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Solid recovered fuels — Guidance for the specification of solid recovered fuels (SRF) for selected uses

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO-specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 300, *Solid recovered materials, including solid recovered fuels*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Waste-to-energy is a broad term that covers much more than waste incineration. It includes various treatment processes that have different environmental impacts but also offer potential for the progress desired towards a low-carbon and circular economy. Processes that convert waste into solid fuels and generate electricity and/or thermal energy from it can play an increasing role in achieving such goals.

Traditionally, solid fuels recovered from waste have been used as an integrative fuel in incineration or co-incineration plants treating a mix of wastes, so as to improve the energy performance of the plant. There are also some dedicated SRF-EfW plants (e.g. incineration plants and industrial combustion plants recovering thermal and/or electrical energy from the solid recovered fuel alone).

An increasing role as substitutive fuel has occurred over time to allow a reduction of fossil fuel consumption and the impact on climate change and greenhouse gas emission of industrial activities with a high energy consumption. In recent years, the use of solid recovered fuels has expanded to other interesting and promising fields, such as gasification or combined gasification and pyrolysis. Waste gasification and co-incineration of the resulting syngas in a combustion plant, co-processing to power and material recovery in cement kilns and waste incineration in dedicated facilities can be highlighted as best proven techniques to increase the energy efficiency of waste-to-energy processes and optimize their contribution to national and global climate and energy goals.

All the above-mentioned waste-to-energy processes rank differently in the waste hierarchy and have different needs for fuel quality to ensure better plant management as well as compliance with requirements set by national and supranational legislation.

Quite an extensive family of solid fuels can be recovered from waste, with different physico-chemical properties and a quality that is not always well defined. Those produced from non-hazardous waste, classified as SRF (Solid Recovered Fuel), are specifically of interest in this document. The term SRF itself identifies a family of fuels that can differ in origin (input waste streams), composition and quality.

Many barriers still hamper the extensive development of SRFs. As discussed later, a continuing confusion in terminology can be highlighted. Solid fuels recovered from non-hazardous waste are identified in different countries by different terms (e.g. CSS, CDR, CDR-Q, RPF, SBS, CSR,), shipped with different waste codes, and an ambiguous use of the terms RDF and SRF still occurs. SRF is largely produced and traded as waste, different countries labelling it with different waste codes based on local waste legislation. An end-of-waste of SRF is allowed in some countries (e.g. Austria, Italy) if the fuels produced comply with specific and mandatory requirements legally set.

Solid recovered fuels are intended to be classified and specified according to ISO/TC 300 standards. Fuel specification is also the subject of national guidelines, in places addressed to specific end uses of the fuel (e.g. in cement kilns), and of local voluntary commitments on fuel properties between the producer and the end user aimed at ensuring that the latter meets its own technological, economic and environmental needs.

Generic (all solid waste) or specific (SRF) quality requirements are set by national or local regulators (e.g. administrative bodies authorized to issue plant permits), mainly to ensure that waste-to-energy plants at least meet the requirements for environmental and human protection and to regulate the role of waste-to energy plants within the national/regional waste management systems as a whole.

There are still acceptance problems in several countries that need to overcome, for example by reliable data, a high level of information and transparency.

To foster the application of SRFs in existing and new fields and to overcome existing barriers, it is therefore strategically essential for all interested stakeholders to define what quality requirements the SRF meets based on homogeneous, unambiguous and well-accepted criteria.

Solid recovered fuels — Guidance for the specification of solid recovered fuels (SRF) for selected uses

1 Scope

This document addresses the provision of background references that are helpful in defining a more detailed specification for SRF according to its specific end use for energy conversion (EfW plants) and to support the SRF market. The aim is to enable all the interested stakeholders – producers, end users, legislators, local authority bodies and standardization bodies – to guarantee that the SRF complies fully with technical, environmental and economic requirements and to facilitate its social acceptability when utilized for energy conversion.

This document is intended to provide references for the specification of SRF produced from non-hazardous waste streams and traded to EfW plants as waste. The quality of such SRF is specified through values for relevant fuel properties, appropriate to the subsequent end uses that have an expected growth or an established/well consolidated role in heat and power generation in waste-to-energy systems:

- coal co-combustion in cement kilns,
- gasification,
- coal co-combustion in power plants.

The SRF can also be used in other end-use applications but these are not addressed in this document.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviations

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1 Terms and definitions

3.1.1
BAT
best available technique
term used within the European Union for the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole

Note 1 to entry: "Techniques" includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

Note 2 to entry: “Available techniques” means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator.

Note 3 to entry: “Best” means most effective in achieving a high general level of protection of the environment as a whole.

[SOURCE: Directive 2010/75/EU, Art. 3 (10)]

3.1.2
BAT reference document

term used within the European Union for a document, resulting from the exchange of information drawn up for defined activities, that describes, in particular, applied techniques, present emission and consumption levels, techniques considered for the determination of best available techniques as well as BAT conclusions and any emerging techniques

Note 1 to entry: “BAT conclusions” means a document containing the parts of a BAT reference document laying down the conclusions on best available techniques, their description, information to assess their applicability, the emission levels associated with the best available techniques, associated monitoring, associated consumption levels and, where appropriate, relevant site remediation measures.

Note 2 to entry: “Emission levels associated with the best available techniques” means the range of emission levels obtained under normal operating conditions using a best available technique or a combination of best available techniques, as described in BAT conclusions, expressed as an average over a given period of time, under specified reference conditions.

Note 3 to entry: “Emerging technique” means a novel technique for an industrial activity that, if commercially developed, could provide either a higher general level of protection of the environment or at least the same level of protection of the environment and higher cost savings than existing best available techniques.

