amounts of wastes, as well as satisfy their internal demand for energy, recently started to develop domestic pre-treatment systems to SRF. They have also become a quite consistent importer of SRF/RDF from neighbouring producing countries. The ongoing intensive growth of the incineration industry in China, which seems to focus primarily on the use of the bubbling fluidised bed (BFB) technology, could become a large end-user of SRF.

The transboundary shipment of SRF and RDF is significant, also in Europe. As an example, the United Kingdom exports significant amounts to countries like Germany, Netherlands and Sweden. The trade is driven by different factors but policy, waste treatment capacities and current market prices (including factors like taxes) are some of the main reasons.

Currently there is ongoing work within the international Standards organisation (ISO) to develop standards on SRF. This might be an important tool to increase the trust in SRF as a secondary fuel and thus overcome some of the market barriers caused by the lack of a common denomination and methods to determine the quality in a comparable way. The work also includes countries where the use of SRF/RDF is quite limited today.

The waste hierarchy clearly recognizes a role for waste-to-energy and, in particular, to waste fuels produced through processes complementary to material recycling; this implies fuels that origin from waste streams no more suitable for re-use, preparation for re-use or an efficient material recycling. Solid recovered fuels (SRF) would meet that requirement and contribute to the expected change in the waste-to-energy feedstock (improvement of the recyclability and reusability of residues such as plastics, wood, paper, and biodegradable waste) and towards a most energy-efficient waste-to-energy system.

Another area where development of the use of SRF is foreseen is the thermochemical recycling of waste. A lot of attention is being put into this and it is believed to be an important building stone to a more circular economy. In this case the SRF could play an important role, not as solid recovered fuel but rather as a solid recovered feedstock.

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Introduction

Waste-to-energy (WtE) is a broad term that identifies a value chain aimed to exploit the energy potential of wastes by means of the generation of electricity and/or heat in Energy from Waste (EfW) plants. Within that value chain, wastes can follow a "first address" or a "second address" pathway to EfW plants, as Figure 1 schematically shows.

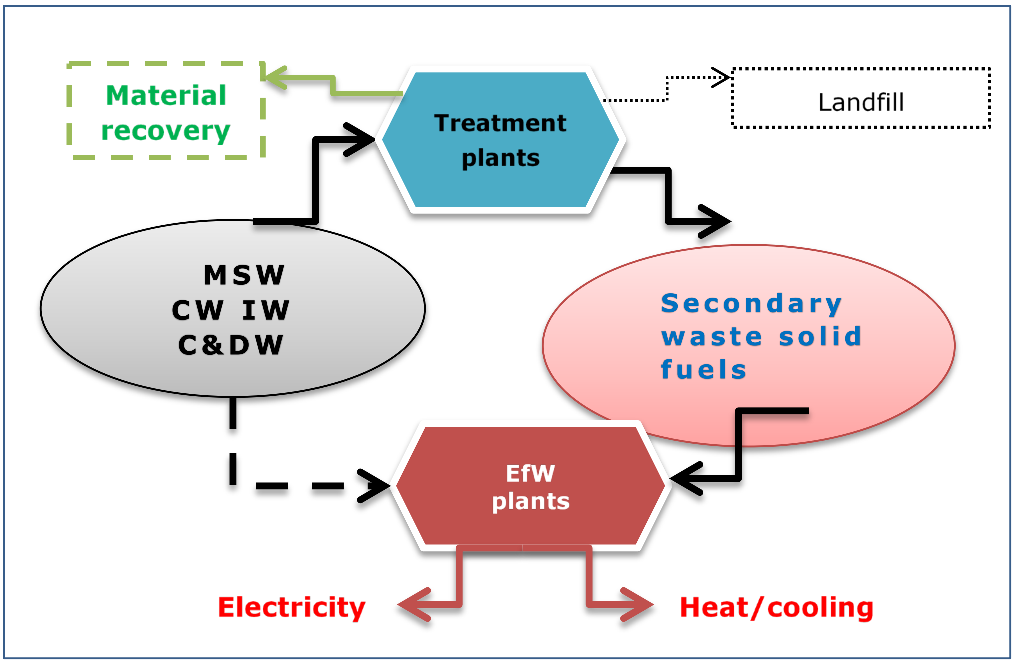

Figure 1. A schematic view of the waste-to-energy value chain. Dashed arrows and boxes identify paths/fuels that do not fall within the specific field of interest of this report.

The first pathway is based on a direct use of the waste as produced, without any pre-treatment, for energy generation. Incineration is historically a way widely followed as waste disposal (as an alternative to landfill) that over time became an option to recover electricity and thermal energy from wastes. As an example, in the Europe Union (EU-28) the amount of municipal waste incinerated has risen by 32 million tonnes (Mton), since 1995, and accounted for 64 Mton in 2015 [1] (in the reference period, the total municipal waste landfilled fell by 83 Mton, from 144 Mton in 1995 to 61 Mton in 2015). In the United States [2] about 262.4 Mton of municipal solid waste (MSW) were generated in 2015, of which 33.6 Mton were combusted with energy recovery in incineration plants. In addition, 67.8 Mton was recycled, 23.4 Mton composted and 137.7 Mton landfilled. Worldwide [3], the number of Waste-to-energy (WtE) facilities for MSW reached a total of 1618 plants in 2016.

According to the second pathway, individual/mixed waste streams are subjected to a pre-treatment in mechanical treatment (MT) /mechanical biological treatment (MBT) plants. Such treatment processes that prepare the residual waste stream for a disposal in landfill through sorting out waste for material recovery and to produce waste derived fuels, are widely implemented in some countries. In those plants, waste fractions that cannot easily be recycled, are sorted out into a fuel fraction for energy recovery.

The secondary fuels in Figure 1, more or less refined with respect to the incoming waste so that their economic (e.g. calorific value), technical (e.g. form and particle size, ash and moisture content, chemical properties) and environmental (e.g. chemical properties; biomass content) characteristics allow a better exploitation of the waste potential. This allows them to be used for other energy applications than the normal waste incineration plants.

As a response to growing market demand the production of secondary fuels has become a quite popular waste management option in different countries, originating in Europe.

There are different end-users in the market of SRF/RDF with different drivers for the use:

- Incineration plants that want to move from disposal to energy recovery (although it is fully possible to reach energy recovery status even with the first pathway).
- Industrial sectors like the cement industry and coal power plants where the use of secondary fuels substitutes fossil fuels (e.g. coal, pet-coke). This generates benefits in the form of less dependence on fossil fuels and lower environmental impact.
- Locally, other industrial EfW plants exploit the potential of secondary fuels (e.g. in co-combustion with other waste streams or residues) ensuring an economic benefit. The economic benefits could be through covering the own energy need; sale of electricity to the national grid and access to economical supports like green certificates or other incentives to support renewable energy sources (RES).
- Un upcoming end-use that is foreseen is the use of SRF/RDF for thermochemical recycling processes. This could either be aimed at converting the waste into liquid or gaseous fuels or to convert it into platform chemicals to be used for the production of new products.

The produced secondary fuels in practice include a large family of fuels differing in origin, composition and quality. Often, they have been generically referred to as refuse-derived fuel (RDF), without compositional quality and environmental parameters well described. This is due to lack of requirements to comply with a well-defined regulation or standard. The European Board for Standardisation (CEN), for example, moved in this direction through the development of standards [4,5] that introduce the concept of "standardised" secondary fuel - the solid recovered fuels (SRF) - by setting the need for producer to classify and specify the fuel. More countries outside Europe have also identified this need and either developed their own sets of standards or adopted the European ones. Some of the main drivers for the development of SRF standards were to create confidence for the fuel as well as to make available a common and well shared language and analytical procedure for the produced fuels placed on the market. The confidence in the product is essential regarding aspects such as potential impacts on human and environment health, impact on plant equipment, risks for end-users and to gain the public and competent authorities' acceptance.

The waste hierarchy (Figure 2) is now a widely accepted and pursued cornerstone of policies and legislation on waste. The hierarchy guides towards a long-term and sustainable waste management and is in a close agreement with the equally shared transition towards a circular economy [6] and decarbonisation of industrial activities. The waste hierarchy defines an order of priority in waste management aimed to minimize adverse effects on the environment and the human health and to optimize resource efficiency, highlighting the preferred options: waste prevention, reuse and recycling. Disposal in landfills or incineration with little or no energy recovery are the least favourable options.

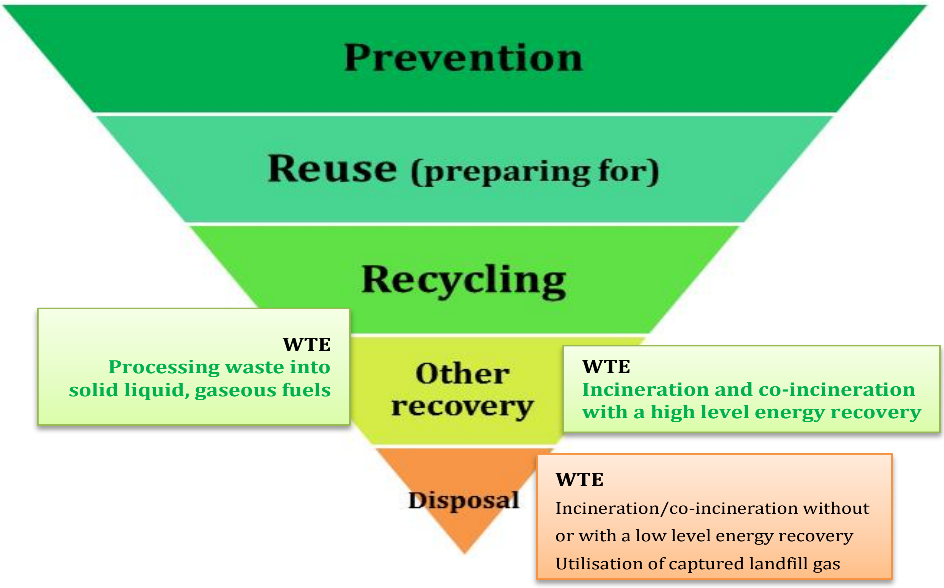

Figure 2. The Waste Hierarchy and the role of Waste-to-Energy (Adapted from: EU COM (2107)34).

According to the mentioned strategic choices, for example the Action Plan promoted by the European Commission [7, 8] and the framework of common laws on waste management (Circular Economy Package) [9–12], recognize a role for waste-to-energy [4] and, in particular, to waste fuels produced through processes substantially complementary to waste recycling. In practice that means fuels that origin from waste streams not more suitable for re-use, preparation for re-use or an efficient material recycling.

Changes in waste-to-energy feedstocks are expected based on the goals of recyclability and reusability that could divert residues, such as plastic, wood, paper and biodegradable wastes, from the options currently adopted for their management which include the energy recovery (incineration or co-incineration). Waste minimisation will also influence the feedstock available for energy recovery.

A waste-to-energy sector more focused on the treatment of non-recyclable waste is a critical point to avoid potential economic losses and barriers to the achievement of higher recycling rates.

This Report provides first a background reference on terminology and origin (waste stream and treatment processes) of SRF followed by a brief analysis of the SRF market in different countries, in term of current situation (production and final end uses). In addition, it highlights some of the main drivers and barriers that can affect its future perspectives.

Background

TERMINOLOGY

Solid fuels that are produced through processing of non-hazardous mono or mixed waste streams[1] to make them a suitable feedstock for energy recovery, are here assumed as secondary fuels. They will in this report be named RDF (refuse derived fuel) (Figure 3). The waste streams sent to energy-from-waste (EfW) plants as generated (e.g. the not pre-treated and unsorted waste) mentioned in Figure 2, are therefore in this report excluded from the field of secondary fuels.

Solid Recovered Fuels (SRF) are depicted in Figure 3 as a subset of the large family of RDFs, based on the assumption that a secondary fuel, produced from not hazardous waste streams, can be considered an SRF or an RDF whether it meets or not requirements (i.e. classification and specification) defined by a national or international standard for SRF. It is in this context the term SRF will be used in this report. This does not necessarily imply that SRF always are of a better quality than RDF- but that the quality is known and defined according to standards. In other words, SRF is always regulated by standards while RDF is a wider term not necessarily encompassed by any standards (even though they exist in some markets).

As a guiding principle from the waste hierarchy all secondary fuels should be based on waste streams that are not suitable for re-use, preparation for re-use or efficient material recycling. The meaning is to identify a fuel product – the SRF, whose added value is to be more defined (Figure 4) than a generic RDF not submitted to specific standardisation.

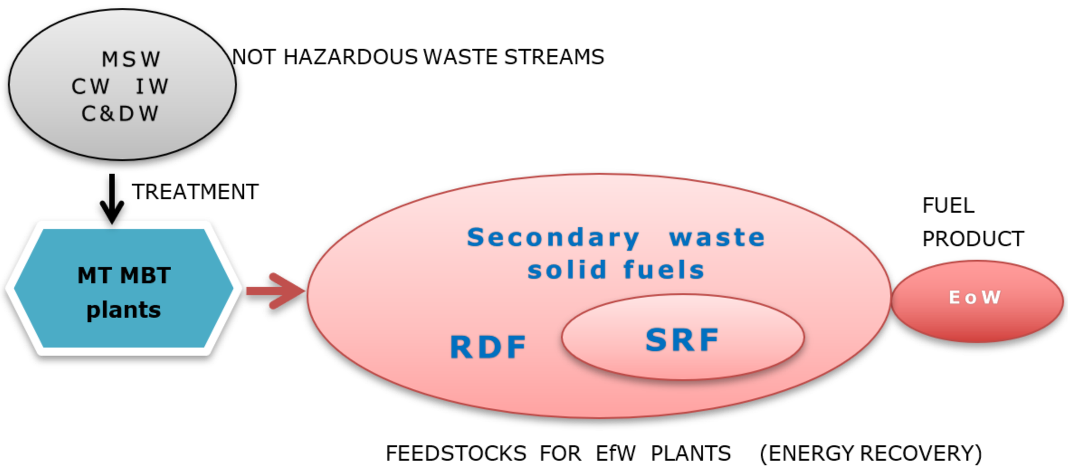

Figure 3. The value chain of energy recovery from wastes through the production of secondary fuels. The status of end-of-waste (EoW) is only possible in specific countries like Italy and Austria.

[1] Mixed waste streams include waste of different origin (e.g. urban, industrial and commercial)

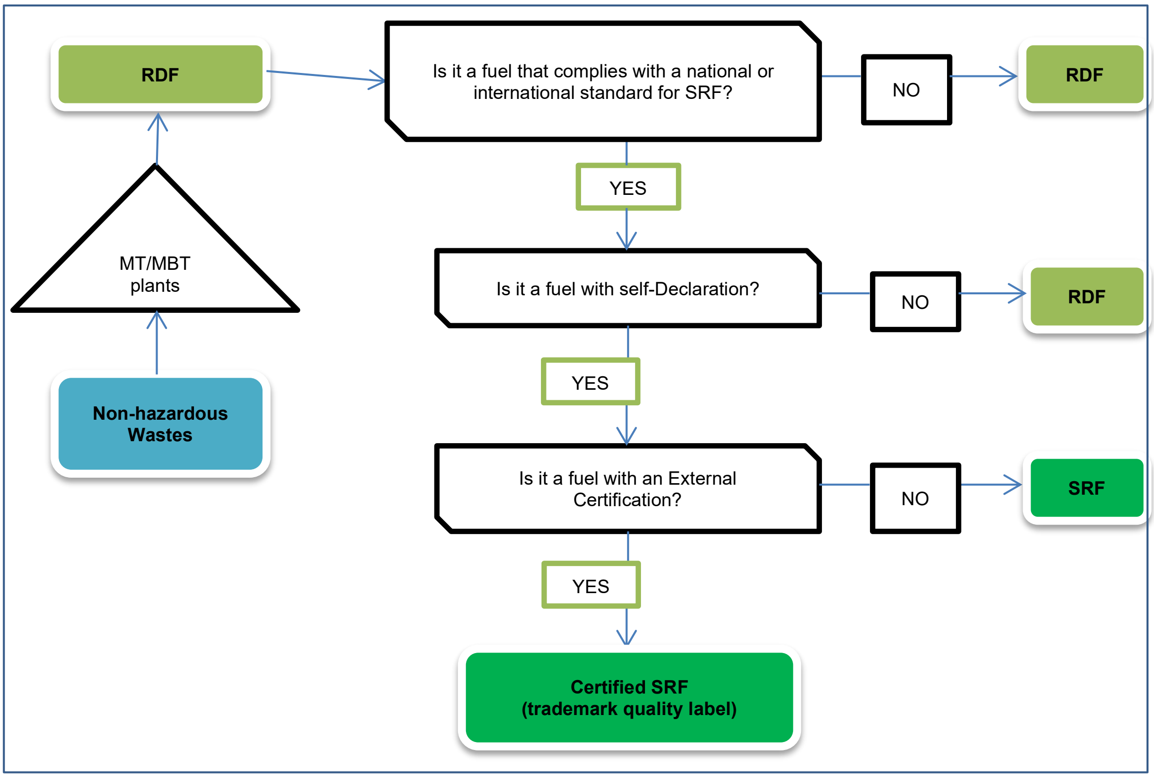

Figure 4. A schematic approach to distinguish between RDF and SRF.

The assumptions above proposed on the meaning of SRF and RDF are the ones being used in this report.

Figure 4 shows that the SRF can further became a certified SRF (quality trademark) if produced according to a defined quality assurance procedure to respond to a market demand (fuel with a well-defined quality).

The above does not hinder the fact that an SRF compliance with further or more stringent quality requirements for fuel properties can be voluntary asked by fuel end-users (e.g. cement kilns, power plants, gasification plants) through a private commitment (specification) with the producer, so to receive a fuel that fit well with their own economic/technological needs. It is worth mentioning that the use of such voluntary, private commitment is foreseen by standards on SRF, such us the EN 15539 [13] and the ongoing development of ISO 21640 [14].

SRF are mainly traded and managed as waste. However, they can became a fuel product in all aspects in some countries (e.g. Italy, Austria [15, 16]). Then the SRF have to comply with legally set mandatory requirements that allow the SRF to be declared as end-of-waste (Figure 3) so that the fuel is no more submitted to the waste legislation.

It is important to note that SRFs put in the market, as well as the RDFs, never identify a univocal fuel, but fuels of which the qualitative properties (e.g. composition, physico-chemical properties) might differ from each other. The achieved degree of quality depends on the fuel origin (waste stream), production processes and, of course, to a main driving factor: the need for a fuel with a quality that complies with the market demand (the technological, economic and environmental requirements of its final end-user).

ORIGIN, PRODUCTION PROCESSES AND SPECIFIC MARKET DEMANDS FOR QUALITY

SRFs can be produced locally from individual or mixed streams of municipal (MSW), commercial (CW), industrial (IW) and construction and demolition (CDW) wastes. These streams include different share of waste fractions which influences their elemental composition. As indicative reference, some results of studies carried out in MT plants that produce SRF from MSW streams [17] (Table 1 and Table 2), from IW and CW streams [18] (Table 3 and Table 4) and from CDW streams 19 (Table 5 and Table 6) are here provided.

Table 1. Results for incoming and outgoing streams from a MT plant: MSW, SRF and other processed waste streams – Some analytical results [28].

Component	MSW[a] wt.%	SRF wt.%	Reject material wt.%	Ferrous metal wt.%	Non-ferrous metal wt.%	Heavy fraction wt.%	Fine fraction wt.%
Paper and cardboard	24.5	30.0	8.6	1.2	1.4	0.4	5.4
Plastic (hard)	12.0	13.0	16.0	2.3	1.6	6.4	2.8
Plastic (soft)	16.6	19.6	5.4	–	2.0	–	5.2
Textile	8.8	10.0	11.0	0.3	1.8	–	2.6
Wood	6.5	8.2	4.5	2.0	–	3.0	3.8
Bio waste	5.0	0.4	10.0	–	–	–	20.0
Rubber	4.8	2.2	24.0	–	–	–	2.5
Metal	4.6	0.5	1.0	92.0	90.0	10.0	3.0
Foam	1.8	2.6	0.5	0.8	0.6	–	6.5
Glass	3.2	0.7	7.8	–	–	–	22.2
Stone	2.6	–	6.0	–	–	78.2	16.8
Fines	9.6	12.8	5.2	1.4	2.6	2.0	9.2

[a]MSW: energy waste collected from households.
MSW: municipal solid waste; SRF: solid recovered fuel.

Table 2. Results for incoming and outgoing streams from a MT plant: MSW, SRF and other processed waste streams – Some analytical results [28].

Streams	Moist. cont. wt%	Ash 550 °C wt%	Volat. matter wt%	Bio[a] cont. %C	C (d.) wt%	H (d.) wt%	N (d.) wt%	S (d.) wt%	$O_{calc.}$ (d.) wt%	NCV (a.r.) MJ kg^{-1}	NCV (d.) MJ kg^{-1}
MSW[b]	13.5	22.4	n.a.	n.a.	47.0	6.2	0.5	0.2	19.6	16.7	19.6
SRF	15.0	9.8	79.4	50.8	53.0	7.4	0.6	0.2	28.0	20.2	22.4
Reject	26.8	32.5	n.a.	n.a.	40.3	5.2	0.9	0.5	16.3	12.0	16.8
Fine f.[c]	33.0	50.3	n.a.	n.a.	28.0	3.6	0.9	1.0	14.8	7.3	12.0
Heavy f[d]	8.9	96.0	n.a.	n.a.	8.3	1.1	0.2	0.1	4.0	2.5	3.0

[a]Bio. cont. represents the biomass content (bio carbon).
[b]MSW: energy waste collected from households.
[c]Fine f. fine fraction stream.
[d]Heavy f heavy fraction stream.
n.a.: not available.

Table 3. Results for incoming and outgoing streams from a MT plant: C&IW stream, SRF stream, other processed waste streams – Composition [18].

Component	C&IW (wt.%)	SRF (wt.%)	Reject material (wt.%)	Ferrous metal (wt.%)	Non-ferrous metal (wt.%)	Heavy fraction (wt.%)	Fine fraction (wt.%)
Paper and cardboard	31.0	35.6	12.4	1.0	2.6	2.0	4.5
Plastic (hard)	14.6	16.5	14.0	1.2	2.8	3.5	2.6
Plastic (soft)	17.0	24.0	4.7	0.6	2.0	n.a.	5.8
Textile	9.0	8.5	9.2	1.4	1.4	n.a.	3.8
Wood	6.8	6.4	4.0	3.6	0.4	4.6	5.6
Rubber	2.6	1.0	6.8	0.2	0.8	4.5	0.8
Metal	6.4	0.8	3.2	92.0	88.0	16.0	0.8
Foam	1.0	1.2	0.2	n.a	0.6	n.a.	4.5
Glass	3.6	n.a.	10.0	n.a	1.4	1.4	16.8
Stone	3.0	n.a.	18.5	n.a	n.a	66.2	28.2
Fines	5.0	6.0	17.0	n.a	n.a	1.8	26.6

Table 4. Results for incoming and outgoing streams from a MT plant: C&IW stream, SRF stream, other processed waste streams – Some analytical results [18].

Process stream	Moisture content (wt.%)	Ash content 550 °C (wt.%)	C (wt.%)	H (wt.%)	N (wt.%)	S (wt.%)	$O_{calc.}$ (wt.%)	NCV[a] MJ/kg (a.r.)[c]	GCV[b] MJ/kg (d.)[d]	NCV[a] MJ/kg (d.)[d]
C&IW	26.5	16.6	48.0	7.0	0.6	0.2	18.0	13.0	19.8	18.5
SRF	25.0	12.5	57.4	8.0	0.5	0.3	17.8	18.0	26.6	25.0
Reject material	26.0	23.0	41.0	5.8	1.0	0.3	20.8	11.6	18.8	16.6
Fine fraction	44.5	48.0	29.6	4.0	1.2	0.8	16.0	5.5	12.6	12.0
Components of commercial and industrial waste (C&IW)										
Paper & cardboard	n.a.	13.0	42.5	5.6	0.4	0.1	38.0	n.a.	17.3	16.0
Plastic (soft)[e]	n.a.	10.3	74.6	12.0	0.3	0.2	2.3	n.a.	39.5	37.0
Plastic (hard)[e]	n.a.	6.0	74.4	11.4	0.3	0.1	5.0	n.a.	37.4	35.0
Textile	n.a.	10.4	57.4	7.6	1.8	0.24	21.3	n.a.	26.5	24.8
Wood	n.a.	1.6	49.0	6.2	0.8	<0.02	42.2	n.a.	20.0	18.6
Rubber	n.a.	23.0	48.0	5.2	1.0	0.5	14.3	n.a.	21.0	20.0
Foam	n.a.	5.0	62.5	8.4	4.0	0.1	19.8	n.a.	29.0	27.3
Fines	n.a.	54.4	26.8	3.5	1.3	1.0	22.6	n.a.	10.6	9.8

[a] NCV net calorific value.
[b] GCV gross calorific value.
[c] (a.r.) as received basis of material.
[d] (d.) dry basis of material.
[e] Plastic (soft) and plastic (hard) were separated on the basis of their physical softness and hardness. n.a. not available.

Table 5. Results for incoming and outgoing streams from a MT plant: C&DW stream; SRF stream; other processed streams - Composition [18].].

Component	C&DW[a] (wt%)	SRF (wt%)	Reject material (wt%)	Ferrous metal (wt%)	Non-ferrous metal (wt%)	Heavy fraction (wt%)	Fine fraction (wt%)
Paper and cardboard	12.0	22.0	6.0	0.6	0.4	1.2	1.6
Plastic (hard)	6.0	9.2	7.4	0.2	1.2	6.8	0.3
Plastic (soft)	3.6	6.8	1.2	–	0.4	–	0.6
Textile	3.8	6.0	3.4	0.2	0.6	–	0.6
Wood	23.6	38.0	12.6	1.4	0.8	14.0	2.8
Rubber	4.8	2.4	15.0	–	1.0	4.0	–
Metal	10.0	2.0	3.0	92.0	90.0	6.0	0.8
Foam	2.0	0.5	1.8	–	–	–	1.6
Glass	3.4	0.6	11.6	–	–	–	10.0
Building material[b]	14.2	1.5	22.0	2.6	2.0	64.0	58.0
Fines	16.6	11.0	16.0	3.0	3.6	4.0	20.5

[a] C&DW refers to C&D waste (i.e. input waste stream) and its composition was determined after primary shredding.
[b] Building material refers to stone/rock, concrete and gypsum, etc.

Table 6. Results for incoming and outgoing streams from a MT plant: C&DW stream; SRF stream; other processed waste streams - Some analytical results [18].

Process streams	Moist cont. (wt%)	Ash 550 °C (wt%)	Volat. matter (wt%)	Bio[a] cont. (% C)	C (d.) (wt%)	H (d.) (wt%)	N (d.) (wt%)	S (d.) (wt%)	$O_{calc.}$ (d.) (wt%)	NCV (a.r.) (MJ/kg)	NCV (d.) (MJ/kg)
C&D waste	14.0	46.8	n.a.	n.a.	30.0	4.0	0.5	0.7	17	9.8	11.0
SRF	16.5	9.0	76.6	66.7	50.0	6.4	1.0	0.3	31.6	18.0	20.0
Reject material	12.0	47.2	n.a.	n.a.	31.2	3.8	0.6	0.7	16.2	10.0	12.0
Fine fraction	23.6	78.8	n.a.	n.a.	12.0	1.3	0.4	2.8	4.8	2.5	4.0
Heavy fraction	10.4	65.6	n.a.	n.a.	20.0	2.6	0.5	0.3	13.2	6.5	7.6

[a] Bio. cont. represents the biomass content (bio carbon) in % carbon.

By using different processes in the production of SRF the producers the properties of the incoming waste will be changed, and the chosen process will determine the achievable yield in the outgoing waste fuels in both quantitative and qualitative terms.

In mechanical treatment plants (MT) plants several operations/sorting techniques can be used to produce SRF. This could as an example be primary shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting, near-infrared (NIR) sorting, and secondary shredding. The purpose of using various sorting techniques is to selectively separate inert material, metals and highly chlorinated/pollutant waste components from the input waste material into small streams in order to obtain a high yield of SRF with specific quality features.

Figure 5 provides an example of a multistage processing applied in an Austrian treatment plant to produce medium (coarse material) and premium (fine material) quality SRF with cement kilns as final end-user [20]. The inputs to the process are commercial waste, packaging waste, industrial waste, and pre-processed household waste. Figure 5 shows the medium and high quality SRF obtained in the process, while Table 7 and Table 8 summarize their sorting and chemical analyses respectively.

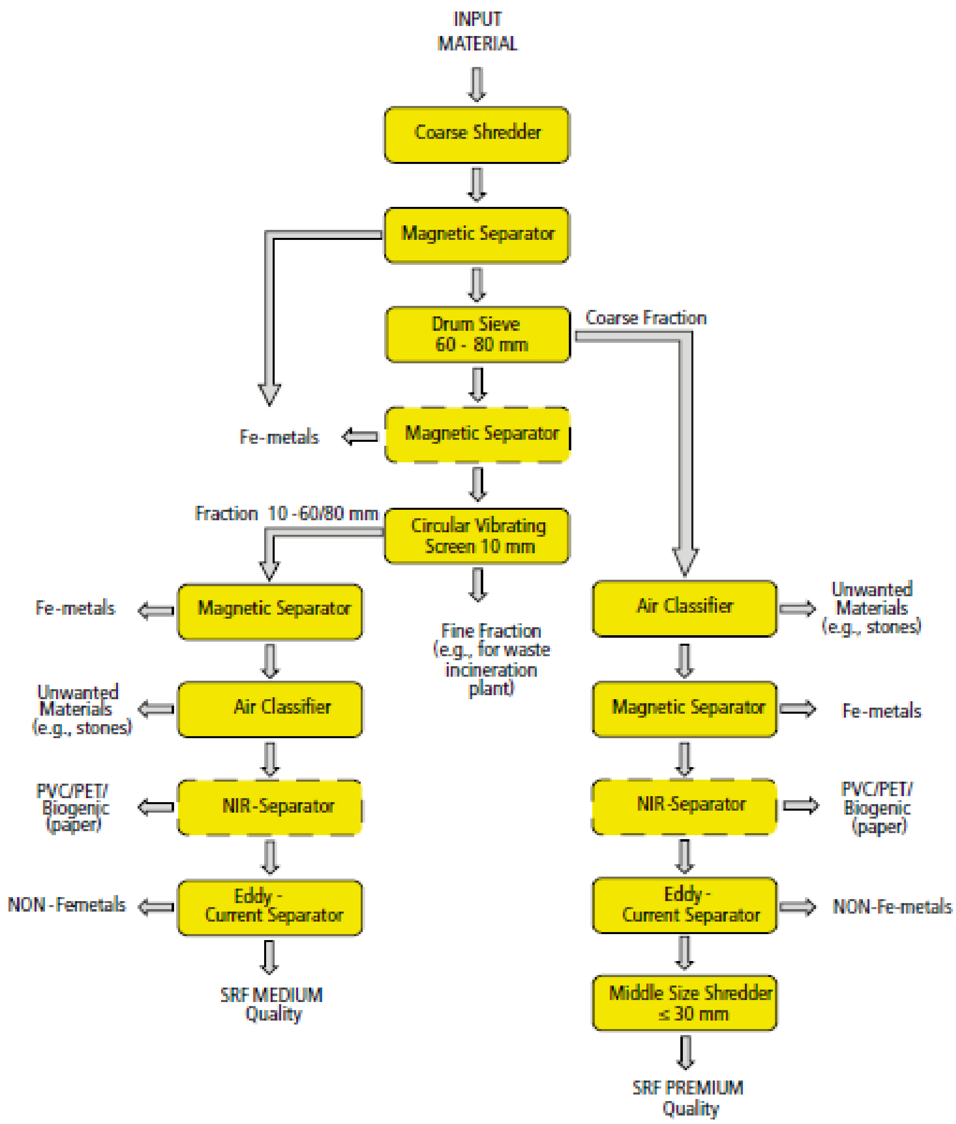

Figure 5. Multistage processing scheme adopted in an Austrian treatment plants for the combined production of SRF medium quality (i.e. coarse material) and SRF premium quality (i.e. fine material). Figure from [20].

Table 7. Results of manual sorting analysis of the medium and high quality SRFs produced according to the treatment process showed in Figure 4, compared to those of a low quality SRF [20].

Fractions	SRF low quality, wt%	SRF medium quality, wt%	SRF high quality wt%
PPCT (paper, plastic, composites, textiles)	35,6	56,2	52,4
INERT (glass, inert, metals, hazardous wastes)	10,6	7,1	1,1
Fine fraction and organic (biogenic fraction)	53,8	36,7	46,5

Table 8. Results for selected physico-chemical properties of the medium and high quality SRFs produced according to the treatment processes showed in Figure 5, compared to those of a low quality SRF. [Data from [20]. (ar: as received; d: dry basis).

Parameter	Unit	SRF low quality		SRF medium quality		SRF high quality	
		median	80th perc	median	80th perc	median	80th perc
Moisture	%, ar	26,5	31,4	25,0	29,1	15,1	29,3
Net calorific value (NCV)	MJ/kg, ar	8,9	10,3	15,5	16,8	19,3	22,8
	MJ/kg, d	14,3	15,7	21,2	21,4	25,0	26,6
Ash	%, ar	29,6	35,2	12,7	15,8	12,4	14,8
Cl	g/kg, d	9,2	12,3	10,8	22,2	13,8	17,1
S	g/kg, d	2,9	3,7	3,4	4,6	3,3	4,5
Total C	w%, d	-	-	46,9	48,6	52,8	58,3
Fossil $C0_2$ emission factor	g/MJ, d	-	-	34,5	41,3	43,2	55,7

A scheme of the multistage process adopted in the Austrian MT plant of the ThermoTeam company to recovery materials and produce a premium quality SRF for use in cement kilns from mixed wastes [21] is presented in Figure 6.

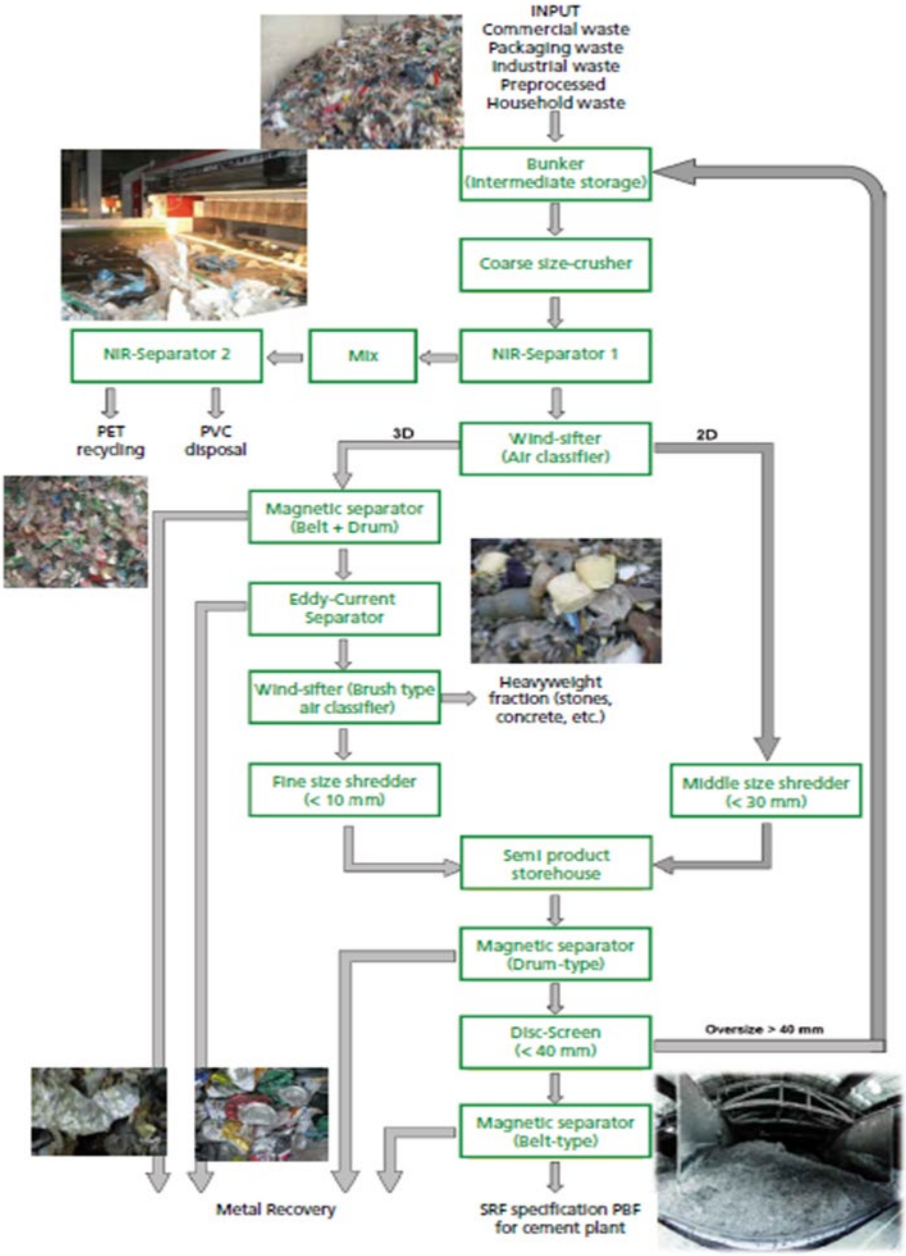

Figure 6. Multistage processing scheme of 100,000 tonnes per year ThermoTeam plant for separation of Fe and non-FE metals, PVC, PET, heavyweight Fraction and manufacturing of premium SRF [21].

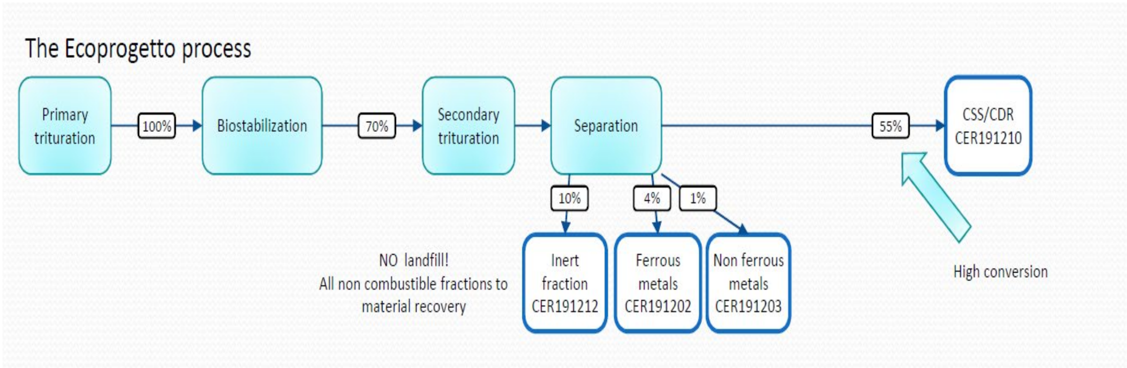

Figure 7. Scheme of the single flow process applied in the Italian MBT plant of the Ecoprogetto company to produce SRF used in coal fired power. Figure from [22].

An example of a Mechanical Biological treatment process is depicted in Figure 7 that refers to an Italian MBT plant producer of SRF from MSW with coal power plants as typical end user [22]. In this case, a treatment based on a "single flow process" was adopted that allows a high conversion of the waste stream into SRF with respect to a more classic two paths process (Figure 8). The process includes a biostabilization stage (Figure 9) aimed to guarantee dehumidification for biological pathway (no energy or fuel consumption for heating), sanitation and stabilization of organic compounds. As an example, the product in from the process depicted in Figure 7 has a stable moisture content (10–15% max), mass reduction (30% by weight), and an increase of the calorific value (+35% with respect to the MSW stream). Figure 10 provides a scheme of the separation process applied in that MBT plant. The SRF generated in the process is in the form of fluff and requires to be densified to produce a final pelletized SRF sent to the end-user.

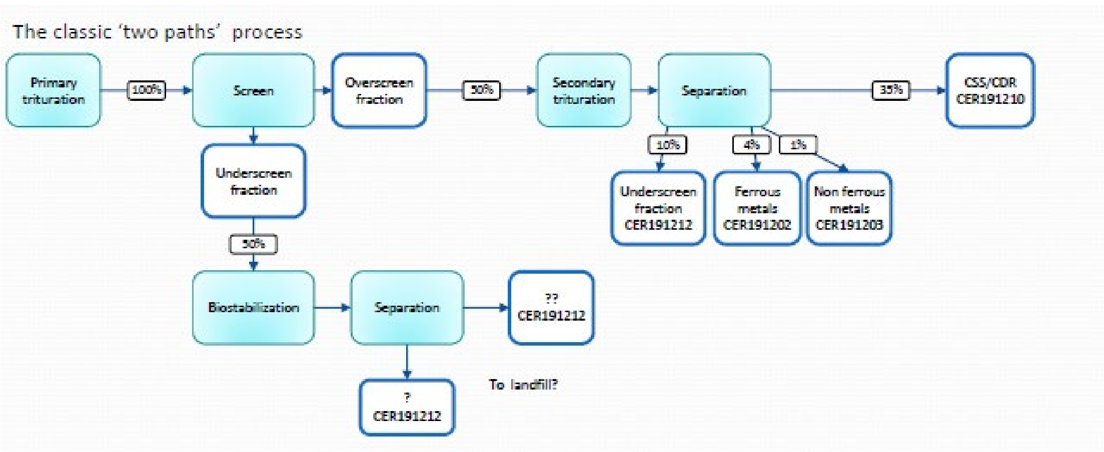

Figure 8. A scheme of a two paths MBT process Figure from [22].

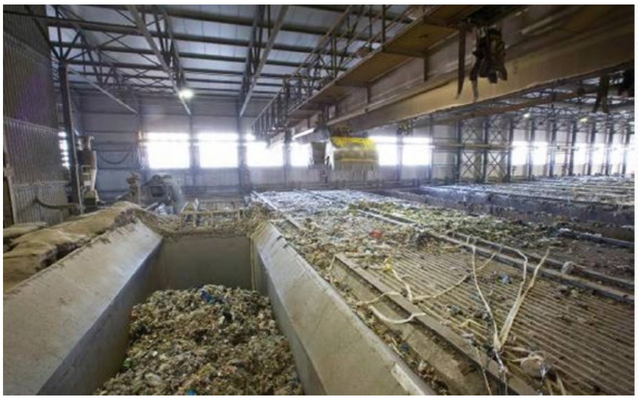

Figure 9. The biocell stabilization under operation in the Italian MBT plant of the Ecoprogetto company to produce SRF used in coal fired power. Figure from [22].

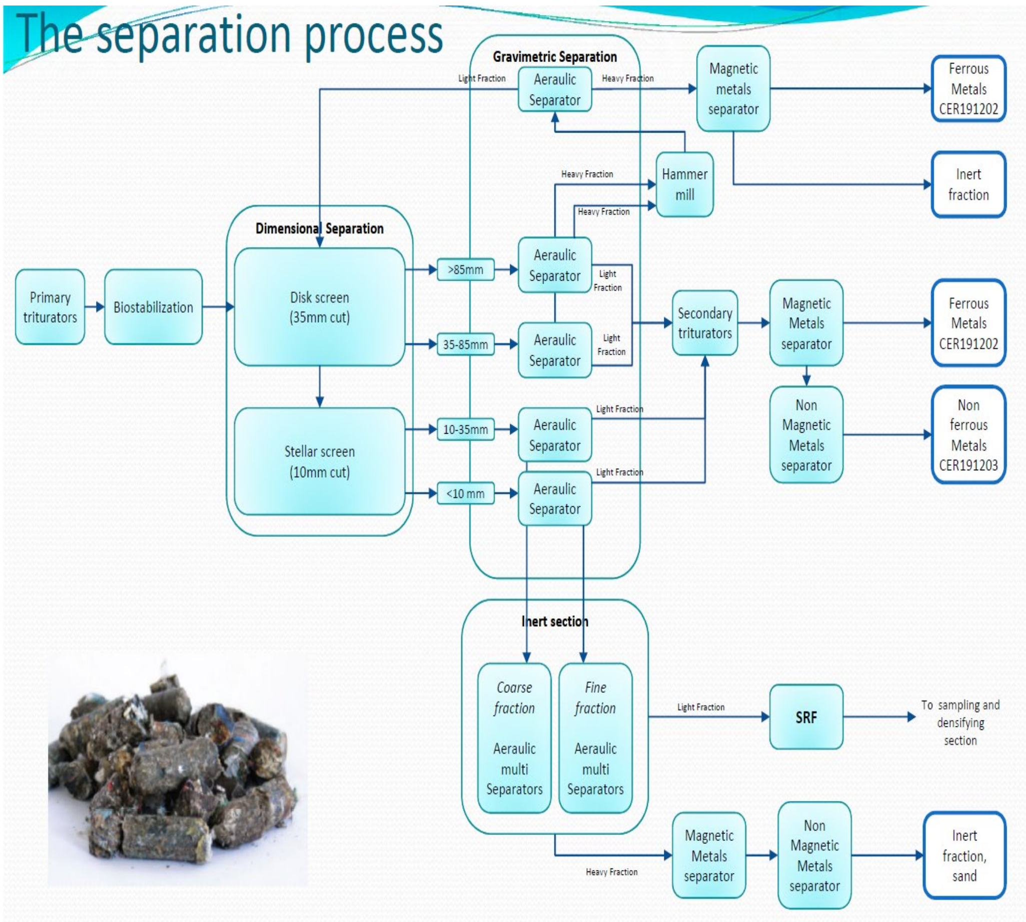

Figure 10. Scheme of the separation applied in the Italian MBT plant of the Ecoprogetto company to produce SRF used in coal fired power Figure from [22].

Further examples of applied mechanical biological processing schemes in Croatia are reported in [23].