[SOURCE: Directive 2010/75/EU, Art. 3 (11)]

3.1.3
classification of solid recovered fuels

categorization of *solid recovered fuels* (3.1.18) into classes by focusing on the key properties net calorific value, chlorine and mercury, that are defined by boundary values

Note 1 to entry: The classes are defined by boundary values for the chosen fuel characteristics to be used for trading as well as for the information of permitting authorities and other interested parties.

[SOURCE: ISO 21637, 3.12, modified — Note 1 to entry is added.]

3.1.4
co-incineration plants

term used within the European Union for any stationary or mobile technical unit whose main purpose is the generation of energy or production of material products and which uses *waste* (3.1.19) as a regular or additional fuel or in which waste is thermally treated for the purpose of disposal through the incineration by oxidation of waste as well as other thermal treatment processes, such as pyrolysis, gasification or plasma process, if the substances resulting from the treatment are subsequently incinerated

[SOURCE: Directive 2010/75/EU, Art. 3 (41)]

3.1.5
combustion plant

term used within the European Union for any technical apparatus in which fuels are oxidized in order to use the heat thus generated

[SOURCE: Directive 2010/75/EU, Art. 3 (25)]

3.1.6

composition of solid recovered fuels

breakdown of *solid recovered fuels* (3.1.18) by types of components

Note 1 to entry: This is typically expressed as a percentage of the mass fraction component in the fuel on an as received basis (m % ar).

Note 2 to entry: Examples of components - wood, paper, board, textiles, plastics, rubber.

[SOURCE: ISO 21637, 3.14]

3.1.7

dedicated SRF- EfW plants

any technical unit in which the energy conversion is from the *solid recovered fuel* (3.1.18) alone

3.1.8

EfW plants

energy from waste plants like municipal waste incineration (MWI), mono- and co-combustion plants including cement kilns

3.1.9

energy conversion

use of the calorific value of the *solid recovered fuel* (3.1.18) for energy purposes alone or with other fuels

Note 1 to entry: Solid recovered fuels may be an intermediary energy carrier and used directly or indirectly for the energy conversion such as in multi-stage production and use of synthetic gas. Examples of energy conversion processes are incineration, co-incineration, combustion, co-combustion, gasification and pyrolysis, in which energy is used for supplying heat, cooling and/or electric power.

[SOURCE: ISO 21637, 3.27]

3.1.10

energy purposes

use of the calorific value within industrial processes or for the supply of heat and electrical power

Note 1 to entry: For industrial processes, the use of solid recovered fuel may contribute to the energy source within the process of producing specific materials, such as cement clinker, bricks and lime.

[SOURCE: ISO 21637, 3.29]

3.1.11

EoW

end-of-waste

term used within the European Union for status of a specified substance or object that ceases to be a *waste* (3.1.19) when it has undergone a recovery, including recycling, operation and complies with specific criteria, to be developed in accordance with the following conditions: (a) the substance or object is commonly used for specific purposes; (b) a market or demand exists for such a substance or object; (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts

[SOURCE: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste, art. 6]

3.1.12

gasification plant

any stationary or mobile technical unit whose purpose is converting feedstock fuels into a syngas (synthesis gas) for different final uses

3.1.13
hazardous waste

waste (3.1.19) which has proprieties that may be harmful to human health or the environment

Note 1 to entry: These wastes are categorized by waste streams and hazardous characteristics. The hazardous characteristics relevant to solid wastes are: explosives substances; flammable solids; wastes liable to spontaneous combustion; wastes which, in contact with water emit flammable gases; wastes which oxidizing; organic peroxides; acute poisoning and infectious substances.

Note 2 to entry: Further identification of the waste's status can be determined using the Annex I and Annex III tables of the Basel Convention on the control of transboundarym of hazardous wastes and their disposal.

Note 3 to entry: Additional categories of hazardous waste to those in the Basel Convention Annex I and Annex III may be established by stakeholders to the agreement or at a national level.

[SOURCE: ISO 21637, 3.35, modified — Example and Notes 4 and 5 to entry were removed.]

3.1.14
incineration plant

term used within the European Union for any stationary or mobile technical unit and equipment dedicated to the thermal treatment of *waste* (3.1.19), with or without recovery of the combustion heat generated, through the incineration by oxidation of waste as well as other thermal treatment processes, such as pyrolysis, gasification or plasma process, if the substances resulting from the treatment are subsequently incinerated

Note 1 to entry: According to the US Environmental Protection Agency, incinerators are any furnace used in the process of combusting solid waste for the purpose of reducing the volume of the waste by removing combustible matter. A solid waste incineration unit is defined as a distinct operating unit of any facility which combusts any solid waste material from commercial or industrial establishments or the general public (including single and multiple residence, hotels and motels). The term does not include: a) materials recovery facilities (including primary or secondary smelters) which combust waste for the primary purpose of recovering metals; b) qualifying small power production facilities or or qualifying cogeneration facilities which burn homogeneous waste (such as units which burn tires or used oil, but not including refuse-derived fuel) for the production of electric energy or in the case of qualifying cogeneration facilities which burn homogeneous waste for the production of electric energy and steam or forms of useful energy (such as heat) which are used for industrial, commercial, heating or cooling purposes; c) air curtain incinerators provided that such incinerators only burn wood wastes, yard wastes, and clean lumber.

[SOURCE: Directive 2010/75/EU (40); US Environmental Protection Agency. Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Commercial and Industrial Solid Waste Incineration Units; [Technical Amendments] Federal Register / Vol. 83, No. 116 / Friday, June 15, 2018 / Proposed Rules 3.17]

3.1.15
MSW
Municipal Solid Waste

waste (3.1.19) collected and treated by or for municipalities

Note 1 to entry: It typically covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste.