Regarding SRF quality, some examples of requirements (i.e. typical values and/or limit values) occurring in voluntary agreements among producers and end users are provided in Table 9.

Table 9. SRF quality requirements set in a specification agreed upon producer and end user (coal power plant, 2016, Italy) - Required class of SRF: 3:3:3–Data from personal communication of an Italian SRF end user [24]. (ar: as received; d: dry basis).

Parameter	Unit	Typical value	Limit value
Ash	%, d	≤20	≤20
Moisture	%, ar	≤15	≤15
NCV	MJ/kg, ar	value set in table 1 of 15539 for the required class code	value set in table 1 of 15539 for the required class code
NCV	MJ/kg, d	≥15	≥15
Cl	%, d	value set in table 1 of the EN 15539 standard for the required class code	value set in table 1 of the EN 15539 standard for the required class code
Sb	mg/kg, d	≤70	≤150
As	mg/kg, d	≤9	≤15
Cd	mg/kg, d	≤7	≤10
Cr	mg/kg, d	≤100	≤500
Co	mg/kg, d	≤7.5	≤100
Cu	mg/kg, d	≤1300	≤2000
Pb	mg/kg, d	≤200	≤600
Mn	mg/kg, d	≤400	≤600
Hg	mg/kg, d	value set in table 1 of the EN 15539 standard for the required class code	value set in table 1 of the EN 15539 standard for the required class code
Ni	mg/kg, d	≤40	≤200
Tl	mg/kg, d	≤1	≤10
V	mg/kg, d	≤7.5	≤150
Σ Heavy metals (a)	mg/kg, d	to be declared	to be declared

This agreed specification requires that SRF complies with UNI EN 15539 and the Italian UNI TR 11581

(a) Sum of heavy metals does not include Hg, Tl and Cd according to EN 15539:2011

Table 10. SRF quality requirements set in a specification agreed upon producer and end users (co-combustion power plants and cement kilns, 2016, Italy). – Data from personal communication of an Italian SRF producer [25]. (as: as received; d: dry basis).

Parameter	Unit	Limit values (min – max)	
Ash	%, d	15	30
Moisture	%, ar	10	30
NCV	kcal/kg, ar	3583	9500
Cl	%, d	0.6	1.5
S	%, d	0.3	0.8
Pb (volatile)	mg/kg, d	100	200
Cr	mg/kg, d	70	833
Cu (soluble)	mg/kg, d	300	500
Mn	mg/kg, d	217	500
Ni	mg/kg, d	40	333
As	mg/kg, d	9	15
PCB	mg/kg, d	0.5	30
Zn	mg/kg, d	500	1000
Co	mg/kg, d	67	100
Cd	mg/kg, d	27	33
Sn	mg/kg, d	70	100
Sb	mg/kg, d	20	267
Hg	mg/kg, d	1.0	1.7
Tl	mg/kg, d	3.3	10
V	mg/kg, d	20	100
Cn	mg/kg, d	2	2
F	mg/kg, d	1000	1000
Be	mg/kg, d	50	50
Ba	mg/kg, d	200	200
Se	mg/kg, d	5	5
Te	mg/kg, d	10	10

Table 11. SRF quality requirements set in a specification agreed upon producer and end user (cement industry, 2016, Italy). Data from personal communication of an Italian SRF producer [25]. (as: as received; d: dry basis.; TE: total concentration;).

Parameter	Unit	Limit value
NCV	GJ/t, ar	≥15
Cl	%, d	1
S	%, d	nd
Hg	mg/kg, d	1
As	mg/kg, d	5
Cd	mg/kg, d	3
Cr	mg/kg, d	100
Cu	mg/kg, d	500
Pb	mg/kg, d	240
Mn	mg/kg, d	250
Ni	mg/kg, d	30
Tl	mg/kg, d	1
Co	mg/kg, d	18
Sb	mg/kg, d	50
V	mg/kg, d	10
IPA (total)	mg/kg, d	30
PCB	mg/kg, d	3
PCDD/PCDF	ng TE/kg, d	20

Table 12. RDF quality requirements set in a specification agreed upon producer and a cement industry. Data from [26]. (ar: as received; d: dry basis).

Parameter	Unit	Limit value
NCV	MJ/kg, ar	>16
Moisture	%, ar	<25
Ash	%, d	<15
Cl	%, ar	<0,8
Hg	mg/kg, d	<1,5
Cd	mg/kg, d	<9
Tl	mg/kg, d	<2
Br	mg/kg, d	<0,25
I	mg/kg, d	<0,25
Sb	mg/kg, d	<150
As	mg/kg, d	<20
Cr	mg/kg, d	<150
Co	mg/kg, d	<20
Cu	mg/kg, d	<500
Pb	mg/kg, d	<200
Mn	mg/kg, d	<150
Ni	mg/kg, d	<70
Sn	mg/kg, d	<50
V	mg/kg, d	<100

Table 13. Typical end-user demands applied (2006) in German cement kilns. Data from [27]. (d: dry basis).

Key Parameter	Range of typical concentrations (a)		Typical concentrations (b)	
	Unit	Values	Unit	Values
Pb	mg/MJ	0,09 - 25	mg/kg d	400
Cd	mg/MJ	0,01 - 0,7	mg/kg d	9
Cr	mg/MJ	0,09 - 21	mg/kg d	250
Ni	mg/MJ	0,1 - 25	mg/kg d	100
Hg	mg/MJ	0,01 - 0,1	mg/kg d	0,5 – 1
Tl	mg/MJ	<0,01 - 0,1	mg/kg d	1 -2
Zn	mg/MJ	0,5 - 625	mg/kg d	--
As			mg/kg d	13
Co			mg/kg d	12
Cu			mg/kg d	700
Mn			mg/kg d	500
Sb			mg/kg d	120
V			mg/kg d	25
Sn			mg/kg d	70

(a) VDI 2094 Germany (2003). "Emissionsminderung Zementwerke/Emission control cement industry, VDI 2094, March 2003

(b) Germany, V. (2006). "Cement manufacturing industries, German contribution

About the use of SRF in gasification plants, the following quality requirement (i.e. limit values) are mentioned in literature [28] that refer to SRFs utilises in the Lahti gasification plant in Finland:

- 18–24 MJ/kg,db NCV;
- <30 wt.% and of <15 wt.% the moisture and the ash content, respectively;
- <0.6 wt.%, db Cl
- <0.1 mg/kg, db Hg.

Experiences carried out in the SRF-BFB plant at Anjalankoski (Finland) [29] pointed out the chlorine content as the main problem (i.e. corrosion risk and fouling) and a need for a moisture content of the SRF within 15–30% and an ash content within 8–12%. Regarding chlorine content, preferred values <0.6 wt.% are reported for co-combustion in fluidized bed boilers and gasification, and values in the range 0,6–0.9 wt.% for the use of SRF in cement kilns [30].

The market of SRF and RDF: status and perspectives

ASIA

Japan

The total amount of municipal solid waste generated in Japan accounted for about 44.3 Mton/y in 2014 and 42.8 Mton/y in 2015 [31]. RDFs are produced from the so called "general waste" that includes household and commercial wastes, according to the national legislation on waste. The RDF is dried by chemical addition and pelletized; includes the putrescible fraction of the waste stream, and it shall comply with requirements set in dedicated national standards [32] such as NCV >12,500 kJ/kg, moisture content <10% or ash content < 20%.

A number of 50 RDF facilities is reported in the country [33]. RDFs quantitatively accounted for about 270,000 ton in 2013 [33] and 300,000 ton in 2015 [35], showing a decreasing trend if we consider the previous volume of around 650,000 ton/year [31]. With a reported average NCV of about 18 MJ/kg [35], RDF produced in Japan is essentially intended to be used in urban WtE facilities, e.g. mainly power generation plants to satisfy the local demand for electricity; other end-users are cement and pulp industries and district heating facilities.

A further secondary fuel named RPF (*Refuse derived Paper and Plastics Densified Fuel*), is also produced in Japan. RPF is a pelletized waste fuel produced from dry and non-hazardous paper and plastic waste from industrial origin (residual wood, textile and rubber waste streams are admitted too as long as the standardized fuel quality requirement are met). The National standards [34], well recognized and applied by all the operators, regulate the matter of RPF, of which the JIS Z7311:2010 classifies it in four qualitative "classes". One of them is the so-called *RPF-coke* which is defined by a high quality RPF with a calorific value >33 MJ/kg close to that of coal. It differs from the above-mentioned RDF by origin (i.e. waste streams) and properties (i.e. lower values for moisture and ash content; higher calorific values).

Around 1,2 Mton/y of RPF were produced [31,35] in the year 2013 and 2015 from several operating RPF facilities (85 in 2013 and 227 in 2015). This data is also supported by results of a nationwide survey performed by the Japan RPF Industry Association [31] (Figure 12). The survey shows a fast increase on the demand of RDF between 2004 and 2009, followed by a plateau (around 1,6 Mton/year) until 2016, when it rose to 1,7 Mton/year. The provided estimations for 2016 and 2017 highlight an increasing demand trend. According to this survey, the national production capacity was able to satisfy such RPF demand by 70–75 since 2013 and is supported by a recent increase of the number of RPF-facilities.

RPF is intended mainly as substitute fuel due to its properties (e.g. NCV > 25 MJ/kg) and its national main users are the Japanese paper and steel industries, followed by cement kilns [37]. The Japan Iron and Steel Federation [38] estimated a consumption of plastics wastes (not specifically identified as RPF) and other wastes such as waste tires of about 450,000 tons in 2016, that has remained substantially unchanged since 2005. No data were found on the use of RPF in the paper industry. About the Japanese cement industry, statistics published in the website of the Japan Cement Association [39] show a low and yearly decreasing consumption of RPF and RDF from about 50,000-55,000 ton/y (2010–2014) to 35,000-37,000 ton/y (2015–2016), that corresponds to only a 1.2–1.3 wt.% of the total yearly consumption of substitute fuels.

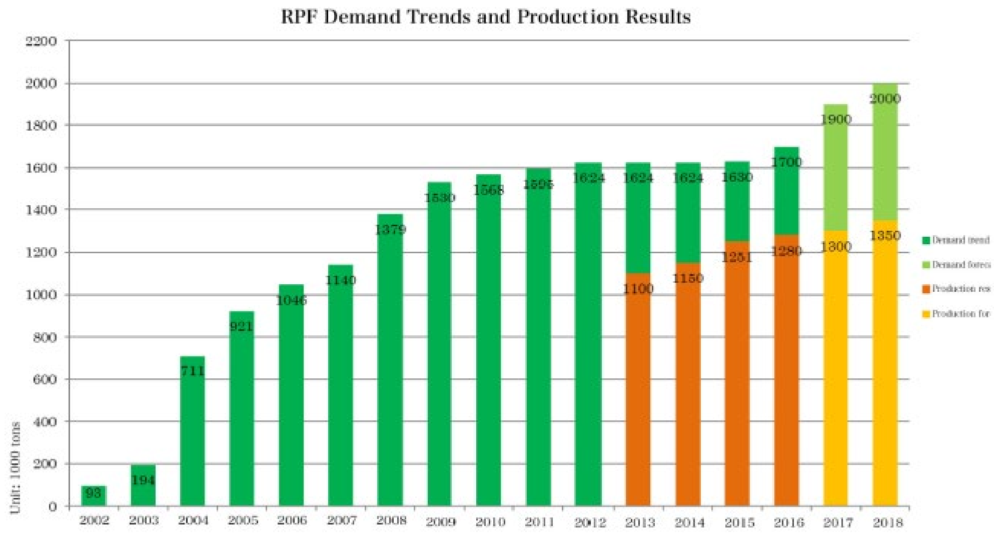

Figure 11. Trend of annual demand (green) and production (red) of RPF in Japan; the light green (demand) and the yellow bars (production) for the 2017 and 2018 years correspond to a partial yearly estimation [36].

In Japan, the RPF market is supported by dedicated national standards that are well recognized and applied by all the national operators, of which the JIS Z 7311:2010 [34] provides criteria for fuel classification and specification (Table 14). More qualitative "classes" of RPF are defined, of which one (RPF-coke) identifies a high quality solid recovered fuel with a calorific value close to that of coal.

Table 14. Classification system and fuel quality requirements set in the Japanese standard JIS Z 7311 for waste derived fuels named RPF (Refuse derived paper and plastics densified fuel) and RPF-coke (RPF with coke-level gross calorific value). (ar: as received; d: dry basis).

Key parameter	Value (mean) RPF-coke	Value mean) RPF class A	Value (mean) RPF class B	Value (mean) RPF class C	Unit	Boundary (End-uses)
NCV	≥33	≥25	≥25	≥25	MJ/kg, ar	Coal co-combustion (cement kiln, power plants) Incineration Co-incineration
Moisture	≤3	≤5	≤5	≤5	%, ar	
Ash	≤5	≤10	≤10	≤10	%, d	
Cl (residual)	≤0.6	≤0.3	>0.3 - ≤0.6	>0.6 - ≤2.0	%, ar	

The following Table 15 summarize the results of a statistical analysis applied to national series of measured values for of RPFs produced in 2018 by some Japanese RPF facilities [37], that RSE [41] performed for the purposes of an ongoing ISO project [42]

Table 15. Overall outcomes expressed as: (top table) sum (n° of assays, n° of assays <Detection limit (DL)) or average (mean, min, max, median, 80th percentile) of the descriptive statistics derived individually for the examined series of measured values; (bottom table) ranges.

Parameter	Unit	N° of Assays	N° of Assays <DL	Mean	Min	Max	Median	80th perc.
NCV	MJ/kg, ar	134	0	26.96	21.76	31.46	27.65	29.59
	MJ/kg, d	134	0	27.72	22.66	32.11	28.33	30.31
Moisture content	%, ar	156	0	2.96	1.29	7.25	2.53	3.62
Ash content	%, d	156	0	5.04	2.26	8.06	5.24	6.58
Cl content	%, ar	156	1	0.241	0.045	0.408	0.251	0.331
Al content	mg/kg, d	74	0	0.309	0.051	1.805	0.166	0.316

Korea

Until 2012, Korea (Rep. of South Korea) had codified secondary fuels on the whole as solid fuels [43] that were qualitatively differentiated into RDF (refuse-derived fuel that could be pelletized or not), RPF (analogue of the RPF produced in Japan), TDF (tire derived fuel) and WCF (wood chip fuel). In 2013 [44], the term SRF (solid recovered fuel) was introduced in Korea by the national legislation, and two types of SRF are currently recognized: an SRF and a biomass-SRF.

Figure 13 shows regulations, relevant parameters and limit values set for SRF adopted over time in the country. Detailed data about the current yearly production of SRF in Korea as well its national consumption and shipment were not found.

Parameter		Solid Fuel (Until 2012)					Solid Refuse Fuel (Since January of 2013)			
		RDF (Refuse Derived Fuel)		RPF (Refuse Plastic Fuel)	TDF (Tire Derived Fuel)	WCF (Wood Chip Fuel)	SRF		Bio-SRF (Biomass-SRF)	
Type		Pellet	Non-pellet	Pellet	-	-	Pellet	Non-pellet	Pellet	Non-pellet
Diameter (mm) *width		≦30	-	≦50	-	-	≦50	≦50*	≦50	≦120
Length (mm) *heigth		≦100	Passing rate≧95% (50mm x 50mm)	≦100	≦120	≦100	≦100	≦50*	≦100	≦120
Moisture (% wt.)		≦10	≦25	≦10			≦10	≦25	≦10	≦25
Low Heating Value (kcal/kg)		≧3,500		≧6,000		≧3,500	≧3,500	≧3,500	≧3,000	≧3,000
Ash (% wt., dry basis)		≦20			≦4	≦8	≦20		≦15	
Chlorine (% wt., dry basis)		≦2				≦0.3	≦2		≦0.5	
Sulfur (% wt., dry basis)		≦0.6			≦2.0	≦1.2	≦0.6		≦0.6	
Metals (mg/kg, dry basis)	Hg	≦1.2				≦1.0	≦1.0		≦0.6	
	Cd	≦9.0				≦2.0	≦5.0		≦5.0	
	Pb	≦200.0				≦30	≦150		≦100	
	As	≦13.0				≦2.0	≦13.0		≦5.0	
	Cr	-				≦30.0	-		≦70.0	
Heating Value (kcal/kg)	1	≧6,500					-			
	2	5,500~6500		6,000~6,500		5,500~6,500	-			
	3	4,500~5,500	-	-		4,500~5,500	-			
	4	3,500~4,500	-	-		3,500~4,500	-			
Chlorine (%wt, dry basis)	1	<0.5				<0.3	-			
	2	≧0.5~<1.0				-	-			
	3	≧1.0~<1.5				-	-			
	4	≧1.5~<2.0				-	-			

*Ministry of Environment: Act on the Promotion of Saving and Recycling of Resources Enforcement Regulation (Addendum 7)

Figure 12. Korea regulations for solid recovered fuels [43].

The waste management policies [44,45] adopted in Korea in 2013, include a comprehensive plan on Waste-to-Energy (main part of the produced renewable energy) and according to that, it was expected an increase from 1.8 Mt in 2013 to 3.8 Mton in 2020 of combustible fractions (e.g. paper, plastics, wood) of municipal/industrial wastes transformed in SRF, to be combusted or converted to energy at boilers, and cogeneration plants. Twelve SRF-plants are reported in operation in the country [45], almost all of them producing SRF in form of pellets (plants capacity from 25 tons/day to 200 tons/day). In addition, there are 4 plants under construction and 2 more being planned.

Regarding EfW plants, 185 incinerators and 10 MSW-gasification plants (with a capacity from 10 to 150 ton/day) are mentioned to be in operation in the country [45].

Thailand

It is estimated that about 27 Mton of MSW were generated in Thailand in 2015 and 2016 [46,47]. An integrated waste management system was recently introduced in the country, with the aim of accelerating the material and energy recovery from MSW through source waste separation, pre-treatment systems, WtE and/or composting facilities. According to the national energy Statistics and based on data reported by Intharathirat et al. [47], the country has 4 MSW incineration plants in operation (2 CFB, 2 moving grate plants; 1 rotary kiln plant halted operation), 5 under construction and additional plans for the construction of 8 more. Four of these plants (only one under operation at the time, the rest in construction or planning) were reported as RDF processing plant, with a treatment capacity ranging from a minimum of 250–500 ton/d to 1550–2700 ton/d, with an estimated potential consumption of RDF in incineration facilities of about 4950 ton/d. In

2017, there were two RDF-gasification plants [47] in operation. These plants use a CFB and a two-stage gasification (i.e. updraft and ash melting) technology and together they processed 259 ton/d of RDF or 602 ton/d of MSW. Additional MSW/RDF gasification/pyrolysis facilities were declared under construction or planned in the country, for an estimated potential consumption of RDF around 468 ton/d.

A total of 23 cement kilns were reported [47] under operation, under construction and planning covering a clinker capacity of 38 Mton/y. These plants have a potential to substitute 40% of its own energy demand by RDF. The characteristic of a suitable RDF for being used in the cement kilns in Thailand [47] needs at least 18.8 MJ/kg of calorific value, a moisture content < 30 %, and a chlorine and sulphur content <1 %.

Thailand has a potential yearly production for around 2.46 Mt of RDF [47]. A typical RDF would consist of 40 % plastic, 30 %-yard waste, 10 % food waste, less than 10 % paper and around 10 % of non-combustible materials, with an NVC value of about 19.6 MJ/kg and a moisture content of 12%. Three national cement companies [47] have invested in MSW sorting plants with the aim of producing a suitable RDF: six "dedicated" sorting plants are reported already under operation with an estimated capacity of handling more than 350,000 ton/y of RDF, two are under construction or planned for a potential whole production of RDF within this industrial sector of 1.5 Mton/y.

In 2016, the Thailand's WtE system [48] consisted of 8 RDF facilities, 7 MSW/RDF incineration plants and 5 RDF gasification plants. Data on fuel substitution in the Thailand cement industry [46] depict in the same year a consumption of 94 Mton (ktoe 43.28) of RDF and of 32 Mton (ktoe 25.15) of used tires at 2016.

A classification of waste fuels according to the American Standards for Testing of Materials (ASTM) is considered as main reference in the country [47]. It identifies seven types of RDF based on pre-sorted MSW (Figure 15).

Table 16. Thailand regulations for SRF/RDF [49].

RDF-1	Waste used as fuel in as-discarded form
RDF-2	Waste processed to coarse particle size, with or without ferrous metal separation
RDF-3	Shredded fuel derived from MSW that has been processed to remove metals, glass and other inorganic materials (95% wt., passes 50–mm^2 mesh)
RDF-4	Combustible waste processed into powder form (95 %wt., passes 50–mm 10 mesh)
RDF-5	Combustible waste densified (compressed) into a form of pellets, slugs, briquettes, or briquettes (d-RDF)
RDF-6	Combustible waste processed into liquid fuel
RDF-7	Combustible waste processed into liquid, gaseous fuel

The secondary fuel RDF-5 (Table 16) is considered to be particularly attractive in comparison to the combustion of the MWS itself. The RDF-5 is a densified combustible waste (mainly produced in form of pellet), derived from densified plastic waste (i.e. quite similar to the Japan RPF) [49]. It can be combusted in different existing boilers such as fluidized bed combustors, gasifiers, cement and brick kilns and it is easily transported or stored It contains a lower percentage of non-burnable residuals (e.g. metals and glass), a higher heat content per unit weight than the unprocessed solid waste. When the RDF-5 is burnt in a dedicated boiler, it can offer up to 8–10 % greater thermal efficiency compared to untreated waste (no considerations taken to the energy demand to generate the RDF-5 fuel though).

The feasibility to produce an RDF-5 from MSW plastic wastes mixed with crude oil sludge from petroleum wastes have been tested in the country [49].

The RDFs produced from used and unused plastic wastes have been tested on pilot-scale downdraft fixed bed gasification system [50]; while an RDF made from MSW of reclamations of dumpsites and with high content of combustible wastes, low moisture content, and fewer biodegradable fractions was tested on low pilot-scale downdraft gasifiers [51].

India

In India, the term RDF is used to identify a waste fuel that can be used for co-processing in various industries. According to the national legislation, an RDF is a fuel derived from solid combustible waste fraction such as plastic, wood, pulp or organic waste, other than chlorinated materials. It is usually in the form of pellets or fluff produced by drying, shredding, dehydrating and compacting of solid waste. The term SCF (Segregated Combustible Fraction) is also used in India to identify MSW non-recyclable fractions containing plastics and other combustible materials that are not biodegradable and release toxic gases when they are burnt or dumped in the dump yards/landfills. These fractions can be processed in WtE plants or used in pre-processing facilities to produce an RDF. Unfortunately, no data has been found on current national production of either RDF or SCF.

Quality requirements (Table 17) for RDF when utilized in the cement industry (pre-calciner/kiln) have been defined in a Guideline of the Central Public Health and Environmental Engineering Organization [61].

More recently, classification rules and specification requirements (Table 18) for the cement industry sector have been proposed by an Expert Committee appointed by the national Ministry of Housing and Urban Affairs (MoHUA) [59] and confirmed by the Cement Manufacturing Association; and are reported to be well accepted by other stakeholders for the use of both SCF and RDF in waste-to-energy plants.

Other than the use as supplementary fuel in thermal power stations and incineration plants, the Guideline highlights the cement industry as the most suitable industry to adopt RDF as substitutive fuel. On the other hand, RDF is considered an unsuitable fuel for the thermal and Iron & Steel industry and the brick kilns, due to different constraints that might have a negative impact on the production process, the product quality and the environment.

Table 17. Quality requirements (mean) for RDF utilised in the cement industry (pre-calciner/kiln) [59].

Key parametrs	RDF - Desiderable values	Unit	Boundary (End-uses)
NCV	>3000	kcal/kg	Coal co-combustion (cement kiln)
Moisture	<20	%	
Cl	<0,7	%	
S	<2	%	
Particle Size	<120 - <70mm	mm	

Table 18. Classification criteria and limit values (mean) for waste fuels utilised in cement kilns proposed (2018) in India by the Expert Committee appointed by the national Ministry of Housing and Urban Affairs (MoHUA) [59].

Key parameters	SCF Limit value	RDF Grade III Limit value	RDF Grade II Limit value	RDF Grade I Limit value	Unit	Boundary (End-uses)
NCV	>1500	>3000	>3750	>4500	kcal/kg	Coal co-combustion (cement kiln)
Ash	<20	<15	<10	<10	%	
Moisture	<35	<20	<15	<10	%	
Cl	<1.0	<1.0	<0,7	<0,5	%	
Particle size	<1,5	<50, if ILC plant (a) <20, if SLC plants (b)			mm	

(a) ILC: In Line Calciner
(b) SLC: Separate Line Calciner

After China, India is one of the largest cement consumers in the world with a total 163 operating kilns in 2017 [62] In 2017, India accounted for 9,5% of the total cement world consumption [63] Despite this fact, the current exploitation of alternative fuels in the cement industry measured in a Thermal Substitution Rate (TSR) is still quite low, with an increase from a 0,6% in 2010) to a 3% in 2017, of which 24% was biomass [64].

RDF from MSW is considered one of the most promising alternative fuels (other utilised substitute are used tires, industrial plastic wastes, hazardous wastes, dried sewage sludge, slaughterhouse waste and biomass [65, 66]). There is an estimated potential availability of about 1.37 Mton/y of MSW-RDF for co-processing. Some of the challenges in the exploitation of RDF in India are:

i. technical barriers such as poor quality of MSW: high moisture, chlorine a heavy metals content of RDF, customization of MSW treatment plants to a cement grade RDF;
ii. financial barriers such as high investment costs for pre-processing plants or high costs for MSW collection and transportation;
iii. policy and regulatory barriers on the matter of MSW conversion to RDF and RDF co-processing in cement kilns are still being elaborated. If we look at data on the amount of wastes utilized in cement industries in India during 2016, RDF seems to have a negligible impact, with only 848 ton/y treated in 1 cement kiln.

China

China, with an increment of 33.8% of the MSW production over the last 10 years, reaching more than 203 Mton/y in 2016, has recently made a political choice towards a significant increase of its daily disposal capacity through incineration [67, 60]. Incineration is expected to increase from about 235,000 ton/d in 2015 to about 591,000 ton/d in 2020, it means an increase of its weight in the national MSW waste management from 31% in 2015 to 54% in 2020. It also means an increased number of incineration plants, already changed form 249 plants in 2016 to 303 in 2017.

Figure 14 describes the planned evolution (2015) in the different provinces of China. The grate furnace technology prevails in China (it used in 202 of the 303 MSW incineration power generation plants under operation in 2017), however a quick development of the circulating fluidized bed (CFB) technology is now promoted [67] as well as a larger exploitation of the source (MSW) separation processes and the use of SRF. The matter of SRF is regulated in the country by national standards [60] widely recognized, accepted and used by stakeholders in China even though many industrial and local standards are available as well.

China remains the largest cement consumer in the world, in 2017 covering the 59,1% of the total world consumption [63] and leading the ranking of the top ten cement producing countries with a total of 804 operating kilns in 2017[62]. No detailed data on the reached TSR were found for the cement industry in China, even if some projects on municipal waste and sludge co-processing in cement kilns ongoing in the last seven years are reported [69]. On the whole, China and India seem to remain below the 6% of thermal substitution rate reached in cement sector at global level [70] in 2016, and very far from that of the EU-28 zone as later showed.

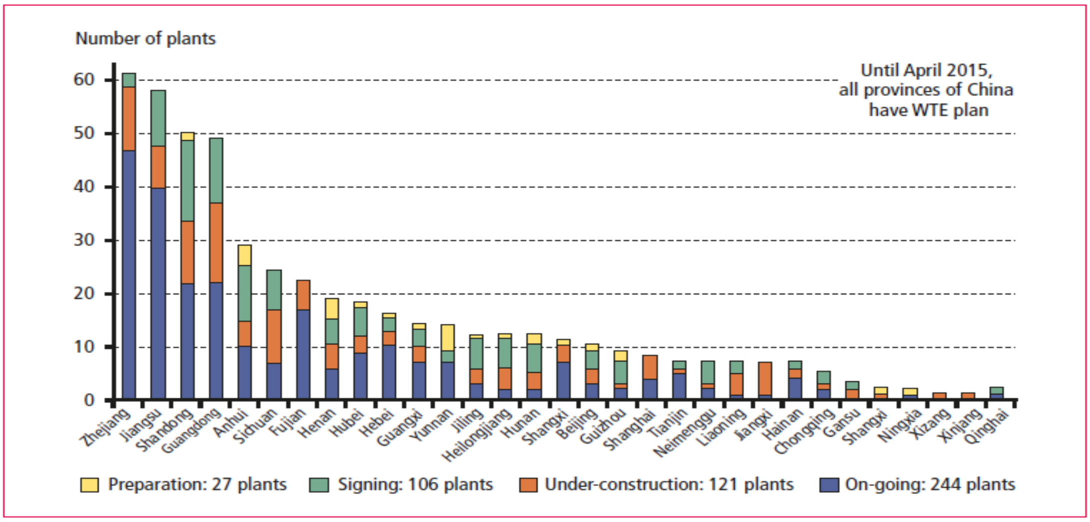

Figure 13. Situation and trend of WtE incineration plants in the provinces of China in 2015 [67].

Trade within Asia

As the following Figure 15 shows, different South-East Asian countries are involved in transboundary shipments of secondary fuels (i.e. SRF, RDF), with India and China the prevailing final customers [35].

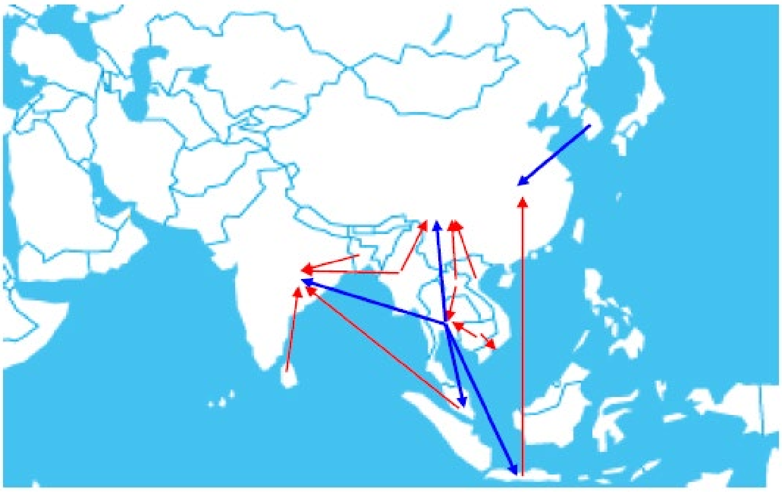

Figure 14. Transboundary shipments of RDF (red line) and SRF (blue line) in Asia [35].

Countries recently experiencing a demographic and/or an economic expansion, such as China and India, look with an increasing interest to secondary fuels as a reasonable way to tackle the management of the very large volumes of urban wastes yearly produced [52,53,54,55,56,57]. Both countries have recently revised their legislations on waste management. Furthermore, China has also recently introduced import bans for specific waste streams such as low-quality plastics and paper. The Annex 1 provides some discussions on their effects, mainly focused on the export of plastic wastes intended to be submitted to recycling in the recipient countries. China and India are also moving towards a development of own technical guidelines/standards for the use of secondary fuels in different industrial sectors (India) [61, 59] or the alignment of the existing ones (as it is the case of China) with those internationally addressed [60].

AFRICA

Egypt

Based on the national data [71], the MSW sorting and composting sector in Egypt is based on a total of 64 plants, of which 46 were under operation in 2015, with a whole design treatment capacity around 3.2 Mton/y. During 2015 the plants under operation treated about 2.2 Mton of MSW, that means 18% of the total amount of MSW yearly collected in the country, with an average efficiency of the system around 70% of the design capacity.

It was estimated [71] that Delta, Greater Cairo and Alexandria areas (they account for the 83% of the total MSW produced in the) have a potential capacity to produce in the range of 1.7 to 4.2 Mton/y of RDF. In 2015, the national production of RDF was around 223,000 tons and cement kilns seem to be the largest end-user. The RDF is mainly produced by third party producers that conduct pre-processing of MSW coming mainly from the area near Cairo. There is only one cement facility that pre-process urban wastes to produce RDF through a partnership with a local waste management company [71]. A calorific value of the produced RDF falling in the range of 11.7-16.7 MJ/ton is reported [71].

According to the results of a survey carried out by the Egyptian cement industry [71], 8 out of the 14 cement producers interviewed, co-processed about 388,000 tons of agriculture waste, 223,000 tons of RDF and 32,000 tons of shredded scrap tires in 2014. In the same year, an average thermal substitution rate (TSR) of 6.4% was achieved by the national cement sector, with a maximum rate of 13% in two cement kilns. It was estimated [71] that a 20% TSR could reasonably be achieved by 2025 in Egypt, based on the availability of substitute fuels in the country and the expected capability of the waste management system to support the production of RDF. To reach such target, the estimated needs were for 1.36 Mtons of RDF, 1.51 Mtons of agricultural waste, 0.1 Mtons of tire derived fuels and of 0.44 Mtons of dried sewage sludges, a substitutive fuel not utilised at least until 2015.

EUROPE

A view of the SRF/RDF market on a national basis is described below, based on the data that was possible to collect from literature and the responses provided by Expert Members to a dedicated survey carried out on the matter by the ISO/TC 300/WG2 in 2017. Therefore, the provided description of the production and use of SRF/RDF, certainly, does not cover all countries uniformly, and not always provides equally and exhaustive data. However, it can be useful for a knowledge of the state of the art and the perspectives of the individual markets.

Furthermore an overview of the European market, as well as identified barriers are presented.

Spain

In 2015, 31 mechanical waste treatment plants were reported under operation in Spain [89] with a whole treatment capacity of about 4.2 Mton/y. However, no data is available regarding SRF/RDF. About 2.5 Mton of MSW (no data provided about the share of SRF/RDF) were treated in 10 incineration facilities under operation that have in total a capacity of about 2.6 Mton/y.

About the national cement industry, 30 cement kilns under operation accounting them for an overall use of substitutive fuels of about 0.8 Mton of which 0.5 Mton were reported as "other wastes" and 0.3 Mton as a mix of European waste list codes (EWC) that includes both the 191210 and the 191212 ones (individual share were not provided).

Germany

Germany produced about 3 Mton of SRF of which 0.5 Mton were under the brand mark SBS with certified RAL quality, and consumed about 2.2 Mton of SRF in cement kilns which corresponds to 67% of 3.3 Mton utilised substitutive fuels, and 0.8 Mton in the national system of coal (lignite and hard coal) power plants during 2016 [90]. The whole national production of RDF was around 8.7 Mton [91] (4.1 Mton from MSW and 4.6 Mton from industrial/commercial waste streams) of which SRF accounted for 2–3 Mton. SRF was mainly consumed as fuel substitute in co-incineration plants. In 2015, RDF consumption was 1.3 Mton in incineration plants and 4.7 Mton in dedicated industrial facilities (heat generation), so accounting for a whole amount of about 9 Mton of RDF (regulated and not) in the country.

An SRF is assumed in Germany to be a specially prepared fuel made of production-specific or municipal waste streams that have been treated adequately for being used mainly in co-incineration plants. Solid recovered fuels that comply with a defined standardised quality - defined by the German RAL-GZ 724 [92] (Table 19) - are now protected in Germany by brand names (BPG™; SBS™) [93–96].

Table 19. Germany. Fuel quality requirements according to the national standard RAL-GZ 724. (d: dry basis).

Key parameter	Limit Value (median)	Limit value (80th percentile)	Unit	Boundary (End-uses)
As	0.31	0.81	mg/MJ, d	Co-incineration
Cd	0.25	0.56	mg/MJ, d	
Co	0.38	0.75	mg/MJ, d	
Cr	7.8	16	mg/MJ, d	
Hg	0.038	0.075	mg/MJ, d	
Mn	16	31	mg/MJ, d	
Ni	5	10	mg/MJ, d	
Pb	12	25	mg/MJ, d	
Sb	3.1	7.5	mg/MJ, d	
Sn	1.9	4.4	mg/MJ, d	
Tl	0.063	0.13	mg/MJ, d	
V	0.63	1.6	mg/MJ, d	
BGS 2 Gütegemeinschaft Sekundärbrennstoffe und Recyclingholz e. V., Güte- und Prüfbestimmungen für Sekundärbrennstoffe [Quality and monitoring rules for SRF], RAL-GZ 724, Sankt Augustin, Januar 2013				

The BPG™ label identifies an SRF produced only from source sorted industrial and commercial waste. Three qualitative categories of BPG™ are defined: BPG 1™ (power plants), BPG 2™ (cement kilns) and BPG 3™ (lime kilns). The SBS™ label identifies an SRF produced from municipal waste streams and from construction and demolition wastes. Two qualitative categories of SBS™ are defined: SBS 1™ (lignite power plants) and SBS 2™ (coal power plants and cement kilns). Table 20 shows the quality requirements set in Germany for these recovered fuels.

Table 20. Germany: quality requirements for SRFs produced according to the RAL GZ 724 receiving the trademarks BPGTM and SBSTM [93, 94]. (ar: as received; d: dry basis).

Key parameter	Unit	BPG™ 1 value	BPG™2 Value	BPG™ 3 Value	SBS™ 1 value	SBS™ 2 value
NCV	MJ/kg,ar	16-20	20-24	23-27	13-18	18-23
Moisture	%, ar	<35	<20	<12,5	<35	<20
Ash	mg/kg d	<20	<15	<9	<20	<15
Cl	%, dm	<1.0	<1.0	<1.0	<0.7	<1.0
F	%, dm	<0.05	<0.05	<0.05	<0.05	<0.05
S	%, dm	<0.2	<0.3	<0.3	<0.5	<0.8
As	mg/kg,d	<10	<10	<10	<10	<10
Be	mg/kg,d	<1.0	<1.0	<1.0	<1.0	<1.0
Cd	mg/kg,d	<9	<9	<9	<9	<9
Co	mg/kg,d	<12	<12	<12	<12	<12
Cr	mg/kg,d	<120	<120	<120	<250	<250
Cu	mg/kg,d	<400	<400	<400	<1000	<1000
Hg	mg/kg,d	<0,5	<0,5	<0,5	<1,0	<1,0
Mn	mg/kg,d	<100	<100	<100	<400	<400
Ni	mg/kg,d	<50	<50	<50	<160	<160
Pb	mg/kg,d	<100	<100	<100	<400	<400
Sb	mg/kg,d	<120	<120	<120	<120	<120
Se	mg/kg,d	<4	<4	<4	<5	<5
Sn	mg/kg,d	<70	<70	<70	<70	<70
Te	mg/kg,d	<4	<4	<4	<5	<5
Tl	mg/kg,d	<1	<1	<1	<1	<1
V	mg/kg,d	<15	<15	<15	<25	<25
Origin		residues from paper production rejects, punching, photograph y paper, blocks wet-strength paper, cellulose cloths, etc..	paper wastes as BPG® 1, plastics (resins, polyacryli c, polyester, polyolefin, PUR...), fibre fabrics, carpets, etc..	low ash plastics (resins, polyacrylic, polyester, polyolefin, PUR...),	different high calorific fractions from MSW demolition wastes	as SBSTM 1
Boundary (end-use)		power plants	cement kiln	lime kiln	coal (lignite) power plants	coal (hard coal) power plants cement kilns

BPG™ (Brennstoff aus produktionsspezifischen Gewerbeabfällen)
SBS™ (Substitutbrennstoff)

Austria

Austria [97] reported a production of about 2.8 Mton of SRF of which about 1.0 Mton were only from MSW in 2015 and a production of 0.18 Mton of SRF-EoW (fuel product) in 2016.

53 industrial power plants were under operation in the country in 2015 with a total capacity of about 1.0 Mton of waste treated which includes waste wood (about 0.4 Mton), residues from the pulp and paper industry (about 0.4 Mton), plastic wastes (about 0.1 Mton) and to a lower extent, textiles, sewage sludge and other wastes. The 8 cement kilns under operation during 2015 and 2016 consumed 0.5 Mton/y of substitutive fuels; plastics wastes being the the main component of the mix of substitutive fuels contributing with 0.30 Mton in both the year;, followed by sewage sludge, waste wood, animal meal agricultural residues, used tires , paper fibers used tires and waste oil (all more or less >0.1 Mton).No details are provided by the data source about the consumption SRF/RDF. Other source of information [91] quantify a whole national RDF consumption of about 1.3 Mton at 2015, of which 0.27 Mton were incinerated, 0.71 Mton were used in incineration/co-incineration in dedicated industrial facilities and, 0.33 Mton in cement kilns.

About the use of SRF in cement kilns, an increasing role of secondary fuels is reported [80] (Figure 16) with a country consumption that involves two types of recovered fuels: the so-called "medium quality SRF" (e.g. with 12 ≤ NCV ≤ 18 MJ/kg d, used for energy recovery in secondary firing systems of cement kiln and/or in special pre-combustion chambers like *Hotdisc*) and a "premium quality SRF (e.g.: 18 ≤ NCV ≤ 25 MJ/kg d, used for energy recovery in primary firing system of cement kiln.

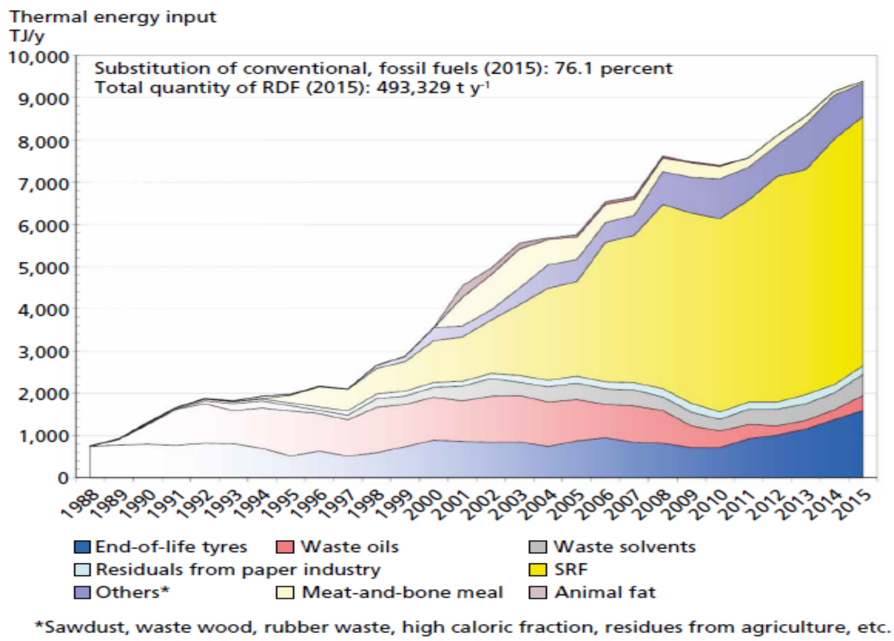

Figure 15. Alternative fuels consumption in Austria between 1998-2015 in cement kilns expressed as thermal energy input [80].

The RDF is legally defined in the Austrian Waste Incineration Ordinance [98] as a fuel waste that: (i) "is used entirely or to a relevant extent for the purpose of energy generation and which satisfies the quality criteria laid down in this ordinance"; (ii) "is produced through an adequate and extended pre-treatment of non-hazardous wastes streams such as sewage sludge, waste wood, high-calorific fractions, from mechanical-physical (MP) or mechanical-biological (MB) treatment plants, calorific fractions of household and commercial wastes, shredder light fractions (i.e. from old vehicles and waste electric and electronic equipment), scrap tires, waste oil, used solvents and animal fat and bone meal .., carried out in facilities that apply a well-defined quality assurance system"; (iii) "can be used in co-incineration plants and is traded and shipped under the European waste list code (EWC) 191212".

The term SRF refers in Austria to a subset of RDF that: (i) "is produced from selected or mixed non-hazardous wastes according to well defined pre-treating process (e.g. multistage shredding, classifying, separation of Fe- and non-Fe-metals, exclusion of heavyweight inert materials, sorting out of unwanted materials like polyvinyl chloride (PVC) or of recycling materials like PET)"; (ii) "comply with quality requirements such as production, classification and specification set in the European standard EN-15539 and is traded, shipped and used under the EWC code 191210".

The above-mentioned Austrian Ordinance legally sets quality requirements that apply to different uses of a generic solid waste fuel or an SRF. The mandatory limits values set are reported in the following Table 21–Table 23. An *end-of-waste* is now admitted in Austria and regulated by the same legal act.

Table 21. End-use: Coal co-combustion in cement kiln. Key properties and mandatory limit values for waste fuels utilised in set in the Austrian legislation [98]. (d: dry basis).

Key parameter	Statistic	Limit value	Unit	End use boundaries
Sb	Median	7	mg/MJ, d	According to the Austrian legal act (annex 8, (1.1)), the limit values apply to those part of cement production plants in which cement clinker are burned (furnace system in accordance with art. 2(1) (c) of the Cement Regulation (ZemetV) 2007, BGBI II n° 60/2007, consisting of rotary furnace, the cyclone or grate preheater and the calciner
	80th Perc.	10	mg/MJ, d	
As	Median	2	mg/MJ, d	
	80th Perc.	3	mg/MJ, d	
Pb	Median	20	mg/MJ, d	
	80th Perc.	36	mg/MJ, d	
Cd [a]	Median	0,23	mg/MJ, d	
	80th Perc.	0,46	mg/MJ, d	
Cr	Median	25	mg/MJ, d	
	80th Perc.	37	mg/MJ, d	
Co	Median	1,5	mg/MJ, d	
	80th Perc.	2,7	mg/MJ, d	
Ni	Median	10	mg/MJ, d	
	80th Perc.	18	mg/MJ, d	
Hg	Median	0,075	mg/MJ, d	
	80th Perc.	0,15	mg/MJ, d	

[a]For quality-assured waste fuels (code number 91108 in accordance with List of Waste Ordinance, BGB1 n. 570/2003, in the applicable version) a limit value of 0,45 mg/MJ applies to the median and a limit value of 0,7 mg/MJ applies to the 80th percentile.