3.1.16
non-hazardous waste

waste (3.1.19) that is other than *hazardous waste* (3.1.13)

3.1.17
specification of solid recovered fuels

list of properties that characterize *solid recovered fuels* (3.1.18)

[SOURCE: ISO 21637, 3.76]

3.1.18
SRF
Solid Recovered Fuel
solid fuel for energy purposes according to ISO 21640, derived from *non-hazardous wastes* (3.1.18)

Note 1 to entry: According to EN 15359, SRF are solid fuels prepared from non-hazardous waste s meeting the classification and specification requirements laid down in this European Standard. “Prepared” means processed, homogenized and upgraded to a quality that can be traded amongst producers and users.

Note 2 to entry: Whether the input material is hazardous or non-hazardous is determined through national laws and Directives or by categorization of the fuel through the Annexes in the *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal.*

[SOURCE: ISO 21637, 3.75, modified – Original Notes 1-2 to entry were replaced by a new Note 1.]

3.1.19
waste
substances or objects which are discarded or are intended to be discarded

Note 1 to entry: The provisions of national laws can apply.

Note 2 to entry: The Basel Convention on the control of transboundary movements of hazardous wastes and their disposal provides the user with the ability to determine whether a material is deemed to be a hazardous waste or non-hazardous waste. By following the Convention’s requirements and Annexes, along with national laws, operators have a clear understanding of the distinction between the different categories of waste.

[SOURCE: Basel Convention on the control of transboundary movements of hazardous wastes and their disposal, 2019]

3.2 Symbols and abbreviated terms

BAT	Best Available Technique
CDW	Construction and Demolition Waste
ICW	Industrial and Commercial Waste
H	Hazardous Waste
NH	Non-Hazardous Waste
MSW[a]	Municipal Solid Waste
EoW	End-of-Waste
RDF[b]	Refuse Derived Fuel
SRF[c]	Solid Recovered Fuel
ar	as received
d	dry basis
BD	bulk density, kg/m^3
DM	dry matter, % in mass
NCV	net calorific value, MJ/kg; kcal/kg
M	moisture content, $q_{p,\text{net}}$, % in mass

A	ash content, % in mass
TC	total carbon content, % in mass

[a] Municipal solid waste is a *waste* (3.1.18) collected and treated by or for municipalities. It typically covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste.

[b] RDF differs from SRF (*solid recovered fuel* as defined in 3.1.17) in that it is not in compliance with standardized classification and specification requirements. RDF includes high calorific fractions, which are coarser fractions from waste streams that contain materials with a high calorific value that have not been processed as extensively as fractions for power plants running on secondary fuels such as SRF.

[c] As defined in 3.1.17.

4 Compilation, structure and use of data

Background references and data provided in this document have been collected from:

- national/international legislation, standards, guidelines and statistics on waste management;
- sectoral statistics reported in documents or websites (e.g. Global Cement; AITEC, Italian Cement Technical and Economical Association; VDZ, German Cement Works Association; Japan Cement Association; European Recovered Fuel Organisation; German Quality Assurance Association for Solid Recovered Fuels and Recycled Wood (BGS e. V.; Japan RPF Association);
- reference documents on the best available techniques;
- public documents of national producers/end users;
- a review of literature studies;
- international databases (e.g. the ECN Phyllis Database);
- responses sent to questionnaires. Four online surveys were promoted in 2017 by the ISO TC 300/WG2 to collect background information on:
    - profiles of the SRF-RDF produced. Responses (25) were provided from European (88 %: Germany, Italy, Sweden, Spain, Finland) and Japanese (12 %) producers;
    - market, production and use of SRF-RDF. Only a few responses were collected (5) that refer to European countries (Spain, France, Italy, Austria);
    - legislation, standards and guidelines that have an impact on SRF-RDF. Responses (11) were provided by European stakeholders (60%: Germany, France, Italy, Denmark and Serbia) and Asia (40 %, Japan);
    - needs for the classification and specification of SRF-RDF. Responses (15) were provided by stakeholders (end users, producers, authorities, mirror committees) of European countries only (Sweden, Spain, Italy, France, Austria and Germany);
- personal communications (e.g. Italian producers/end users of SRF; Japanese producers of RPF).

Background references on the main characteristics of the end-user plants of interest are provided in Annex C, while the collected background references on provisions in national legislations, standards, plant permits, guidelines, voluntary agreements, results of statistical assessments for typical values, reference data for properties of the produced SRF/RDF, are reported in Annexes A, B and D.

It is highlighted that:

- the background references for fuel specification are presented as reported in the documentary source;
- the use of non-homogeneous units occurs in the documentary sources, in particular in the case of fuel requirements for trace elements;
- the time dating is not necessarily homogeneous, and a geographical origin, largely from European countries, characterizes most of that background reference material, as well as the collected measured values, on which the statistical assessments for typical values in Annex D are based.

In the body of this document, an introductory framework is given in Clause 5. This is aimed at clarifying what this document means by SRF/RDF, what are the most widely used terms and the available rules for the classification and specification of solid recovered fuels, and to provide a brief overview of global markets. For each of the end users of interest, a summary description of technological needs, main requirements for quality achievable from mandatory provisions, guidelines, voluntary specifications, and references for typical values in the solid recovered fuels produced, are then provided in Clauses 6 to 8.