Table 22. End use: Coal co-combustion in power plant. Key properties and mandatory limit values for waste fuels set in the Austrian legislation [98].. (d: dry basis).

Key parameter	Statistic	Limit value (Proportion of thermal output ≤10%)	Limit value (Proportion of thermal output ≤15%)	Unit	End use boundaries
Sb	Median	7	7	mg/MJ, d	According to the Austrian legal act (annex 8, (1.2)), the limit values apply to boilers employing predominantly hard coal or lignite and serving the generation of electricity and district heat. Th e proportion of the thermal output from the incineration of waste relative to the total thermal output is limited to a maximum of 15%
	80th Perc.	10	10	mg/MJ, d	
As	Median	2	2	mg/MJ, d	
	80th Perc.	3	3	mg/MJ, d	
Pb	Median	23	15	mg/MJ, d	
	80th Perc.	41	27	mg/MJ, d	
Cd	Median	0,27	0,17	mg/MJ, d	
	80th Perc.	0,54	0,34	mg/MJ, d	
Cr	Median	31	19	mg/MJ, d	
	80th Perc.	46	28	mg/MJ, d	
Co	Median	1,4	0,9	mg/MJ, d	
	80th Perc.	2,5	1,6	mg/MJ, d	
Ni	Median	11	7	mg/MJ, d	
	80th Perc.	19	12	mg/MJ, d	
Hg	Median	0,075	0,075	mg/MJ, d	
	80th Perc.	0,15	0,15	mg/MJ, d	

Table 23. End use: co-incineration. Key properties and mandatory limit values for waste fuels set in the Austrian legislation [98]. (d: dry basis).

Key parameter	Statistic	Limit value	Unit
Sb	Median	7	mg/MJ, d
	80th Perc.	10	mg/MJ, d
As	Median	1	mg/MJ, d
	80th Perc.	1,5	mg/MJ, d
Pb	Median	15	mg/MJ, d
	80th Perc.	27	mg/MJ, d
Cd	Median	0,17	mg/MJ, d
	80th Perc.	0,34	mg/MJ, d
Cr	Median	19	mg/MJ, d
	80th Perc.	28	mg/MJ, d
Co	Median	0,9	mg/MJ, d
	80th Perc.	1,6	mg/MJ, d
Ni	Median	7	mg/MJ, d
	80th Perc.	12	mg/MJ, d
Hg	Median	0,075	mg/MJ, d
	80th Perc.	0,15	mg/MJ, d

Ireland and United Kingdom

Despite that a detailed and updated figure of the domestic production and use of RDF/SRF in the Irish Republic and the United Kingdom was not achievable, we considered it relevant to provide here some elements on how recovered fuels are identified in these countries which are largely involved in the transboundary shipment within Europe, as previously mentioned.

The *Environmental Protection Agency* of the Irish Republic established [81] that municipal waste (EWC code 200301) can became a combustible waste (i.e. generically a refuse derived fuel, RDF) if submitted to a "treatment process that substantially alters the properties of the waste and according to the National Transfrontier Shipment Office (TFSO)".

Such refuse derived fuel will receive: (i) the EWL code 191212 if it is a *mechanically treated residual waste* with a NCV falling in the range 9–12 MJ/kg and higher than the waste stream it is produced from: It main use (as well as of the municipal waste stream itself) can be as fuel in incineration and co-incineration plants for electricity and heat production; (ii) the EWL code 191210 if it is a fuel with a higher NVC (13–20 MJ/kg) that complies with quality requirements such as Cl, Hg, Cd, Tl, resulting in suitable as substitutive fuel (e.g. in the cement industry). In fact, this last one is considered as a subset of refuse derived fuels, named *solid recovered fuel* (SRF).

In the UK, the *Waste and Resource Action Program* (WRAP) provided a guideline [99] for the classification and specification of secondary fuels [2], generically named as *waste derived fuel* (WDF).

This guideline sets that a WDF is: (i) a *refuse derived fuel* (RDF) if it is an *unspecified* [3] waste fuel obtained by submitting the waste streams to a *basic processing* that enhances the calorific value. The use of the term *unspecified* here is not referring to quality requirements set in standards; (ii) a *solid recovered fuel (*SRF) if the produced waste fuel reaches a high market value, being able to satisfy *tighter quality specifications*.

The UK Department for Environment, Food & Rural Affairs (DEFRA) [100] defines RDF as a fuel that*" consists of residual waste that is subject to a contract with an end-user for use as a fuel in an energy from waste facility. The contract must include the end-user's technical specifications relating as a minimum to the calorific value, the moisture content, the form and quantity of the RDF".* This is a definition clearly centered on fuel quality, but whose statement seems be primarily based on the end-user requirements.

France

Combustibles solides de recuperation (CSR) is the French equivalent to the English meaning for SRF. As the further Table 36 and Figure 20 and Figure 21 show, the domestic production and consumption of *CSR* seems to be low now in France.

In 2015, between 230–800 kton of CSR were produced, approximately 275 kton of them consumed by cement kilns which are the main national consumers [91] while a negligible consumption in dedicated EfW facilities is reported. In France, the use of CSR from MSW is not eligible for subsidies within the framework of the Energy CSR call for projects now activated (in

[2] The mentioned WRAP Guidelines is intended for use in EfW plants with a treatment capacity < 100000 ton/y, with the aim to provide an approach to waste classification and specification more "sustainable" for these plants than that required by the European standard EN 15539

[3] Not defined by the source, a meaning of the term *unspecified* as not responding to quality requirements set in standards, as well as in a private commitment among producer and end-user, can be reasonably assumed

the country supported by ADEME [4]), so that the sector mainly seems to move to produce CSR from industrial and commercial waste streams.

With the legislative acts recently approved [101–103] France now seems to move towards a promotion (production and domestic use) of secondary waste fuels and, in particular, of those named in the country CSR. The term CSR, is now legally defined [103] as a non-hazardous solid waste fuel that consists of waste which have been pre-treated to extract from the incoming waste stream those fractions recoverable in form of material, under the prevailing technical and economic conditions: it is prepared for use in plants falling within the heading 2971 of the French list of facilities classified for the purpose of environmental protection. CSR also meet the requirements set in the French regulatory framework in terms of characterization and thresholds values (Table 24), quality control and obligation to respect the waste hierarchy. A difference seems therefore to be introduced in France in respect to a generic RDF (a not regulated RDF) and to a regulated RDF (SRF) as according to the European standard EN 15539.

Table 24. Mandatory limit values and boundary condition of end-use for CSR as waste set in the French national legislation [103]. (a: as received; d: dry basis; nd: non-detected).

Waste	Key parameter	Statistic	Limit value	Unit	End use (boundaries)
CSR	NCV	nd	>12	MJ/kg, ar	Relevant WtE plants falling into the class 2971 of the nomenclature of plants for the protection of environment, according to the Decree n. 2016-630 of May 19, 2016 = Plants producing heat or electricity from NHW in form of CSR, prepared in a deputy pre-treatment facility, alone or mixed with other fuels
	Hg	nd	< 3	mg/kg, d	
	Cl	nd	< 15000	mg/kg, d	
	Br	nd	< 15000	mg/kg, d	
	Σ Br, Cl, F, I	nd	< 20000	mg/kg, d	

A complementary classification of CSR was also proposed in France, based on results of a study [104] promoted by ADEME and performed by FEDEREC (French Association of waste recycling companies). The aim was to integrate the European standard on SRF by means of a classification system based on parameters assumed as relevant depending on the combustion equipment and technologies for pollution control chosen, especially in case of dedicated boilers. As Table 25 shows, the proposed scheme is based on seven key parameters and for each one a limit value is defined, so to identify four "qualitative" classes of CSR (from a class A high quality CSR to a class D low quality CSR).

[4] The French Environment and Energy Management Agency.

Table 25. Guideline for the classification and specification of the SRF named CSR in France elaborated by FEDEREC et COMPTE-R for ADEME [93]. (ar: as received; d: dry basis).

Key parameter	CSR Cat. A/1 (mean)	CSR Cat. B/2 (mean)	CSR Cat. C/3 (mean)	CSR Cat. D/4 (mean)	Unit	Boundary (End-uses)
NCV	>20	16 - 20	12-16	<12	MJ/kg, ar	Incineration, co-incineration and combustion plants with grate furnace technology
Halogens (S Cl, Br, F)	<0.5	0.5 - 1	1-2	>2	%, d	
S	<0.25	0.25 - 0.5	0.5 - 1	>1	%, d	
N	<0.5	0.5 - 1.5	1.5 - 3	>3	%, d	
Ash	<15	15 - 25	25 - 35	>35	%, d	Incineration, co-incineration and combustion plants with fluidized bed technology
Bulk density	>350	350 -500	100 - 350	<100	kg/m^3	
Particle size	<30	30 - 60	60 -100	>100	mm	

The nomenclature criteria proposed by the Ferederec Study classifies it based on four class – A (higher quality)÷D (lower quality) - that apply to the key parameters NVC, Total Halogens, S, N) and to four class - 1(higher quality)÷4 (lower quality) - that apply to the key parameters Ash content, bulk density and particle size

CSR is expected [84] to actively contribute to reduce the national dependence on fossil fuel for heat and electricity production and enlarge the share of renewable energy in France, as well as the planned national reduction of landfilling. A decrease of non-hazardous waste landfilling from 21 Mtons (2010) to 11.3 Mt (2020) is expected, meaning that CSR could contribute with 2.5 Mt/year making the energy recovery of non-recyclable waste a pillar of waste disposal in France.

The new legislation focuses also on the thermal treatment of pre-treated waste and its impact on CSR producers and end-user plants, insofar as it defines the ICPE plants [105] allowed to prepare CSR, defines a new ICPE category [106] of RDF combustion plants (i.e. plants relevant for environmental protection) that can use it as fuel and, at the same time, modifies previous dispositions for some other categories of existing thermal and combustion plants (excluding CSR combustion). These legislative and regulatory developments in France are a first step towards the development of a CSR-to energy sector that needs to build-up heat and electricity production capacities based on this waste fuel, already under development and supported in particular through the above mentioned CSR Energy' call for projects [84].

Italy

In Italy secondary waste fuels, both not regulated (RDF) and regulated (SRF: currently named in the country CSS [5], previously CDR [6]) are yearly produced in MT/MBT plants, mainly from unsorted or pre-treated municipal wastes stream [82,109]. In 2017 [109], a total of 130 MTB/MT plants were under operation in the country, most of them located in central and south regions, due to differences still occurring on both the local amount of unsorted waste to manage and the availability of recipient EfW plants (mainly MSW incinerators). RDF and SRF are produced mainly from unsorted (88% of the total waste treated, in 2017) or pre-treated (8.5%, in 2017) municipal solid wastes [82,109]

The MSW-RDF streams that come out of MT/MBT plants include dry and bio-dried waste fractions generally traded inside the country and shipped under the EWC code 191212. In 2017 [109], the domestic production of dry fraction was about 4.49 Mton and that of biodried fraction 0.15 Mton. 23% of the dry fraction and the 78% of the biodried fraction was incinerated, while 1.8% of the dry fraction was used in co-incineration plants (dedicated facilities producing heat and electricity). A significant part is also ending up being landfilled.

In the same year, about 1.34 Mton of CSS were produced by about a third of all the 130 MT/MBT plants under operation in the country; while in 2015 and 2016, about 1.6 Mton (2016 [110]) and of 1.5 Mton (2015 [7]) of MSW-CSS were produced. It is important to mention that a smaller production of CSS from industrial/commercial wastes also occurs in Italy. The available data do not allow to quantify individually the CSS produced from these waste streams. Based on the last available statistics on "special wastes" [8], in the year 2015 [111] 54,876 ton of such CSS has been utilised for energy recovery in cement kiln/co-incineration plants and 85,454 ton in incineration facilities.

CSS and other secondary fuels enter the fuel mix of MSW-incinerators. Nowadays, all the Italian facilities generate electricity and satisfy partially also the local urban heating demand. In 2017, a total of 38 plants under operation [109] - of which 6 of them were fluidized bed boilers which mainly or only fed with CSS - consumed about 2.4 Mton of secondary fuels.

The last available national statistics (2015–2017) reported on the consumption of CSS combine the consumption from MSW-incineration plants as well as for a very limited number of dedicated industrial plants (0.33 Mton in 2017). Therefore, a correct figure of how much CSS (or RDF) is yearly consumed in MSW-incinerated plants cannot be provided. Previous statistical data (2010-2014) [82] estimated a yearly consumption of CDR/CSS by the MSW-incinerators between 0.9 Mton (2010: 16% of the fuel mix) and 1.1 Mton (2014: 18% of the fuel mix); while the RDF consumption (dry fraction, mainly) was between 1,3 Mton (2010: 22 % of the fuel mix) and 2,0 Mton (2014: 32% of the fuel mix).

CSS plays an important role in Italy as substitute fuel (coal co-combustion). The main consumer is the national cement industry. Only in 2017 [63], about 213,000 ton of CSS were consumed by cement kilns, which is equally by mass to a 59% of the total 360,000 ton of alternative fuels utilised. The mentioned data refers to a total of 27 full cycle monitored by The Italian Cement Technical

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5 CSS: combustibile solido secondario (secondary solid fuel)

6 CDR: *combustibile derivato da rifiuti* (refuse derived fuel); it was differentiated in CDR-N (it means of normal quality) and CDR-Q (it means of high quality)

7 ISPRA, 2016. Annual report on municipal solid wastes. Report n. 251/2016. Eds. The Italian Institute for Environmental Protection and Research (ISPRA), Rome, pp. 570

8 The industrial/commercial wastes that fall in Chapters of the European list of waste other the Chapter 20, are commonly named in Italy "special wastes"

and Economical Association (AITEC), equivalent to more than the 95% of all the facilities under operation in the country. Figure 17 shows the amounts of SRF and of plastic, rubber and ELT in the mix of alternative fuels over time (2010–2017).

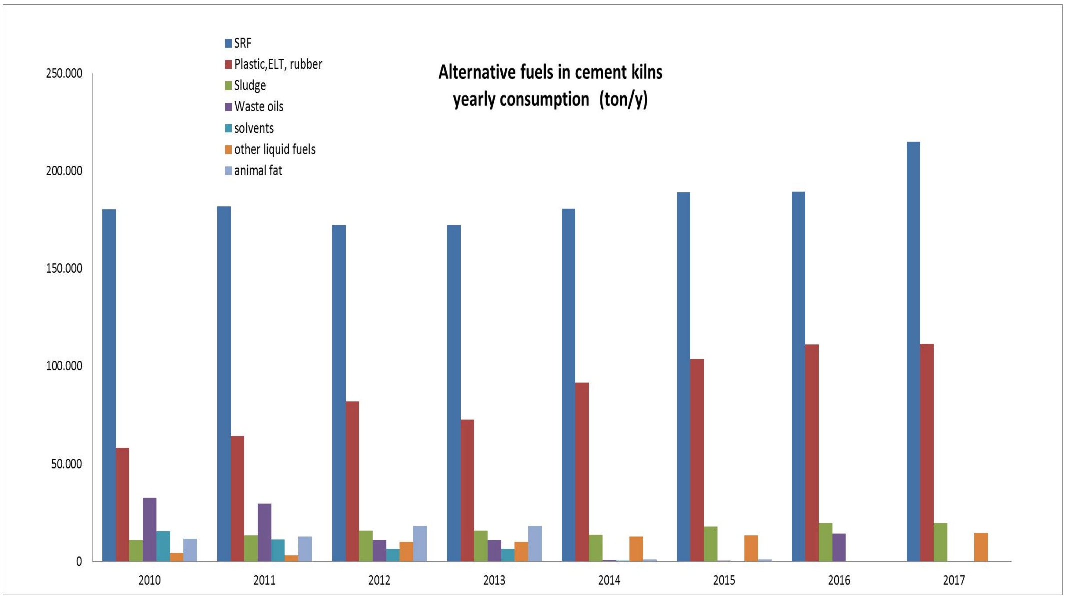

Figure 16. Alternative fuels consumption in the Italian cement kilns: trend 2010-2017 [63]

With respect to the use in cement plants, when asked on the status and perspectives of SRF market in the country for the purposes of this Report, Mr. Daniele Gizzi (AITEC) pointed out that, in contrast to what happens in other countries (e.g. The Netherlands), the production of SRF and other substitutive fuels in Italy is always linked to treatment plants external to the cement kiln.

About the future of substitutive fuels and, in particular, SRF, Mr. Gizzi reported that previsions made by the AITEC Research Office foresee a national cement production of about 22–23 Mton/y within 2.5 years. This production corresponds to an expected consumption of substitutive fuels of 1-1,2 Mton/y of which a main contribution is expected from SRF (i.e. CSS in Italy), together with an expected increasing contribution of sludge too.

In 2017, the average caloric substitution rate through use of SRF was 17.3%, which remains below that already obtained in different European countries, as well as, on average value by the EU 28 countries. When asked about a realistic potential, Mr. Gizzi answered that based on recent trends, a 40–50% share of caloric substitution could be achieved in the Italian cement sector by 2025.

CSS is traded and shipped within the country as waste under the EWC 191210. About 131,000 ton were exported during 2017 [109] compared to 175,767 ton in 2016 [110] and 139,062 ton in 2015 [111]). No import of SRF is recorded in Italy.

The term RDF above mentioned is used to identify waste fuels (i.e. dry and bio-dried waste fractions outcoming from MT/MBT plants and sent to EfW facilities). There waste fuels are not required to meet standard requirements in Italy and, therefore, not specifically characterized for properties. Only EfW plants that ask for an economic revenue for the share of renewable energy they put in the national grid can be required to qualify these fuels, but only with respect to their biomass and energy content.

Otherwise, CSS is legally identified in Italy [114] as a secondary solid fuel produced from waste streams that shall respect the requirements for classification and specification set by the European standard EN 15539. CSS is assumed in the country to be a solid recovered fuel.

National standards have been provided to support the application of the European standards [115] and a need for fuel quality requirements [116] (as for the characterization of CSS (and of other waste fuels) with respect to the biomass and the energy content [117].

Table 26. Fuel quality requirements for the SRF named CSS, in Italy, set in the national standard UNI/TS 11553 [116]. (ar: as received; d: dry basis).

Key parameter	Limit Value (statistic: median)	Unit	Boundary (End-uses)
Cd	10	mg/kg, d	incineration coal co-combustion (cement kiln) coal co-combustion (power plant) co-incineration
Tl	10	mg/kg, d	
As	15	mg/kg, d	
Co	20	mg/kg, d	
Cr	500	mg/kg, d	
Cu	2000	mg/kg, d	
Mn	600	mg/kg, d	
Ni	200	mg/kg, d	
Pb	600	mg/kg, d	
Sb	150	mg/kg, d	
V	150	mg/kg, d	
Hg [a]	Limit values for classes 1 and 2 in table 1 of EN 15539	MJ/kg, ar	
Cl [b]	Limit values for classes 1, 2 and 3 in table 1 of EN 15539	%, d	

[a] Statistic: median and 80th percentile. Limit values: see Table A.3.3
[b] Statistic: mean. Limit values: see Table A.3.3

In the past, a waste fuel named CDR[9], meeting classification and specification rules set in a dedicated national standard [118], was produced in Italy from not-hazardous waste streams and traded under the EwL code 191210.

As reported in Table 27**,** two classes of CDR have been defined by UNI 9903 national standard: an average and a high-quality CDR. The high quality one was legally admitted in the year 2006 [119] as fuel substitute in cement kilns and thermoelectric power plants. To date, CDR is almost completely replaced in Italy by CSS. Also, that CDR were considered in the country as a solid recovered fuel.

Like in Austria, an end-of waste of the CSS is legally admitted and regulated for production and use in Italy [119] .The production of such fuel seems now to start in the country with 10 authorized producers.

[9] CDR: combustibile derivato da rifiuti (Refuse derived fuel)

In our opinion, a substantial growth, at least in the short-medium term, of the domestic CSS (SRF) is of doubtful implementation, due to different factors:

(i) the expected reduction over time of the amount of waste (MSW) to manage;

(ii) the expected large improvement of waste management prioritising material recovery and recycling;

(iii) the potential effects of the implementation of legislative decisions that would translate into a relative strengthening of the "first address way" (see Figure 2) of residual MSW to WtE (incineration) plants, so diverting them from the pre-treatment and CSS production;

(iv) the need of a technical improvement of the pre-treatment systems themselves (costs, time, authorizations, social acceptability…) to produce, at larger extent, a "high quality "fuel;

(v) the doubt that a real consistent increase of the demand could derive from the recipient facilities in all the industrial sectors involved (current national and global economic situation; and

(vi) locally: costs, time, authorizations, social acceptability etc..

Table 27. Italy. Fuel quality requirements set in the national standard UNI 9903 for the SRFs labelled in Italy CDR normal and CDR-Q, traded as waste.[118] (ar: as received; d: dry basis).

Fuel	Key parameter	Limit Value (statistic: mean)	Unit	Boundary (End-uses)
CDR of normal quality	Moisture	<25	%, ar	incineration/co-incineration combustion industrial plants
	Ash	<20	%, d	
	NCV	>15000	KJ/kg, ar	
	Cl (total)	0.9	%, ar	
	As	<9	mg/kg, d	
	Cd	<7	mg/kg, d	
	Hg	<3	mg/kg, d	
	Cr	<100	mg/kg, d	
	Cu (soluble)	<300	mg/kg, d	
	Mn	<400	mg/kg, d	
	Ni	<40	mg/kg, d	
	Pb (volatile)	<200	mg/kg, d	
	S	<0.6	mg/kg, d	
CDR –Q of high quality	Moisture	<15	%, ar	coal co-combustion (cement kiln) coal co-combustion (power plant)
	Ash	<15	%, d	
	NCV	>20000	KJ/kg, ar	
	Cl (total)	<0.7	%, ar	
	As	<5	mg/kg, d	
	Cd	<7	mg/kg, d	
	Hg	<1	mg/kg, d	
	Cr	<70	mg/kg, d	
	Cu (soluble)	<50	mg/kg, d	
	Mn	<200	mg/kg, d	
	Ni	<30	mg/kg, d	
	Pb (volatile)	<100	mg/kg, d	
	S	<0.3	mg/kg, d	

Sweden

The estimated production of RDF in Sweden during 2012 was 0.4 Mton (the origin being a mix of MSW and I/CW) [84], while the internal consumption in 2015 reached 1.8 Mton of which 1.7 Mton were used in dedicate incineration/co-incineration facilities to supporting the urban heat demand, and 0.1 Mton in cement kilns. Based on these data, it is clear that a large part of the internal demand is covered by imported waste fuel.

Finland

Table 28. Average values for physio-chemical characteristics of SRFs from three Finnish MT plants that treat different types of waste streams [Data from:121-123]. (ar: as received; d: dry basis).

Key parameter	Unit	SRF from residual MSW	SRF from IW and CW	SRF from C&DW
NCV	MJ/kg, ar	20.2	18.0	18.0
NCV	MJ/kg, d	22.4	25.0	20.0
Moisture	wt%, ar	15.0	25.0	16.5
Ash	wt%, d	9.8	12.5	9.0
C	wt, d	53.0	57.4	50.0
Biomass content	%C	50.8	na	66.7
Cl	wt%, d	0.6	0,6	0.4
F	wt%, d	0.01	0.01	0.004
Br	wt%, d	0.004	0.003	0.003
S	wt%, d	0.2	0.3	0.3
Na	md/kg, d	1590	3458	1470
K	md/kg, d	924	2174	1078
Ca	md/kg, d	28925	36260	17150
Mg	md/kg, d	1390	1482	1274
P	md/kg, d	338	958	519
Al	md/kg, d	6262	8200	4802
Si	md/kg, d	9244	18871	12152
Fe	md/kg, d	1392	4841	1274
Ti	md/kg, d	1988	3162	1274
Cr	md/kg, d	368	48	35
Cu	md/kg, d	268	375	350
Mn	md/kg, d	55	79	68
Ni	md/kg, d	12	22	8.0
Zn	md/kg, d	229	336	176
Sb	md/kg, d	537	52	84
As	md/kg, d	0.7	1.8	6.6
Ba	md/kg, d	278	287	140
Cd	md/kg, d	0.7	0.6	4.4
Co	md/kg, d	3.4	3.6	2.8
Pb	md/kg, d	31	120	42
Mo	md/kg, d	3.2	3.6	1.5
Se	md/kg, d	0.5	0.5	2.7
Tl	md/kg, d	0.5	<0.5	0.5
Sn	md/kg, d	12	18.8	14.7
V	md/kg, d	8.0	5.3	4.0
Hg	md/kg, d	0.1	0.1	0.2

During 2014 [84], about 0.5 Mton of RDF were produced in Finland: 0.35 Mton from MSW and 0.15

Mton from industrial/commercial waste streams, of which <0.25 Mton were regulated RDF (SRF). The total RDF domestic consumption in 2015 was about 0.65 Mton, of which 0.25 Mton were used in gasification facilities (urban heath demand), 0.30 Mton and 0.10 Mton, in incinerations and industrial incineration/co-incineration plants (industrial heat demand), respectively.

There are several studies that provide elements on the characteristics of SRFs used in the country over time [17–18,19, 121–123]. As an indication**,** the following Table 28 shows results of an assessment of physic-chemical properties of SRFs produced at MT from different waste streams (e.g. MSW, industrial and commercial waste, construction and demolition wastes).

Regarding gasification of SRF, as indicative figure of the fuel quality is here reported in Table 29. The average values showed in the table refer to an SRF produced from a mix of MSW and other wastes utilised in Lahtii gasification facility in Finland in 2001 [124]. That biomass gasifier, built in 1998, has been replaced in 2012 by a new combined heat and power (CHP) waste gasification plant (Kymijärvi II) with a SRF treatment capacity of 250,000 tons/year (such SRF mainly consists of plastic, wood and paper products unsuitable for recycling) [125].

Table 29. Main characteristics of SRF gasified in the Lathi plant in Finland [124] (data refer to year 2001). (ar: as received; d: dry basis).

Key parameter	Unit	Measured value (average)
NCV	MJ/kg, ar	16,0
Ash	%, d	6,3
Cl	%, d	0,26
S	%, d	0,08
Na	mg/kg, d	1190
K	mg/kg, d	670
Br	mg/kg, d	<3
F	mg/kg, d	43
Hg	mg/kg, d	0,3
As	mg/kg, d	1,4
Cr	mg/kg, d	21
Cu	mg/kg, d	20
Ni	mg/kg, d	8,5
Pb	mg/kg, d	4,3
Zn	mg/kg, d	74

Portugal

In Portugal[10], statistics on municipal solid wastes for 2017 provided by the National Agency for the Environment (APA) [126] account for an yearly production of MWS of about 5 Mton (an average annual increase of 2% from 2013 to 2017 is reported). The MSW management has landfills as main final destination (32 wt.%) followed by MT/MBT (7% and 28% respectively), waste to energy (21%), material reuse and recycling (10%) and enhancement of the organic fraction (2%) by means the production of compost (in dedicated or MT/MBT plants).

[10] data refer only to the continental Portugal

In 2017, APA estimated that a total of 379 tons of MSW were used for the production of a secondary fuel - named in the country as CDR [11] - in MBT plants, which was lower compared to the previous two years (21,509 tons in 2016 and 114,566 tons in 2015 respectively) when the municipal solid residues were treated in MT/MBT plants and in other treatment facilities named in the country "screening stations", under operation in Portugal.

A yearly production of 1,466 ton of CDR was reported by APA which was doubled compared to 2016 (749 tons), but significantly lower than that recorded in 2015 (29,476 tons). Such trend is explained by the unavailability of EfW plants (mainly cement kilns) to receive CDR that did not comply with minimum specification requirements. In particular, the CDR from MSW produced in the country showed a moisture content (average values 20%–45%) higher than the limit values (12%–15%) required for co-processing the waste fuel (cement industry).

In the last available CEWEP [12] assessment of WtE plants in Europe [127], it is mentioned that there were four incineration facilities under operation in Portugal with a total capacity of 1.2 Mton of MSW/non-hazardous wastes. Furthermore, the CDR consumption in cement kilns (6 plants) was reported to be about 137,000 ton [128] of which 96% CDR was not produced from urban wastes; 3.75% imported CDR and 0.22% MSW-CDR produced in the country. The transboundary shipment of waste derived fuels (EWC 191210), mainly from UK, Spain, Italy and The Netherlands, showed a progressive and significant increase in Portugal (+130% in 2016 with 75,909 ton imported with respect to 2014).

The Portuguese CDR definition, first at the Order 21295/2009[13] and most recently the under revision Strategic Plan for MSW Management [128], is in agreement with the EN 15539: CDR is a solid fuel prepared from non-hazardous waste for being used for energy recovery in incineration or co-incineration in strict compliance with the law, where the word "prepared" means processed, homogenized and improved to a quality that allows its exchange/commercialization between producers and users. CDR is considered in the country to be a solid recovered fuel. A national regulation of CDR was introduced in the past with the standard NP 4486:2008 [130] that defines a framework for the production, classification and quality management of refuse derived fuels, in alignment with the technical specifications of CEN/TC 343. Currently the European standard EN 15539 is recognized.

Croatia

In 2016 a total 1,679,765 tonnes MSW were generated in the country [23] and 21% MSW material recycling was reached.

No energy recovery or incineration of MSW is applied in the country, so that most of the produced MSW (about 79% in 2016) is landfilled without any pre-treatment [23].

Three MBT plants are reported [23] under operation in the country with a total capacity of 285,000 ton/year. The national MBT system is planned to treat mixed municipal solid waste and non-hazardous wastes from stores, industry and institutions, which in its properties and composition are similar to household waste that has not been subjected to special procedures for material recycling (e.g. paper and glass).

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[11] CDR: Combustivel Derivado da Residuos

[12] CEWEP: Confederation of European Waste-to-Energy Plants

[13] In addition to the national Strategic Plan for MSW Management (PERSU), the Order 21295, 2009 defines a national strategy for refuse derived fules, to support the recycling/recovery policy and the diversion of waste from landfill

In 2016 [23], 1,251,299 tonnes of MSW were treated in the country. Other than RDFs (Traded as EWC 191212), MBT plants produce quality assured waste fuels named as "Croatian SRF Premium Quality SRF" (e.g. SRF with NCV>18 MJ/kg_{OS}[14] and particle size 95< 30–35 mm), able to meet quality requirements established by the Austrian Premium Quality SRF. The recovered fuels produced at MBT plants are legally not considered as a product but still as a waste and, therefore, they are traded under the EWC 191210 (if quality assured combustible waste, SRF) or the EWC 191212 (if a not qualified RDF).

The following Table 30 provides results of an investigation on the characteristics of the premium SRF produced by three MBT plants recently carried out during four months during 2018, according to analytical methods of the Austrian Standards Institute [23].

Table 30. Results (average values) of the analytical characterization of SRFs produced during four months of 2018 in three Croatian MBT plants [23] (ar: as received; d: dry basis).

Key parameter	Unit	SRF plant 1	SRF plant 2	SRF plants 3
NCV	MJ/kg, ar	16,6	14,4	23,8
NCV	MJ/kg, d	20,6	18,3	28,1
Total C (TC)	%, d	49,6	46,6	62,9
Biomass content (related to TC)	w%, d	34,7	52,4	20,7
Non-Biomass content (related to TC)	w%, d	65,3	47,6	79,3
Fossil CO_2 emission	g/MJ, d	57,5	44,4	65,0
Ash	w%, d	19,4	18,6	11,0
Cl	g/kg, d	4,8	4,9	7,4
S	g/kg, d	2,6	3,0	1,3
Sb	mg/MJ, d	0,9	1,2	1,5
As	mg/MJ, d	0,1	0,1	0,1
Pb	mg/MJ, d	4,4	4,6	1,2
Cd	mg/MJ, d	0,026	0,014	0,009
Cr	mg/MJ, d	2,6	2,1	0,7
Co	mg/MJ, d	0,3	0,3	0,1
Ni	mg/MJ, d	0,8	0,8	0,3
Hg	mg/MJ, d	0,012	0,014	0,09

The national cement industry is the only user of such premium SRF [23]. All the cement kilns (6 plants are reported under operation in Croatia in 2016–17) are technically able to use the SRF Premium at primary burner only (no kilns are equipped with secondary firing system yet). Apart from SRF, other substitutive fuels such as scraps tires or waste oil are utilised by the cement industry. The average thermal substitution rate (TSR) below 10% was reached in 2017 [23].

[14] os refers to original substance

Market and quality aspects of the SRF/RDF

A summary analysis of the European market of SRF/RDF was elaborated by the European Recovered Fuel Organisation (ERFO) and the European Cement Association (Cembreau) [72]. SRF/RDF are produced in Europe from different waste streams such as MSW, C&IW or C&DW, and treated in sorting (MT) and mechanical-biological treatment (MBT) plants with a reported average yield ranging from 35% (MSW streams) to 15% (C&IW, and C&DW streams).

Cement kilns and dedicated WtE plants are highlighted as the biggest markets for SRF/RDF in Europe accounting for about 12 Mton/y of the SRF/RDF produced, to which cements kilns contribute for 40% (a consumption of about 5 Mton/y). At the same time, a consumption of about 1.5 Mton/y of SRF/RDF is mentioned in other EfW plants such as power plants, gasification/pyrolysis plants, dedicated industrial combustion plants, blast furnaces or lime kilns.

Based on assumptions for yearly production and waste management of MSW, C&IW and C&DW, ERFO and Cembreau [72] estimated there is a potential production of approximately 63 Mton/y of SRF/RDF in Europe. Concerning the demand, other than the cement industry that remains the most relevant European market (a potential for substitution of 40% is assumed), the report [72] identified a number of industrial sectors with a higher potential for the use of SRF/RDF as fossil fuel substitute. These sectors were:

i. the paper and the chemical industry, potential for substitution of about 5 %;

ii. power generation plants and co-combustion with biomass, with a potential for substitution of about 2 %;

iii. district heating systems, with a potential for substitution of about 3 %.

A total potential demand of SRF/RDF around 50 Mton/y was assumed by ERFO and Cembreau, mainly coming from the cement industry, while the above-mentioned industrial sectors can contribute for 12 Mton/y.

In the field of standardisation of SRF, Europe has already adopted common regulations such as the EN 15539:2011 [73] and EN 15538:2011 [74] standards as well as other related standards, of which the first one defines criteria for the classification (Table 31) and specification (Table 32) of the SRF.

Table 31. Rules for the classification of SRF according to the European standard EN 15539 [5]. (ar: as received; d: dry basis).

Fuel property	Unit	Class 1	Class 2	Class 3	Class 4	Class 5	Statistical measure
Net Calorific Value (NCV)	MJ/kg, ar	≥25	≥20	≥15	≥10	≥3	mean
Chlorine	%, d	≤0.2	≤0.6	≤1.0	≤1.5	≤3	mean
Mercury	mg/MJ, ar	≤0.02	≤0.03	≤0.08	≤0.15	≤0.50	median
	mg/MJ, ar	≤0.04	≤0.06	≤0.16	≤0.30	≤1.00	80th percentile

Table 32. Specification of SRF: list of fuel properties obligatory to specify according to EN 15539. [5]. (ar: as received; db: dry basis).

General	Physical	Chemical
Class **code** **Origin**	Particle form and size Ash content (%, db) [b] Moisture content (%, ar) [b] Net calorific value (MJ/kg, ar; MJ/kg d) [b]	Cl (%, d) [b] Sb, As, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Tl, V [c] Σ metals [a] (mg/kg, d) [c]

[a] Sum of Sb, As, Cd, Cr, Co, Cu, Pb, Mn, Ni, V, according to the Industrial Emissions Directive (IED)

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[b] As typical value of the parameter the mean value over an agreed or specified period of time, and as limit value the maximum, minimum, or the 80 percentiles, are used.

[c] As typical value of the parameter the median value over an agreed ed or specified period of time and as limit value the 80 percentile, are used

An assessment of the quality of the SRFs produced in Europe was performed in the past for the purposes of the CEN TR 15508 [75] based on series of measured values collected in some European countries (Austria, Germany, Belgium, Netherlands, Italy, Norway and Sweden). Summary statistics for Hg and Cd have been derived (Table 33). A proposal of reference values for some physico-chemical properties of the SRF, expressed as range of the median and the 80th percentile, bas Table 34).

Table 35 summarizes the results of a statistical analysis applied to other national series of measured values for SRFs (data collected from literature or provided by producers/end users), that RSE performed for the purposes of the ongoing ISO project ISO TR 21916, already mentioned. The reported statistics do not account for differences in origin or end-use of the examined SRFs.

Table 33. Summary statistics for properties (Hg and Cd content) of solid recovered fuels derived by analysing individually some national series of measured values (origin and end use of the recovered fuel not considered). Values are reported ad as sum/average of the descriptive statistics derived for each national series of data) [Data from CEN TR 15508] – na= data not available

Para-meter	Unit	N° of Assays	N° of Assays <DL	Mean	Min	Max	Median	80th perc.
Hg	mg/kg d	2629	1125	0.675	na	5.440	0.487	0.664
Cd	mg/kg d	2489	1027	2.633	na	10.28	2.154	3.020

Table 34. Reference values for physic-chemical properties of an SRF produced from municipal solid wastes (MSW), produced from commercial wastes or produced for a specific final use in cement outcomes of an analysis applied to measured values collected in several European countries) [75]. (ar: as received).

		Statistic	NCV MJ/kg ar	Cl % ar	Hg mg/MJ ar	Cd + Tl mg/MJ ar
SRF Origin from	MSW	median	9.8-19.9	0.3-0.79	0.006-0.069	0.0050-0.311
		80th perc.	11.4-22.2	0.43-0.88	0.009-0.079	0.084-0.380
	Commercial wastes	median	13.0-31.0	0.04-0.60	0.004-0.019	0.008-0.060
		80th perc.	14.0-31.6	0.07-1.00	0.005-0.064	0.008-0.129
SRF Final use in	Cement kilns	median	3.2-25.5	0.07-1.7	<0.02-0.406	<0.12-<0.93
		80th perc.	3.4-25.8	0.14-2.00	<0.02-0.781	<0.12-0.94

Table 35. Overall outcomes expressed as: (top table) sum (n° of assays, n° of assays <DL) or average (mean, min, max, median, 80th percentile) of the descriptive statistics derived individually for the examined series of measured values ; (bottom table) ranges for median and 80th percentile. (as: as received; d: dry basis).

Parameter	Unit	N° of Assays	N° of Assays <DL	Mean	Min	Max	Median	80th perc.
NCV	MJ/kg, ar	372	0	18.61	15.25	22.71	18.34	20.19
Moisture	%, ar	372	0	15.29	8.80	22.04	15.72	18.58
Ash	%, d	470	0	13.83	8.83	20.67	13.42	16.38
Cl	%, d	198	0	0.60	0.26	1.38	0.57	0.76
Hg	mg/kg, d	321	73	0.48	0.15	1.67	0.43	0.64
Tl	mg/kg, d	184	137	0.96	0.85	3.06	1.07	1.13
As	mg/kg, d	355	99	1.81	0.56	21.10	1.43	2.80
V	mg/kg, d	64	4	3.61	1.63	7.82	2.67	4.44
Pb	mg/kg, d	274	5	102.98	22.19	371.23	71.25	150.05
Co	mg/kg, d	184	24	4.65	1.31	33.15	2.70	4.40
Cd	mg/kg, d	314	35	1.60	0.30	18.25	1.11	3.08

A common definition of solid recovered fuel (SRF) is given by the above mentioned EN 15539:2011 standard: a solid fuel prepared[15] from non-hazardous waste[16] to be utilised for energy recovery in incineration or co-incineration plants that meets the classification and specification requirements laid down in the standard itself. The standard does not apply to solid biofuels and to an untreated municipal solid waste.

[15] For the purposes of the EN 15539, the term "prepared" means: processed, homogenised and up graded to a quality so that the SRF can be traded amongst producers and users

[16] According to the EN 15539, the non-hazardous waste stream SRF is produced form, shall include: production specific waste, municipal solid waste, industrial waste, commercial waste, construction and demolition waste, sewage sludge (and other wastes).

There is currently ongoing work within ISO on standardisation of SRF. Since the current draft is not in a public state at the time of the release of this report a clear reference to the standard cannot be made. However, the definitions and compliance in the existing draft is similar to the CEN-standards.

The normative tool called List of Waste or European Waste Catalogue [76,77], provides an EU-wide common terminology regulation for waste classification in a broad range of activities (e.g. production, transport, trading, shipment, plant permits, waste statistics). In the Chapter 19 subchapter of the List of Waste the code EWC 191210 refers to a combustible *waste,* , without any reference to a correspondence of the RDF to standardized requirements. As below discuss, the EWC 191210 is largely used also to identify SRF.

In some European countries (e.g. the United Kingdom), secondary fuels named as both SRF and RDF seem to be released by producers (stored, locally used and shipped) under such waste code [79]. However, in other countries (Italy, Germany, Austria, Republic of Ireland[20, 80–82]), the EWC 191210 is applied more strictly to SRF.

The analyses of the market carried out by ERFO and Cembreau and previously mentioned in this report [83], confirms that both standardised (SRF) and not standardized refuse derived fuels (RDF) are currently produced and used in European plants. The same conclusions can be derived when the shipment of secondary fuels within Europe is considered. A recent analysis performed by the Chartered Institution of Wastes Management (CIWM) [79], shows that the United Kingdom leads the export of SRF/RDF (Figure 18) with around 60% of the total of 5.9 Mton of RDF exported by European countries in 2016, while the Netherlands, Sweden and Germany lead the list of importing countries. However, SRF still represents a relatively small share (<7%) of the total RDF exported by the UK. On the other hand, the RDF exported by the Republic of Ireland also includes SRF.

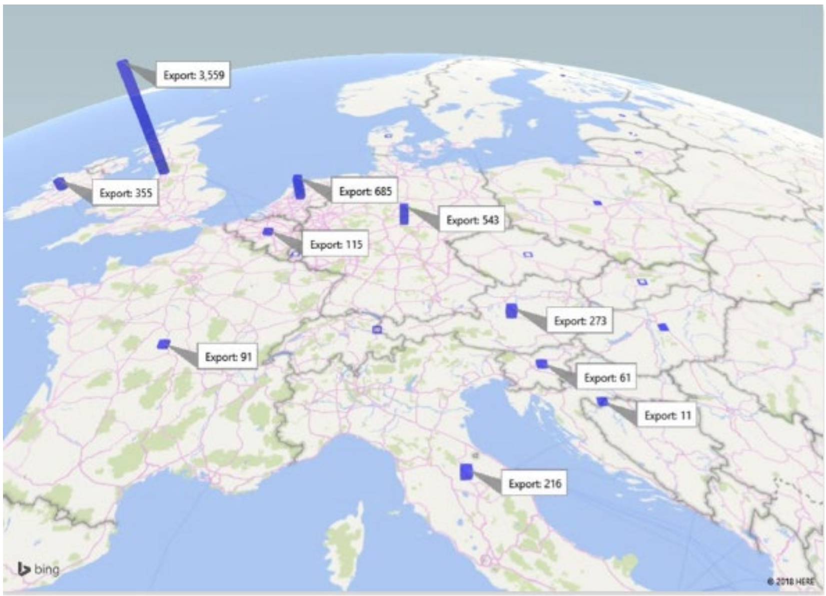


*Figure 17. Situation of the RDF/SRF export in Europe in 2016 (*1000 ton) [79].*

A scenario analysis [79] carried out with the aim of forecasting the residual waste supply (i.e. waste generation and waste recycling performance) and the internal demand (i.e. capacity of operational and planned/proposed facilities) by 2030, indicated a potential long term decrease of the export from both the countries. For the recipient countries, CIVM inferred the net import

(import minus export, by assuming that all the domestic EfW capacity is utilised) as depicted in Figure 19 and evaluated that the greatest estimated capacity surplus (1.3 Mt) could occur in the next years in the Netherlands, followed by Germany and Sweden, even if different factors (e.g. new national policy and legislation on waste, creation of new EfW capacity, decommissioning of existing EfW facilities, increase in MSW recycling) can have a relevant upward or a downward influence on the real capacity gap in these countries.

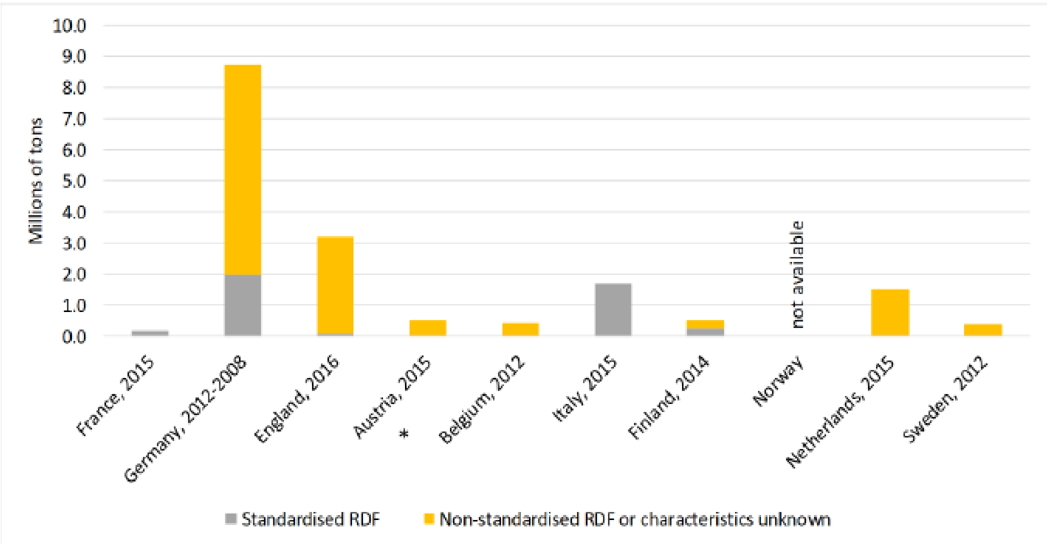
*Figure 18. Net import of RDF/SRF estimated to evaluate the EfW capacity surplus in recipient countries (*1000 ton) [79].*

A recent study performed by RECORD [84] provides an assessment of the amount of secondary fuels produced and used in different countries in Europe (Table 36), evaluates the ratio between standardised (SRF) and not standardised RDF produced per country (Figure 20) and the main industrial sectors where the RDF are consumed (Figure 21).