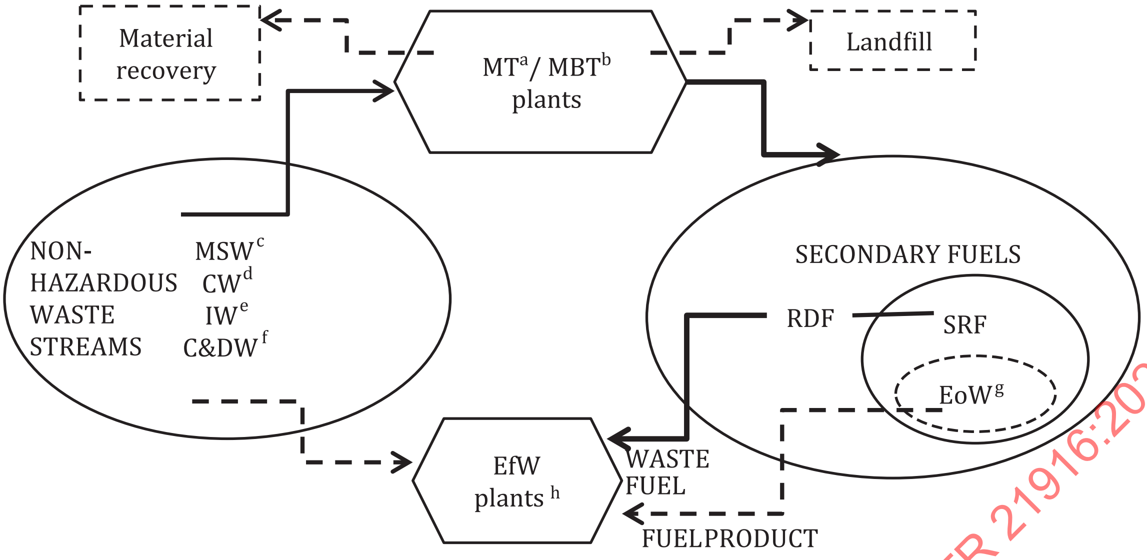
5 SRF and other waste derived fuels

5.1 General

Waste-to-energy is a broad term that identifies a value chain aimed at exploiting the energy potential of waste by means of the generation of electricity and/or heat in different forms of energy-from-waste (EfW) plants.

Within that value chain, waste can follow a “first address” or a “second address” pathway to the EfW plant, as Figure 1 shows schematically. The waste fuels that fall within the field of interest of this document are those referred to as “secondary fuels” in Figure 1 that are:

- produced from non-hazardous (NH) waste streams of urban, industrial or commercial origin, through a treatment process; this means that, if sent to EfW plants as generated, the same input waste streams are excluded;
- traded in national markets or shipped for energy recovery in EfW plants as waste; this means that waste fuels traded as fuel products in all respects, as long as they comply with mandatory requirements legally set to declare their end-of-waste status (the EoW subset in Figure 1), are excluded.



Key

a Mechanical treatment plants.

b Mechanical-biological treatment plants.

c Municipal solid waste.

d Commercial waste.

e Industrial waste.

f Construction & demolition waste.

g End-of-waste (secondary fuel as fuel product, not waste).

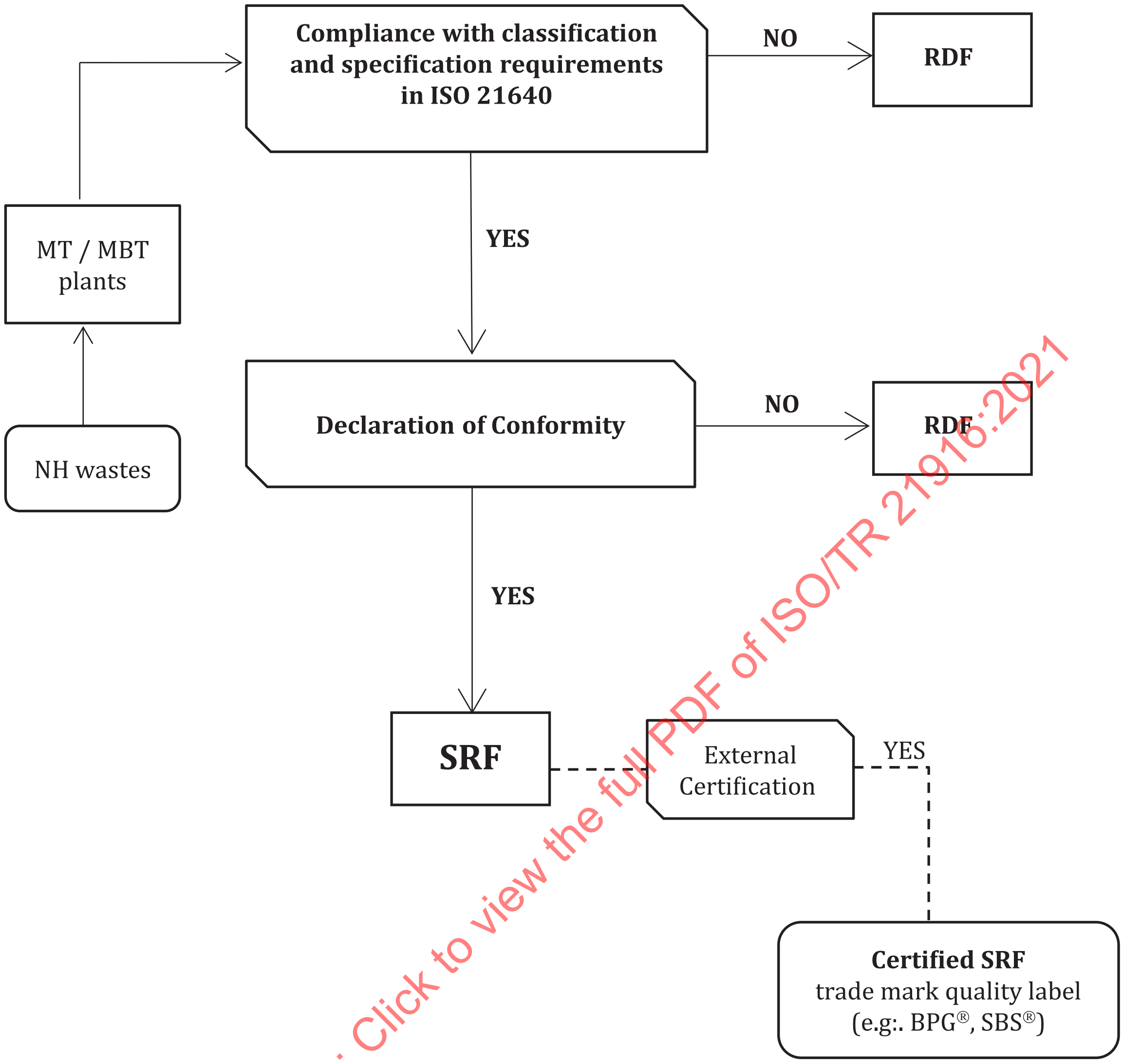
h Energy from waste plants, including cement and lime kilns.