This study identified Germany, the United Kingdom, Italy and the Netherlands as the main producers of RDF in Europe. Non-standardized RDFs were prevalent in most of the examined countries, and only Germany and Italy showed a more consistent production of standardized SRFs. The study also showed that Germany, Austria, the Netherlands and Sweden have an SRF consumption higher than their own production. In Germany, the consumption of MSW and RDF/SRF refers to different EfW plants. SRF/RDF are used as coal substituted in cement kilns in France and England, but at a relatively lower extent compared to other European countries such as Germany, Austria, Belgium or Italy.

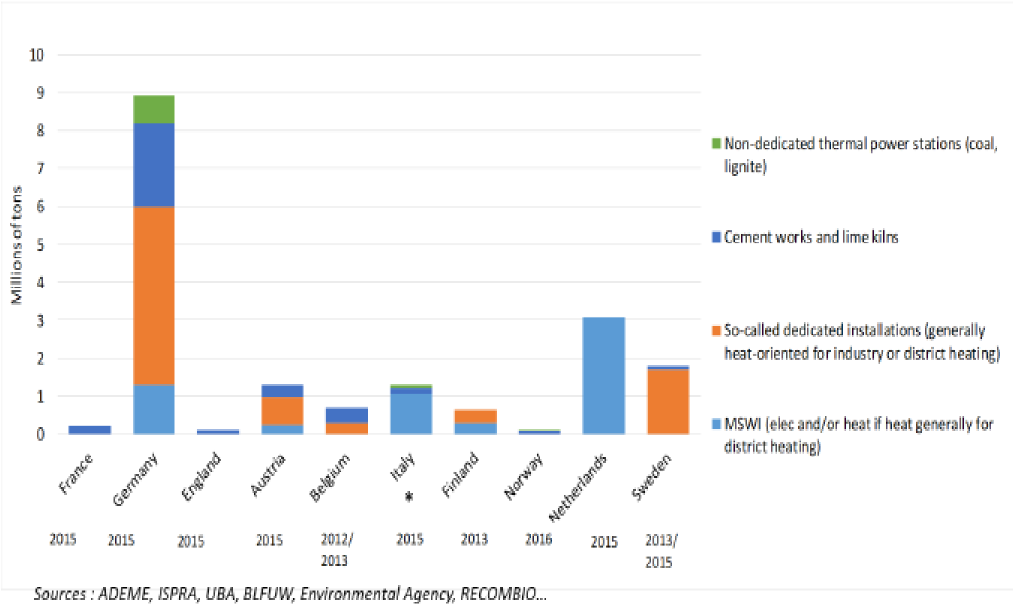
Table 36. A quantitative assessment of production and use of RDF in different European countries. The year the data refers to differs between 2008-2016 [84].

RDF (Million ton)	France	Germany	UK	Austria	Belgium	Italy	Finland	Norway	Netherlands	Sweden
Production	0.2	8.7	3.2	0.5	0.4	1.7	0.5	0.0	1.5	0.4
Use	0.2	9.0	0.1	1.3	0.7	1.3	0.7	0.1	3.1	1.8



Sources : ADEME, ISPRA, UBA, BLFUW, Environmental Agency, RECOMBIO…
* Excluding I&CW

Figure 19. A quantitative assessment of the amount of standardised (SRF) and not-standardised RDF produced in different European countries in different period of time [84].



Sources : ADEME, ISPRA, UBA, BLFUW, Environmental Agency, RECOMBIO...
** Excluding RDF use from I&CW*

Figure 20. A quantitative assessment of the consumption of standardised (SRF) and not-standardised RDF in the inside market of different European countries (MSWI: MSW incineration plants [84].

Another study [85] produced a balance of supply and demand of secondary fuels taking into account the so called Northern Cluster (i.e. includes EU Member States which are actively involved in a trade with others countries as well as in a national use of RDF or SRF), in order to provide an estimation of the current and future waste treatment capacity gap (see countries listed in Table 37).

The collected key data for the *Northern Cluster* described a treatment capacity made up of 383 dedicated EfW incineration facilities, 13 advanced conversion technology facilities, 103 waste pre-treatment facilities, 73 biomass facilities, some already co-firing secondary fuels and 102 cement kilns co-processing SRF (Table 37). Considering the already under development capacity (facilities under construction, committed results in some of the examined countries such as United Kingdom, Irish republic or The Netherlands) and excluding that only planned, a total effective residual waste treatment capacity of 102,2 Mton/y was estimated for the Northern Cluster (Table 38). The residual waste generated (Mton) and effective treatment capacities (Mton/y) were compared as well for countries falling in the Norther Cluster (Figure 22).

Table 37. N° of facilities in countries of the Northern Cluster in 2015 [85].

Facilities (n°)	**Belgium**	**Czech Rep.**	**Denmark**	**France**	**Germany**	**Ireland**	**Netherlands**	**Norway**	**Poland**	**Sweden**	**United Kingdom**
Incineration	16	5	35	97	105	3	13	22	5	35	47
Advanced conversion technology facilities				1				2			10
MBT/MT facilities				4	63						36
IED biomass facilities *			1		40		1	3		9	19
Cement kilns	4	6	1	33	31	3	1	2	10	3	8

- **facilities compliant with the IED Directive (Directive on Industrial Emission)**

Table 38. Estimated total effective treatment capacity for countries member of the Norther Cluster in 2015 [85].

Total effective treatment capacity	**Belgium**	**Czech Rep.**	**Denmark**	**France**	**Germany**	**Ireland**	**Netherlands**	**Norway**	**Poland**	**Sweden**	**United Kingdom**
kton/y	3,800	1,400	4,900	14,500	37,900	1,100	8,500	2,000	2,600	8,000	19,500

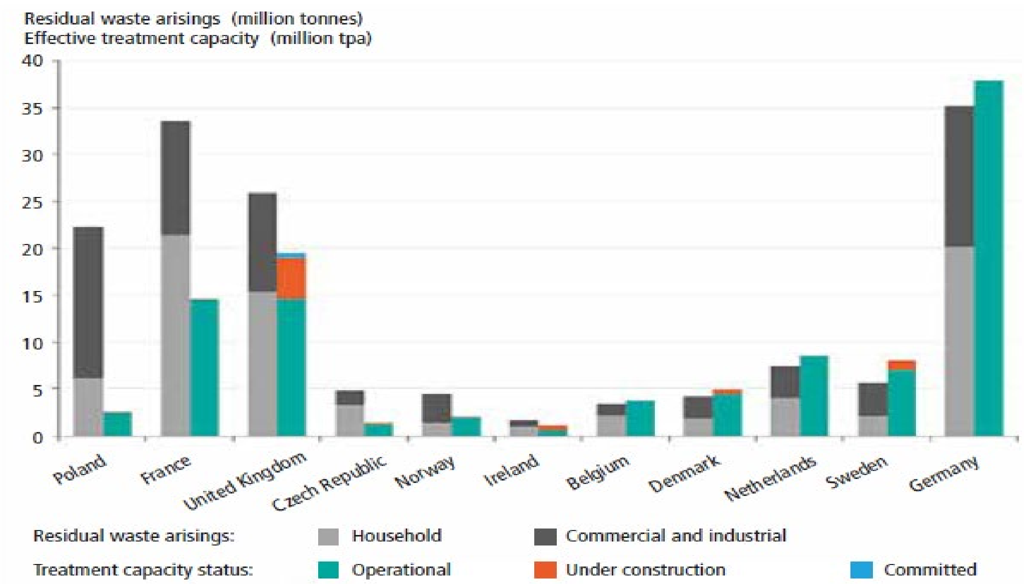


Figure 21. Residual waste arisings and effective treatment capacity within the Northern Cluster in Mtons (2015) [85].

The future residual treatment capacity was modelled based on assumptions about achievable waste growth [17] , waste recycling [18] rates and availability of facilities [19]**.** Figure 23 indicates that a potential overcapacity could be achieved by 2026. This study also shows that some countries (i.e. Germany, Sweden, Denmark and the Netherlands) have already reached an excess of treatment capacity (Figure 23), so that a further need to import waste fuels (RDF and SRF) might be considered assuming that these countries might not close down plants.

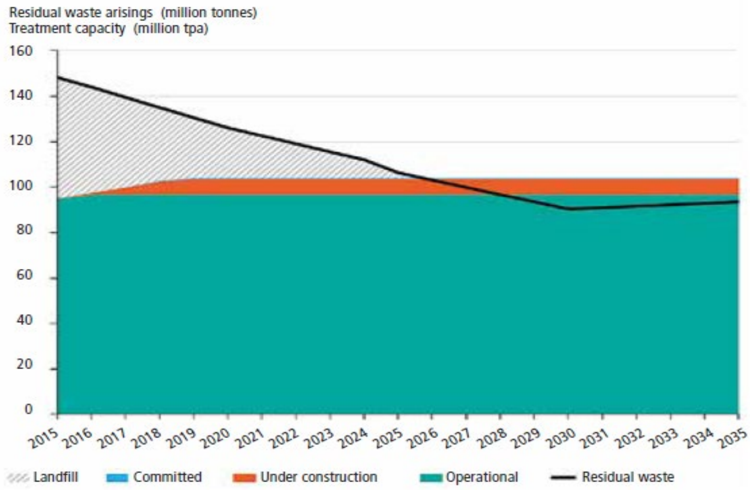


Figure 22. Modelled potential residual waste capacity gap in Northern Cluster countries (2015 to 2035) [85].

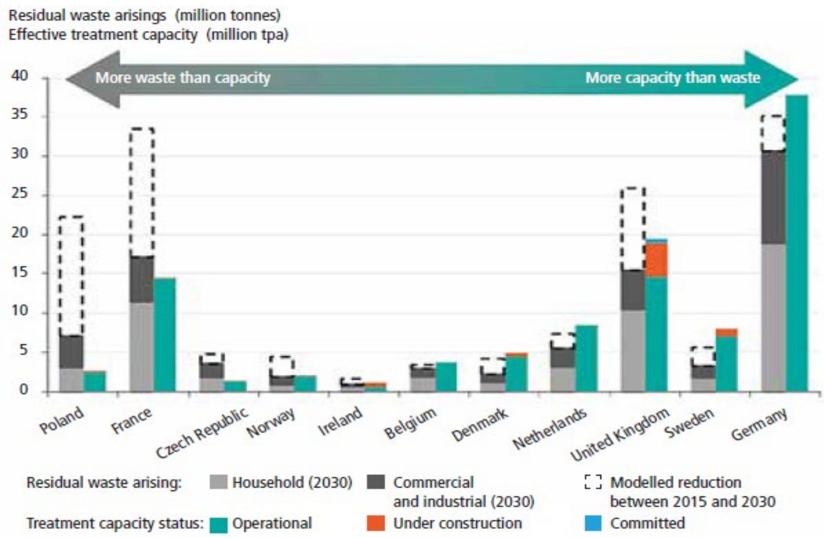


Figure 23. Modelled residual waste arisings and treatment capacity in Northern Cluster countries (2015 to 2030) [85].

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[17] Waste growth rates: MSW 0,5%; CW; 0,5%; IW 0,0%).

[18] Waste recycling rates: at 2020 of 50%, 65%, 75% and at 2030 of 65%, 75% and 80%, for MSW, CW and IW respectively.

[19] Assumption about facilities: no facilities will close over time (other than the already confirmed); other facilities could be retrofitted or replaced maintaining the same scale (an assumption that can results in an underestimate level of future capacity).

Barriers

When discussing barriers with Mr Cuperus, a representative of the European recovered fuels organisation (ERFO), the differences among the European countries on the implementation of the existing European legislation on waste is mentioned as a clear barrier. MSW landfilling is still the most applied waste management option in many countries in Europe; and there is a large need to implement measures able to drive more extensively waste management towards sorting/recycling.

Another barrier mentioned is the insufficient demand but also a lack of homogeneous implemented standards (not standardised RDF are admitted and currently traded in the European market). This is seen as something that can affect and prevent future exploitation of the SRF market. Furthermore, in order to allow the global SRF market to develop, the current efforts of the ISO/TC 300 for the standardisation of solid recovered fuels will be an important factor to overcome that barrier.

Waste and biomass co-processing in the cement industry was investigated by Ecofys [86] with respect to drivers and barriers that affect and/or constrain its current situation and future development, taking into account 14 European countries. Based on the opinion of local experts, a statistical analysis of data sources on waste and cement and a review of relevant literature, limiting/driving factors that affect the current figure of fuel substitution and potentially might play a role in its future growth were evaluated on a country basis, as detailed in the 2017 case study report. Local and global (EU-28) medium-long term outlooks (5 – 10 years) of co-processing rates [20] (provisions based on the opinion of local experts) were assumed by that study Figure 25), that start from a current situation (reference year 2014) characterized by very large differences between countries [86].

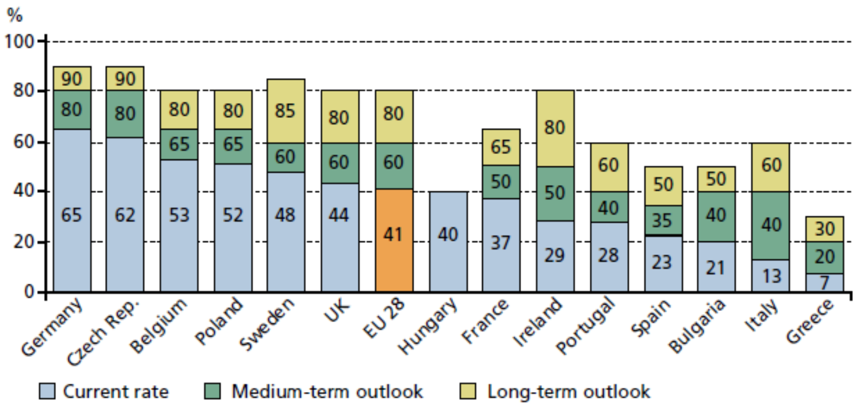

Figure 24. Existing (year 2014) and expected medium-long term co-processing rates in European countries. [86].

[20] Share of specific thermal energy consumption coming from alternative fuels in grey clinker making.

Other than the local availability of a cement industry technically ready (driver) or not (barrier) to use waste-derived fuels or to increase their use and price and price volatility of conventional fossil fuels (driver), the following factors are reported to be perceived as main keys [86]:

- Waste management policy (and its degree of local implementation) that promotes (driver) or not (barrier) advanced waste treatment, production of high-quality pre-treated wastes, landfilling diversion through landfill bans and taxes (driver), for this key factor. Figure 27 maps the status (year 2015) of implementation of landfill ban and taxes in the examined countries. Low landfill taxes and gate fees, especially where a large landfill capacity is available, are perceived as barriers since they can have a negative impact on the adoption of more advanced waste treatment solutions and, consequently, on the production of pre-processed wastes and their use for co-processing. Somewhere also a low level of premiums for pre-processed wastes payed by cement industry is reported to be perceived as an impacting factor (barrier).

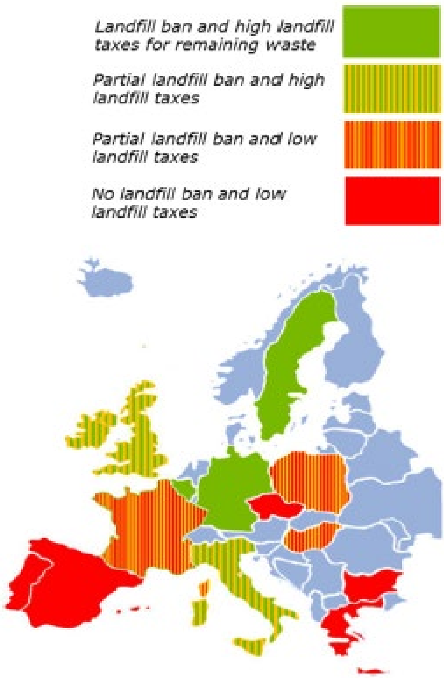

Figure 25. Map of the weight of policy related to waste landfill in the examined European countries (situation in the reference year 2015) [91].

- A low or too high local bureaucracy with respect to permit issuance might be a barrier. The incidence of this key factor in the examined countries is mapped in Figure 27: three countries are reported to perceive this factor as a quite relevant national barrier.

  Cement facilities have to obtain co-processing permits to use waste streams as a substitute fuel. Where not allowed or where relevant delays/constraints occur in the permitting process, an increase of the co-processing share can be significantly limited.

Figure 26. – Map of the perceived bureaucratic barriers impacting on plant permits in the examined European countries (red: low level; green: good level) – Year 2014 – [88].

- The availability (driver) or lack (barrier) of high-quality waste fuels is a factor whose local relevance for co-processing was assessed by Ecofys (Figure 28) resulting it an impacting factor for many of the examined countries.

  The cement industry has a need of stable waste streams of high quality. The Ecofys study [86, 88] highlights that such need seems not to be satisfied everywhere by the local waste management system, due to different factors:

  - infrastructural issues (underdevelopment in pre-processing facilities);
  - a waste *treatment system* not enough incentivized to process waste streams to a "premium" (high quality) recovered fuel;
  - an unbalance of the local WtE system (competition for recovered fuels with other thermal treatment plants such as power plants, incineration plants) that can also be emphasized by further market distortions (e.g. subsidies for energy production from renewable sources that include the biodegradable fraction of wastes, SRF included).

Figure 27. Map of availability of high-quality waste streams for co-processing in the examined European countries (red: low level; green: good level) – year 2014 – [88].

- The public acceptance, for which Ecofys assessed a local relevance as barrier as showed in Figure 29. It refers to a public disagreement (with extreme simplification, the so called Nimby, Not in My Back Yard Syndrome), really not only with the waste co-processing in cement kilns but, in general, to the R1 operations (energy recovery processes), that can play a role (public pressure, more diffuse and relevant as key factor as the figure shows) in political decisions on waste management and release of plant permits.

Figure 28. Map of public acceptance level of waste co-processing in the examined European countries (red: low level; green: good level) – year 2014 - [88].

Conclusions

GENERAL

To study the market (production and end-use) of secondary fuels is a challenge. This partly depends on the multitude of denominations of the fuels. Waste derived fuels (WDF), RDF, and SRF are just some used internationally, when adding the national RPF, CSS, CDR, CSR it gets even more complicated.

The added value of SRF compared to RDF is not primarily better quality, but rather that SRF by default (since they are produced to fulfil set standards) are better documented and the quality is known. There might be RDF that work as well for a given application, but there are generally larger uncertainties in the characterisation and the inter-comparability between different RDF can differ because different methods are used for the characterisation.

Even though different countries used labelling like "high quality SRF" it is difficult to use a grade of high and low quality. The quality must be known, but then the quality depends on how it corresponds to the demands of the end client. A high NCV SRF is potentially not compatible with a large share of biomass in the SRF since high NCV often is related to the plastic content. Generally, though, when speaking about high quality it might be easier to refer to low levels of contaminants like chlorine or mercury.

MAIN USE TODAY

Incineration plants with recovery of electricity and thermal energy are end user of SRF, as well as RDF (it is mainly used in plants equipped with FBB boilers but also in plants with grate technology), with some European countries (e.g. Italy) now using a large share of the national production of SRF for that purpose. At a lower extent industrial co-incineration plants now exploit the potential of SRF to satisfy an internal heat/electricity demand or (in some European countries, Italy for example) to benefit economically from placing electricity on the national grid. This could change rapidly when circumstances become beneficial (such as oil price, pricing of CO_2, …). Some developments are taking place in the power and district heating sectors, but the main outlets in industries such as steel/iron, pulp/paper, glass and chemical industry are yet unexplored in most of the countries.

Energy-intensive industrial sectors - such as cement and lime production - and coal fired power plants can be highlighted, also in the opinion of the experts interviewed for the purposes of this study, as the main expected end-users of SRF, at least in most of the European countries. Some barriers now existing have been highlighted such as waste management policies, availability of SRF of suitable quality (capacity of the waste treatment system to produce it; amount that can be imported), high local bureaucracy, public acceptance, other than an end-user system equipped with technologies that allow the use of SRF, and growing over time. These barriers have been reviewed with respect to the European cement industry but barriers like policies, fuel availability or public acceptance can really be extended locally to other types of end uses.

Other countries such as India and China (just to mention cases documented in the study) that have to manage high amounts of wastes an annual basis and to satisfy their internal demand for energy, more recently started to develop a domestic pre-treatment system of waste (MSW, industrial wastes) to SRF and in any way became a quite consistent importer of SRF from neighbouring producing countries.

The ongoing intensive growth of the incineration industry in China, which seems to be focused on the use of the FBB technology, could become a large end-user of SRF; unfortunately no data was found about the current production and use of SRF in China so that it was not possible to estimate this impact on both the domestic production and the import of SRF.

China and India are the largest cement consumers in the world and cover a raised position in the ranking of the top ten cement producing countries; currently they show a quite low TSR (thermal substitution rate) but have an high potential for SRF utilization especially if some existing barriers (technological, legislative, economical,..) that could affect its real exploitation in a short/medium-term perspectives, will be removed or reduced. Both China and India as well as other Asian countries, are now actively working on the development of national standard and guidelines for the production and end use of SRF.

POTENTIAL FOR THE FUTURE

The waste hierarchy clearly recognizes a role to waste-to-energy and, in particular, to waste fuels produced through processes substantially complementary to waste recycling; it means fuels that origin from waste streams not more suitable for re-use, preparation for re-use or an efficient material recycling. Solid recovered fuels (SRF) as here defined will need to meet that requirement and contribute to the expected change in the waste-to-energy feedstock (improvement of the recyclability and reusability of residues such as plastics, wood, paper, and biodegradable waste) and towards a most energy-efficient waste-to-energy system. Exactly how this role will be in the circular economy will depend on the pre-conditions in different markets, and different solutions will be applied in different countries/regions.

As mentioned in the previous part, large nations like China and India still have a large share of their energy production and supply of process heat from fossil sources. They are also major producers/consumers of cement. European countries have shown that a significant part of the fossil fuels can be substituted with secondary fuels like SRF, which also indicates a large potential in countries like India and China.

The efforts put into international standardisation of SRF through ISO will most probably also lead to an increased trust in SRF as a secondary fuel. This in turn might lead to an increased demand in markets that are not that large today. That is also indicated by the fact that countries that today do not have that active markets, like Pakistan, Egypt and Canada have chosen to enter into the standardisation work.

A new area of application for SRF/RDF is the use as feedstock for thermochemical recycling processes. These are aimed at producing liquid fuels or base chemicals that can be used to produce materials like plastics. Today the commercial facilities in this area are limited, but there are some first of its kind plants up, and the interest for the technologies are steadily increasing. With the right incentives these technologies will develop further and become an important market for SRF/RDF.