NOTE Dashed arrows and boxes identify paths/fuels that do not fall within the field of interest of this document.

Figure 1 — A schematic view of the waste-to-energy value chain

Given the above, all the secondary fuels are assumed to fall under the generic and common name of Refuse Derived Fuel (RDF) and the Solid Recovered Fuel (SRF) are identified as a subset of that large family. Only secondary fuels that meet the classification and specification requirements laid down in a well shared standard can be considered as SRF (see Figure 2). A complementary assumption is that wastes not suitable for re-use, preparation for re-use or for efficient material recovery are intended to be used in MT/MBT plants for the production of SRF.

The meaning of the proposed assumptions is to identify a waste fuel – specifically the SRF - whose added value is to be a more “processed, refined and defined” fuel than a generic RDF not submitted to specific regulations. Therefore, a fuel that is well characterized and known for its properties, that is better able than unregulated RDF to meet the technical and environmental needs related to its specific use for energy recovery, and, in fact, can give results truly complementary to the waste recycling priority, based on the treatment technologies currently available for its production.



NOTE The external certification of SRF mentioned in Figure 2 is a national/company initiative that does not take part in standardization.

Figure 2 — A proposed approach to distinguish between RDF and SRF (adapted from[1])

Countries belonging to the EU have a common reference in in the European standard EN 15359[2] that defines SRF in terms of a solid fuel prepared from non-hazardous wastes to be utilized for energy recovery in incineration or co-incineration plants that meets the classification and specification requirements laid down in that standard. Such a definition is recognized by the European reference document on the best available techniques (BAT) for waste treatment[3]; it explicitly mentions EN 15359 as a reference and assumes that the refuse-derived fuel (RDF) differs from the SRF due to it not being produced in compliance with the specific criteria defined in the European standard.

ISO 21640,[4] developed based on the European standard, confirms that definition of SRF, emphasizes the origin of SRF from wastes that are not more suitable for efficient reuse and recycling of materials and provides shared rules (classification and specification requirements) that can be applied in different countries to identify a secondary fuel as SRF. Therefore, ISO 21640 is here assumed as a reference to distinguish between RDF and SRF (Figure 2).

An overview of national markets clearly showed that secondary fuels can take on different names locally and, above all, how a widespread use of the term RDF occurs that does not always allow a clear identification as a generic, non-standardized, or a standardized solid recovered fuel (an SRF). A list of the most common terms that are locally used to identify secondary fuels and that are referred to in this report, is given in 5.2 (see Table 1), along with an assessment of their compliance with the above-mentioned assumptions in respect of SRF and generic RDF.

SRF and RDF are locally produced in MT and MBT plants from individual or mixed streams of municipal (MSW), commercial (CW), industrial (IW) and construction and demolition (CDW) wastes that can differ in their share of residual fractions and, based on this, also in their elemental composition.[5],[6],[7] Different types and degrees of treatment are applied by the producers to the input waste streams that modify to some extent their properties and determine the achievable yield in waste derived fuels, in both quantitative and qualitative terms. Based on the type of input waste stream, the type and intensity of the pre-treatment process, SRF with a different level of quality can be obtained: indicative references derived from literature and from the statistical assessment of measured values carried out for the purposes of this document are given in Annex A.

5.2 Terms used for secondary fuels from waste

A list of acronyms for waste-derived fuels, which are used in different countries and that are referred to in this report, is provided in Table 1.

Table 1 — List of terms (acronyms and extended names) used in different countries to identify the waste derived fuels and and of their local identification as SRF or a generic secondary fuel (labelled RDF in the table)

Acronym *(extended name)*	Country	Description [Ref.]	SRF	RDF
BPG© *(Brennstoff aus produktionsspezifischen Gewerbeabfällen)*	Germany	The term (brand mark) is commonly used in the country,[1],[8],[9] to identify a solid waste derived fuel, produced from separately collected industrial and commercial wastes, that meets specification requirements as set by BGS e.V (BGS e.V. Quality Assurance Association for Solid Recovered Fuels and Recycled Wood) and that complies with rules laid down in national standards RAL-GZ 724[10].	•	
CDR *(Combustíveis derivados de resíduos)*	Portugal	The term is legally adopted in the country[11],[12] to identify a solid fuel prepared from non-hazardous waste, the use of which is aimed at energy recovery in incineration or co-incineration in strict compliance with the law; the term “prepared” means processed, homogenized and improved to a quality that allows its exchange/commercialization between producers and users. Within the country, the CDR is assumed to be a solid recovered fuel (SRF).	•	
CDR *(Combustible derivato da rifiuto)*	Italy	The term is legally adopted in the country[13] to identify a waste derived fuel (indicated as normal quality) that is prepared from non-hazardous wastes to be used for energy recovery in incineration or co-incineration plants and that complies with rules laid down in a national standard.[14] Within the country, the CDR is assumed to be a solid recovered fuel (SRF) and is shipped and used as waste under the EWL code 191210.	•	
CDR-Q *(Combustibile derivato da rifiuto di elevata qualità)*	Italy	The term is legally adopted in the country[15] to identify a waste derived fuel (indicated as high quality) prepared from non-hazardous waste to be used for energy recovery in defined co-incineration plants and that complies with rules laid down in a national standard.[14] Within the country, the CDR-Q is assumed to be a solid recovered fuel (SRF) and is shipped and used as waste under the EWL code 191210.	•	

Table 1 *(continued)*

Acronym ***(extended name)***	**Country**	**Description [Ref.]**	**SRF**	**RDF**
CSR *(Combustibles solides de récupération)*	France	The term is legally adopted in the country[16] to identify a solid non-hazardous waste derived fuel that: consists of wastes which have been treated in a such way as to extract the waste stream fractions recoverable in the form of material, under the prevailing technical and economic conditions; is prepared for use in plants falling within heading 2971 of the French list of facilities classified for the purpose of environmental protection[17]; meets requirements set in a French regulatory framework in terms of characterization and thresholds, quality control and obligation to respect the waste hierarchy. Within the country, the CSR is assumed to be a solid recovered fuel (SRF).	•	
CSS *(Combustibile solido secondario)*	Italy	The term is legally adopted in the country[18] to identify a secondary fuel produced from non-hazardous wastes that complies with rules laid down in CEN standard on SRF and in the UNI/TS 11553.[19] Within the country, the CSS is assumed to be a solid recovered fuel (SRF) and is shipped and used as waste under the EWL code 191210.	•	
CSS-C *(CSS-Combustibile)*	Italy	The term is legally adopted in the country[20] to identify a secondary fuel that complies with rules (e.g. input waste streams, production process, specifications) laid down in a national decree for the declaration of end-of-waste. The term only applies within the country to a recovered fuel that is produced and shipped as a fuel product.	•	
RDF *(Refuse derived fuel)*	Germany	The term is commonly used in the country[1],[8] to identify a waste-derived solid fuel in differing coarser grain sizes, without any compliance to a standard and without a comprehensive quality assurance system.		•
RDF *(Refuse derived fuel)*	Austria	The term is legally adopted in the country[21] to identify a fuel waste: that is used entirely or to a significant extent for the purpose of energy generation and which satisfies the quality criteria laid down in this directive; that is produced through an adequate and extended pre-treatment of non-hazardous waste streams [sewage sludge, waste wood, high-calorific fractions, from mechanical-physical (MT) or mechanical-biological (MBT) treatment plants, calorific fractions of household and commercial wastes, shredder light fractions (e.g. from old vehicles and waste electrical and electronic equipment), scrap tyres, waste oil, used solvents and animal fat and bonemeal, carried out in facilities with a quality assurance system; that can be used in co-incineration plants. Within the country, the RDF is shipped and used as waste under the EWL code 191212.		•
RDF *(Refuse derived fuel)*	United Kingdom	According to the national Department for Environment, Food & Rural Affairs),[22] the term is used to define a fuel that consists of residual waste and whose utilization in EfW facilities is subject to a contract between the producer and end user. The guideline sets a minimum number of properties (in fact, all the end user's technical needs: calorific value, moisture content, form) to be specified in the contract, but without any mention of standards or reference values that define the required degree of quality for each property.		•

Table 1 *(continued)*

Acronym ***(extended name)***	**Country**	**Description [Ref.]**	**SRF**	**RDF**
RDF *(Refuse derived fuel)*	Irish Republic	According to the national Environmental Protection Agency and the Irish Trans Frontier Shipment Office (TFSO),[23] the term is used to identify a recovered fuel with a final NCV that is higher (indicatively, falling in the range 9-12 MJ/kg) than the waste stream it is produced from; as well as for the municipal waste stream itself; incineration and co-incineration plants for electricity and heat production are reported as the main final destinations of RDF. Within the country, the RDF is shipped and used as waste under the EWL code 191212.		•
RDF *(Refuse derived fuel)*	Japan	The term is legally used in the country to identify a recovered fuel produced from combustible fractions of MSW. The RDF is regulated through specific national standards.[24],[25] Due to a relatively low calorific value (e.g. NCV > 12 MJ/kg) and a high moisture and ash content, it is considered a low quality fuel, essentially intended for use in urban EfW facilities (e.g. power generation plants mainly but also district heating facilities) to satisfy the local demand for electricity and heat.		•
RDF *(Refuse derived fuel)*	South Korea	Until 2012, the term identified a type of solid fuel produced from MSW and legally regulated through the national law on solid fuels. Two classes of RDF (pelleted and non-pelleted) each one with quality requirements (limit values) set for several properties (size; NCV; moisture; ash, Cl, S, Hg, Cd, Pb, As and Cr content) were legally defined.[26] The term RDF was changed to SRF in 2013.	•	•
RDF *(Refuse derived fuel)*	Thailand	The term is used in the country[27],[28] to identify waste fuels derived from MSW and classified according to the ASTM standards.[29] Of the seven classes of RDF, a particular relevance within the country is given to RDF-5 5. This identifies a combustible waste densified (compressed) into a form of pellet, slug, cube, or briquette, mainly derived from plastic wastes (quite similar for example to the RPF produced in Japan)] but also from organic sludge that can be combusted in various existing boilers (fluidized bed combustors, gasifiers, cement and brick kilns). The RDF-5 (as well as the RDF-3 and 4) could an SRF; the ASTM class RDF 1 and RDF-2 can reasonably consider to be a generic RDF.	•	•
RDF *(Refuse derived fuel)*	India	According to Guidelines provided by national Official Boards[30],[31] the term is used in the country to identify a waste fuel derived from combustible waste fractions of solid waste, such as plastic, wood, pulp or organic waste, other than chlorinated materials, that can be used as alternative fuels in various industries (cement manufacturing plants, in particular). Norms for the production and the use of RDF in cement kilns are provided that identify three class of RDF (grade I-III) based on their compliance to reference values (such as range, maximum permissible content or mean value) set for five main properties (size; NCV; ash, moisture, Cl and S content).	•	
RDF *(Refuse derived fuel)*	USA	The term is used in the country[32],[33],[34],[35] to identify a waste fuel recovered from MSW produced according to a set of standards established by the *American Society for Testing and Materials* (ASTM).	•	•
RPF *(Refuse plastic fuel)*	South Korea	Until 2012 the term was used in the country to identify a type of solid fuel produced from plastic wastes, legally regulated through the national law for solid fuels that set quality requirements (limit values) for several properties (size; NCV; moisture; ash, Cl, S, Hg, Cd, Pb, As and Cr content).[26] The term RPF was changed to SRF in 2013.	•	•