Overall, several activities are happening on the production and use of SRF/RDF and its importance in the near to mid-term will most probably increase.

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Annex 1

PLASTICS AND POST-CONSUMER PLASTIC WASTES

As the brief overview of the SRF/RDF market clearly shows, plastic wastes are a relevant component of most of the secondary fuels currently produced. Plastics are a family of organic materials (Figure 30), still mainly derived from fossil feedstocks (e.g. natural gas, oil, coal) and only partially bio-based, that can be transformed into new feedstocks or into energy at the end of the life cycle (Figure 31), so becoming a valuable resource.

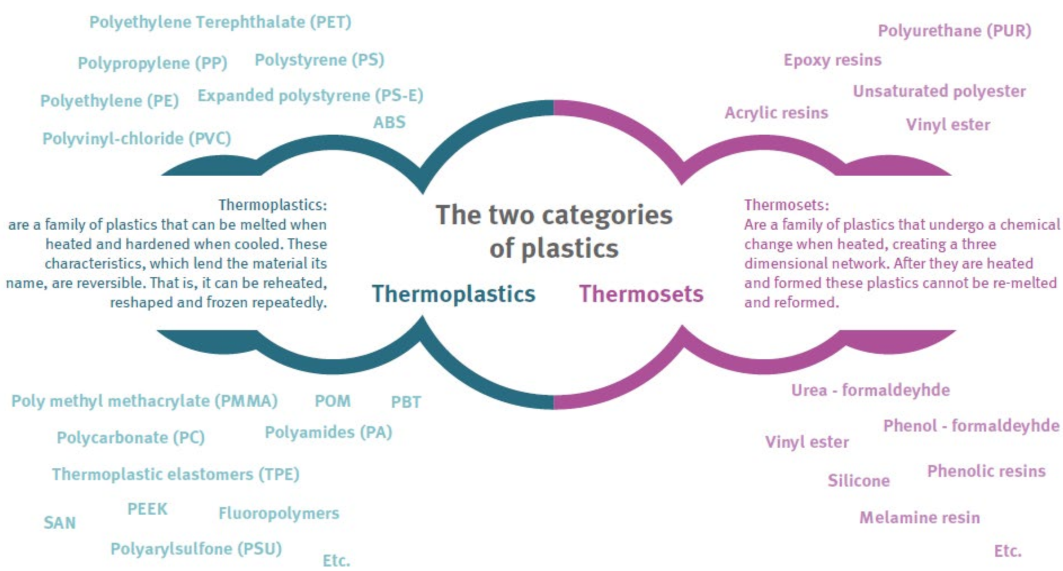

Figure 29. Composition of the plastic's family [Figure from: Association of Plastic Manufactures, 2017].

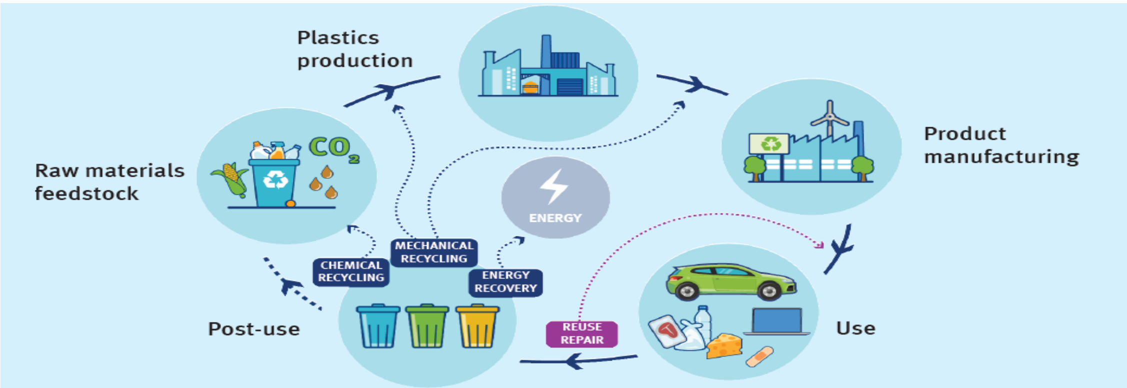

Figure 30. Plastics: a schematic view of the full lyfe cycle.

The production of plastics has grown exponentially over time to 322 Mton in 2015 and 335 Mton in 2016, worldwide. Europe, for example, contributed to such overall production with 58 Mton in 2015 and 60 Mton in 2016 (data refer to EU28 + Norway and Switzerland) [132]. China is the largest producer (29%) of plastic materials (i.e. thermoplastics and polyurethanes), followed by Europe (19%) and NAFTA, the North American Free Trade Agreement (18%). Plastic materials are designed to meet the needs of different domestic, commercial and industrial applications. On the matter,

Figure 32 provides a view of the distribution, by market segment and by polymer types, of the plastics converter demand in Europe that accounted in the year 2016 for a total of 49,9 Mton.

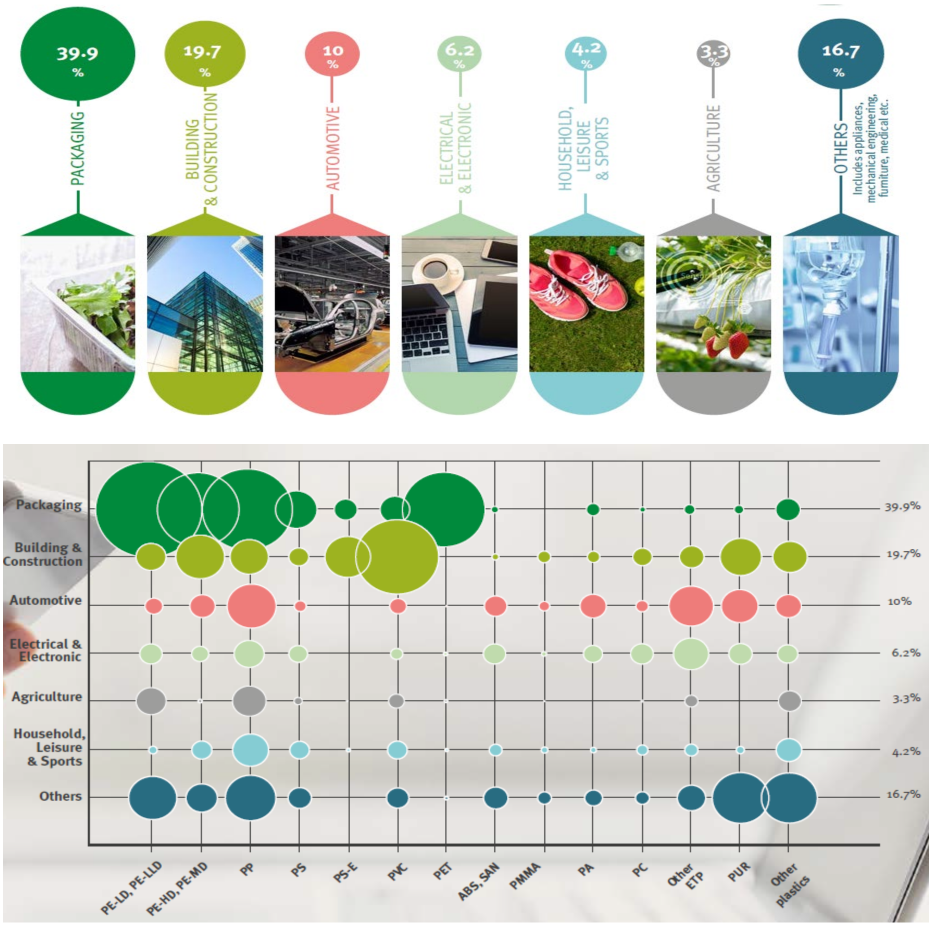

Figure 31. European (EU28+Norway and Switzerland) plastics converter demand by segments and polymer types in the year 2016 [132].

Plastic is mostly used in packaging as a low-cost product. In Europe, for example, it was estimated [136] that plastic packaging cover around a 40% of the total amount of plastic materials yearly produced, a share double than that of plastics in the consumer & household goods sector or in the building and construction sector, and from 4 to 8 and 10 times that of plastic materials used in the automotive sector, in electrical and electronic equipment and agriculture.

A consequence of the increased production and use of plastic materials was a growth over time of plastic post-consumer wastes, whose global estimated production was in 2015 of about 300 million ton [132], about half from packaging. European statistics for the year 2016 [134] account for 27.1 million tonnes of plastic post-consumer wastes collected and managed as showed in Figure 33. A total share of 31% of waste recycling was reached in 2016 (Out of the recycled materials 63% was recycled inside EU and 37% was shipped outside EU for recycling), with the higher recycling rates occurring in European countries which implemented landfill ban.

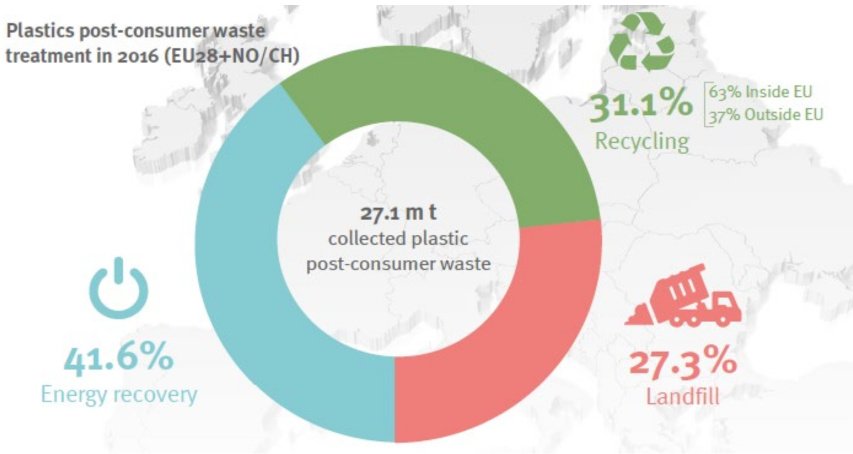

Figure 32. Total amounts of collected plastic post-consumer wastes and management pathways in Europe (EU28 + Norway and Switzerland) in 2016 [132].

Within plastic post-consumer wastes, packaging wastes are the main component also in Europe, with (Figure 34) a total of 16.7 million tonnes of waste collected in 2016 [132] and largely managed through energy recovery and landfill. A total recycling rate of 40.9% was achieved (19 countries with recycling rates higher than 35%, only two countries between 50% and 52%). Based on data published by the European Association of Plastics Recycling and Recovery (EPRO) [132], around 64% of the post-consumer plastic packaging waste was collected from households (recycling rate of 37.8%), and the remaining from the trade/ industry sector (recycling rate of 46.5%)

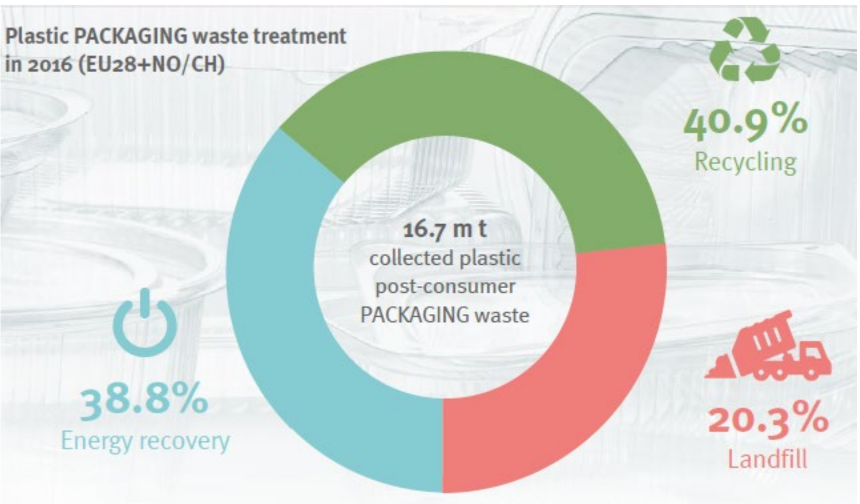

Figure 33. Total amounts of collected plastic packaging wastes and management pathways in Europe (EU28+Norway and Switzerland) in the year 2016 [132].

The EU Commission's strategy for plastics in a circular economy [135] points out that in comparison with other materials recoverable from wastes (paper, glass or metals), the recycling and reuse of end-of-life plastics is still exploited at a low extent Europe, due to: a demand for recycled plastics that accounts for about 6% only of the whole plastics demand in Europe, low commodity prices, market uncertainties and prospects of low profitability are highlighted as main factors that have affected the European plastic recycling sector and held back new investments in the local recycling capacity. Otherwise, the strategy assumes as a priority that by 2030, all plastics packaging (a priority area) placed on the EU market should be reusable or can be recycled in a cost-effective manner.

Different issues affect plastic recycling: the quality and price of the recycled product, compared with their unrecycled counterpart; plastic processors that require large quantities of recycled plastic; the diversity and somewhere (e.g. plastic packaging) the presence of a mix of the raw materials in the plastic waste to be treated (plastics are easily customized to each manufacturer according to the functional/aesthetic use of the products) can complicate/make not cost-effective the recycling process or finally affect the value and/or the quality of the reused material. There is a general agreement on the matter that an improvement of plastic recycling other than move through the adoption of best practices for waste collection and sorting systems and/or a scale up to high-quality recycling processes to exploit plastic, already starts in the product design phase [135–137, 138]. It means a need to implement changes in the choice of materials, additives and formats. For example:

- reduce the use of *Small-format* plastic packaging (about 10% of the market, by weight [138]);
- innovation in material and reprocessing technology for *Multi-material* packaging (about 13% of the market, by weight [138]);
- replacement of *Uncommon* materials (e.g. PVC, EPS, and PS) in packaging (account for about 10% of the market, by weight [138]) that are technically but not economically (their small volumes prevent effective economies of scale) recyclable,
- reduce *Nutrient-contaminated* packaging that can affect high quality recycling.

Low of capacities, technologies, profitability or financial resources for local recycling, led - in Europe as in other countries - to a quite consistent yearly export of plastic wastes to third countries, to be treated for recycling. Broks et al. [139] showed that the export/import of plastic waste was consistently increased over time (figure D) and reported that in the year 2016 about half of all plastic wastes intended for recycling (14.1 MTon), was exported by 123 countries. China was the main recipient country, with 7.35 Mtons imported from 43 different countries. The top ten exporters include in descending order (% of the total waste imported): Hong Kong (although a part of China) (24.9%), Japan (11.8%), USA (9.7%), Thailand (6.1%), Germany (5.5%), Belgium and Philippines (4.5%), Australia (4.1%), Indonesia and Canada (2.7%).

As Figure 35 highlights, in 2017 and more extensively in 2018, a ban on the import of plastic wastes was implemented in China.

Data published by Hook and Reed in the Financial Times in 2018 [140] (Figure 36), show that when China and Hong Kong in the first half of 2017 still received about the 60% of plastic wastes exported by G7 countries, the export flows to these two countries fell down in 2018 to about 10%, with other Asian countries as new main recipient. Following the China's import ban, an general reduction in plastic waste export was recorded: on average of about -20% for the G7 countries, with -30% for USA and Japan, -25% for Italy, -19% for Germany, -18% for Canada, -13% for France and -3% for the UK.

It has to be noted that a similar ban was introduced in China for paper wastes. The above-mentioned article of Hook and Reed provides an assessment of how export flows (again for G7 countries) changed from 2017 to 2018 (Figure 37). They concluded that imports towards China almost halved (it remains the main recipient country), with a reduction of the overall 2018 export from the G7 countries.

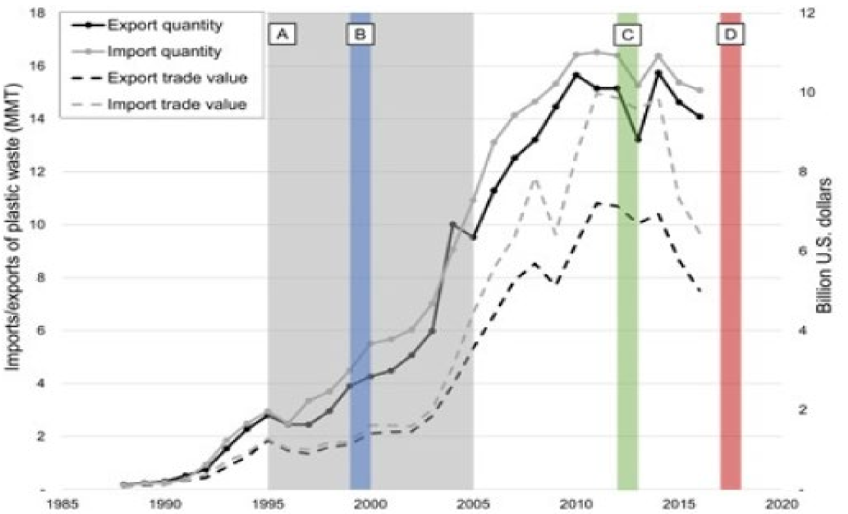

Figure 34. Plastic waste trade (export and import) by mass and by value time. A: Advances in Municipal Recovery Facility (MRF) technology B. Surge in globalization; C: Implementation of temporary Chinese import restrictions (Green Fence, 2013) D. Implementation o of the new Chinese policy banning the import of nonindustrial plastic waste (2017) [139]

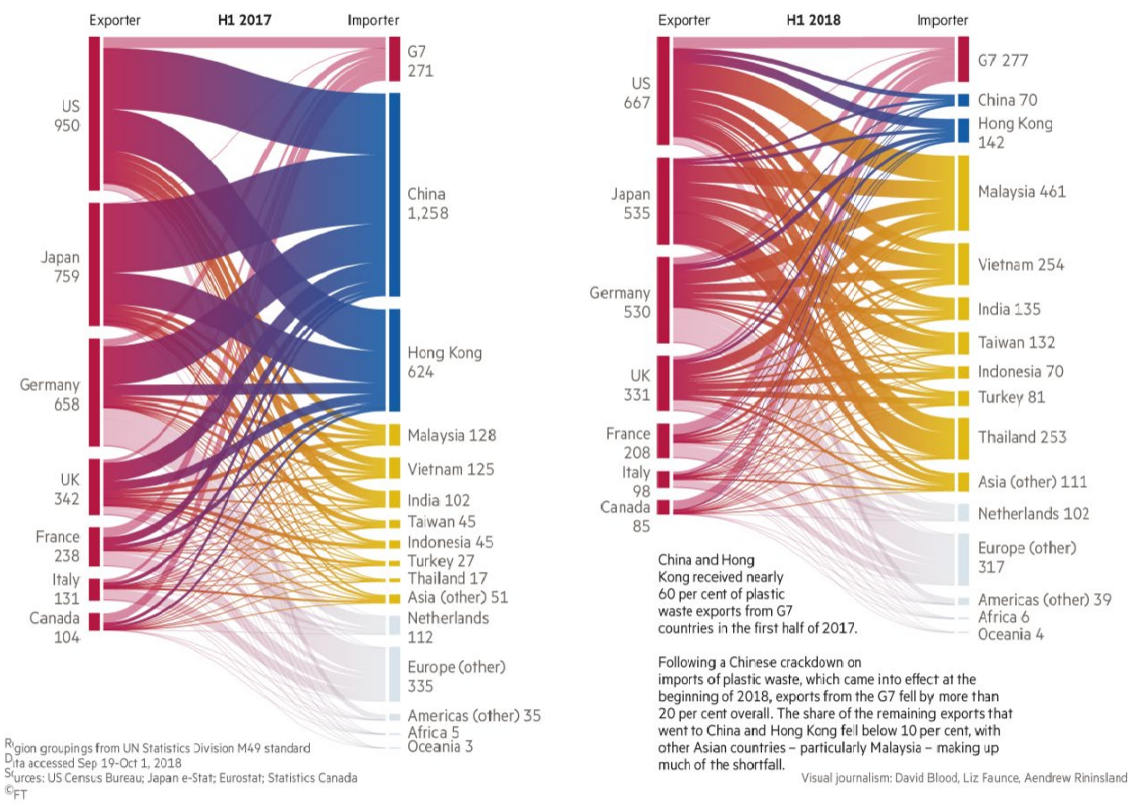

*Figure 35. Plastic waste flows (export and import, *1000, tonnes) in 2017 and 2018 [140].*

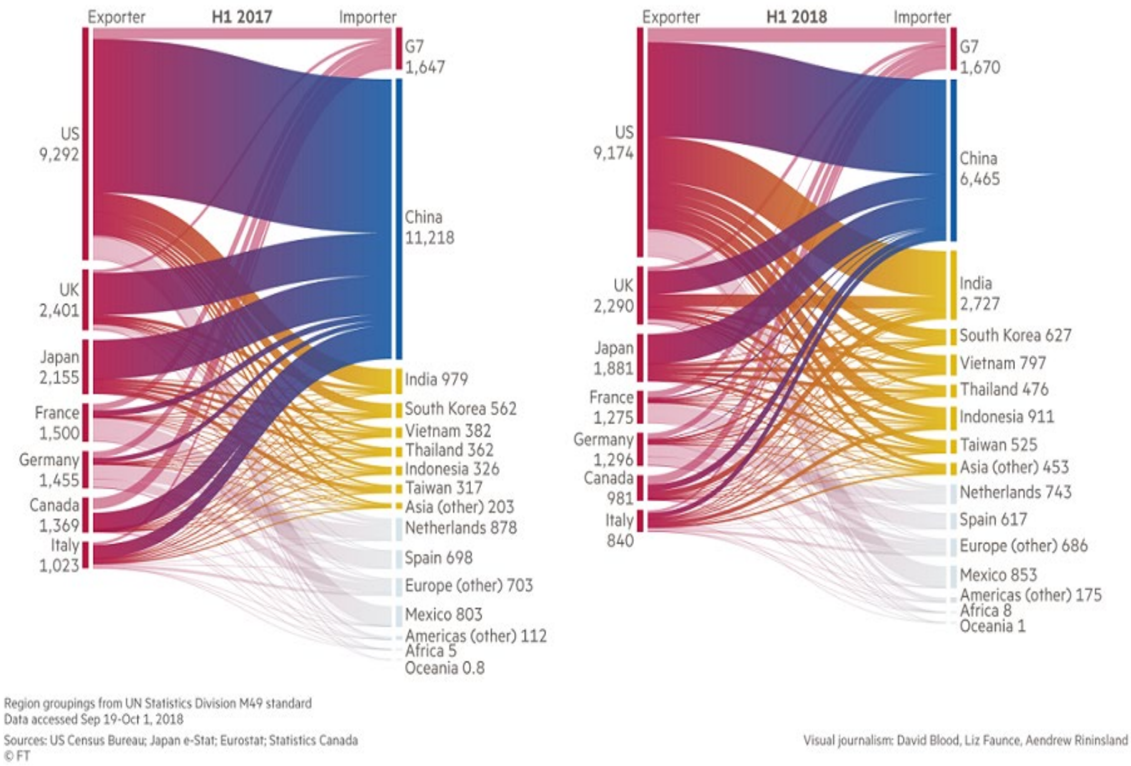

*Figure 36. Paper waste flows (export and import, *1000, tonnes) in 2017 and 2018 [140].*

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