Table 1 *(continued)*

Acronym *(extended name)*	**Country**	**Description [Ref.]**	**SRF**	**RDF**
RPF *(Refuse derived paper and plastics densified fuel)*	Japan	The term is legally used in the country to identify a pelletized recovered fuel that originates from dry and non-hazardous paper and plastic waste streams of industrial origin (residual wood, textile and rubber waste streams are also permitted) and is mainly intended as substitute fuel for the Japanese paper and steel and cement manufacturing industries.[36],[37] The RPF is regulated though a specific national standard[52]: according to limit values set for key parameters (NCV, moisture, ash and Cl content), four classes of RPF are defined, of which one (the RPF-coke class) identifies a high quality RPF with a calorific value close to that of coal.	•	•
SBS© (Substitutbrennstoff)	Germany	The term (brand mark) is commonly used in the country[1],[8],[9] to identify a solid waste-derived fuel, produced from separately collected high calorific fractions from municipal waste treatment, industrial and commercial wastes, that meets specification requirements as set by BGS e.V (BGS e.V. Quality Assurance Association for Solid Recovered Fuels andRecycled Wood*)* and that complies with rules laid down in national standards RAL-GZ 724.	•	
SCF *(Segregated combustible fractions)*	India	According to *Guidelines* provided by national Official Boards[30],[31] the term is used to identify in the country non-recyclable fractions of the MSW that contain plastics and other combustible materials (not biodegradable and that do not release toxic gases when they are burnt or dumped in the dump yards/landfills). These fractions can be directly processed in waste-to-energy plants or used in pre-processing facilities to produce a refuse derived fuel (RDF).		•
SRF *(Solid recovered fuel)*	Austria	The term is commonly used in the country[38],[39] to identify a subset of RDF: that is produced from selected or mixed non-hazardous wastes according to well defined pre-treating processes [e.g. multistage shredding, classifying, separation of Fe- and non-Fe-metals, exclusion of heavyweight inert materials, sorting out of unwanted materials such as polyvinyl chloride (PVC) or of recycling materials such as PET]; that complies with quality requirements (production, classification and specification) set in EN 15359. Within the country, the SRF is shipped and used as waste under the EWL code 191210.	•	
SRF *(Solid recovered fuel)*	Rep. of Ireland	According to the national Environmental Protection Agency and the Irish Trans Frontier Shipment Office (TFSO),[23] the term is used to identify a waste derived fuel of “good quality”; this means a fuel with a higher NVC than RDF (indicatively, from 13 to over 20 MJ/kg), that complies with quality requirements (e.g. for Cl, Hg, Cd, Tl: a reference standard is not specified by the source) suitable for use as a substitutive fuel (e.g. in the cement industry). In the country, the SRF is shipped and used as waste under the EWL code 191210.	•	
TDF *(Tyre derived fuel)*	South Korea	Until 2012 the term was used in the country to identify a type of solid fuel produced from end-of-life tyres, legally regulated through the national law for solid fuels that sets quality requirements (limit values) for several properties (size; NCV; moisture; ash, Cl, S, Hg, Cd, Pb, As and Cr content).[26] The term TDF was changed to SRF in 2013.	•	•

Table 1 *(continued)*

Acronym *(extended name)*	**Country**	**Description [Ref.]**	**SRF**	**RDF**
WCF *(Wood chip fuel)*	South Korea	Until 2012, the term was used in the country to identify a type of solid fuel produced from wood (waste wood), legally regulated through the national law for solid fuels that set quality requirements (limit values) for several properties (size; NCV; moisture; ash, Cl, S, Hg, Cd, Pb, As and Cr content).[26] The term WCF was changed to biomass-SRF in 2013.	•	•
WDF *(Waste derived fuel)*	United Kingdom	According to the Guidelines of the national Waste and Resources Action Program (WRAP),[41] the term is used to identify an unspecified waste fuel obtained by submitting the waste streams to basic processing that increases the calorific value. It can be reasonably assumed that the term 'unspecified', not defined in the Guideline, means not corresponding to quality requirements set in standards or in private commitments among producers and end users. It means that the WDF is essentially an RDF. Only if it reaches - a high market value so as to satisfy higher quality specifications, the WDF is considered to be a solid recovered fuel (SRF) according to EN 15359	•	•

5.3 Rules for the classification and specification of SRF

Rules for the classification of SRF are given in EN 15359[2] and ISO 21640.[4] ISO 21640 is developed based on the European standard EN 15359 and will replace it as ISO 21640 when it has been published.

The classification system is based on three fuel properties – the net calorific value (economic relevance), the chlorine content (technical relevance) and the mercury content (environmental relevance) – with limit values for each property. These are assigned to five classes, as Table 2 shows, which are adopted in both the standards, and compliance rules for the SRF classification are detailed. The selected properties are considered to be equally important and a combination of the class numbers makes up the class code for the SRF (e.g. SRF class code: NCV 3; Cl 2; Hg 2).

Regarding the specification of SRF, EN 15359 and ISO 21640 agree on the choice for identifying a list of relevant properties that are intended to be specified (mandatory properties) or can (voluntary properties: e.g. the producers and the users are free to agree upon which of these properties are relevant) be specified to define the quality of the fuel. The mandatory and non-mandatory properties are summarized in Table 3 and Table 4.

Table 2 — Rules for the classification of SRF according to EN 15359[2] and ISO 21640 [4]

Standard	**Fuel property**	**Unit**	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Statistic**
EN 15359	Net calorific value (NCV)	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3	mean
	Chlorine (Cl)	% in mass (d)	≤ 0,2	≤ 0,6	≤ 1,0	≤ 1,5	≤ 3	mean
	Mercury (Hg)	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 2 *(continued)*

Standard	Fuel property	Unit	Class 1	Class 2	Class 3	Class 4	Class 5	Statistic
ISO 21640	Net calorific value (NCV)	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3	mean
	Chlorine (Cl)	% in mass (d)	≤ 0,2	≤ 0,6	≤ 1,0	≤ 1,5	≤ 3	mean
	Mercury (Hg)	mg/MJ (ar)	≤ 0,02	≤ 0,03	≤ 0,05	≤ 0,10	≤ 0,15	median
		mg/MJ (ar)	≤ 0,04	≤ 0,06	≤ 0,10	≤ 0,20	≤ 0,30	80th percentile

Table 3 — Specification of SRF: list of fuel properties it is obligatory to specify according to the EN 15359 and ISO 21640 standards (adapted from[2],[4])

Standard	General	Physical properties	Chemical properties
EN 15359	Class code [a] Origin [b]	Traded form Particle size, (mm) [c] Ash content % in mass (d) [d] Moisture content % in mass (ar) [d] NCV, MJ/kg (ar), (d) [d]	Cl % in mass (d) [d] Sb, As, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Tl, V mg/kg (d)[d] Sum of heavy metals mg/kg (d) [d e]
ISO 21640	Class code [a] Origin [b]	Traded form Particle size (mm) [c] Ash content (A) % in mass (d) [d] Moisture (M) % in mass (ar) [d] NCV MJ/kg (ar), (d) [d]	Cl % in mass (d) [d] Sb, As, Cd, Cr, Co, Cu, Pb, Mn, Hg, Ni, Tl, Sn, V mg/kg (d) [d]

NOTE

(a) According to the classification system specified in the standard (EN 15359, Table 1; ISO 21640, Table 2).

(b) The origin of the input wastes utilized for the preparation of the SRF; it is specified: according to EN 15359, either by test or by the digit code as reported in the European Waste List; according to ISO 21640, either by text or by the three-digit codes listed in 7.2 (Table 3) of the standard.

(c) By sieving or equivalent techniques; it is expressed as *d*x, where *d* is the particle size on the distribution curve where x percent passes, according to CEN test methods (EN 15415-1). According to ISO 21640, the value could either be specified directly or as a P-designated value.

(d) Typical and limit values per parameter are required. According to EN 15359: the typical value is the mean value for the physical properties and the chemical, except for heavy metals and trace elements, in which case the median value is used, over an agreed or specified period of time; the limit value (minimum, maximum or 80th percentile, where the median has been used as a typical value) will be agreed upon and defined by the user and the producer and refers to a consignment. According to ISO 21640, a typical (mean value) and a limit value (minimum, maximum or 80th percentile value), in case of physical properties, a typical (median value) and a limit value (maximum or 80th percentile value), in case of chemical properties, are required.

(e) Sum of Sb, As, Cd, Cr, Co, Cu, Pb, Mn, Ni, V, according to the Waste Incineration Directive (IED).[42]

Table 4 — Specification of SRF: List of fuel properties it is not obligatory to specify according to EN 15359[2] and ISO 21640[4]

Standard	General	Physical properties	Chemical properties
EN 15359	Fuel preparation Fuel composition % in mass (d), (ar) Biomass fraction % by mass, by energy, by C content [a]	Bulk density kg/m^3 [a] Ash melting behaviour °C [a] Volatile matter content % in mass (d) [a]	C, H, N, S % in mass (d) [a] Metallic Al % in mass (d) [a] Br, F, Al, Fe, K, Na, Si, P, Ti, Mg, Ca, Mo, Zn, Ba, Be, Se, mg/kg (d) [a] PCB mg/kg (d) [a] Others [a,b]
ISO 21640	Fuel preparation Fuel composition % in mass (d), (ar) Biomass content % by mass, by energy, by C content [a] Fossil content % by mass, by energy, by C content [a]	Particle size distribution (including defining fines and coarse material) Bulk density (BD) kg/m^3 (ar) [a] Ash melting behaviour °C [a] Volatile matter content (VM) % in mass (d) [a]	Major and trace elements % in mass (d) mg/kg (d) [a,b]

NOTE

(a) Typical and limit values per parameter are reported, see Note d) in Table 3.

(b) Other chemical properties relevant for the end user and agreed with the producer.

National Standardization Bodies have also intervened over time in respect of the classification and/or the specification of waste-derived fuels and SRF, which is locally well accepted by producers and end users and assumed as a reference in administrative approval procedures. Details on national standards are provided in B.1. Like those mentioned above, the national standards also generally mediate technological, economic and environmental needs for use in EfW plants, but in some cases provisions for specific end uses are given. Different choices have been made about the number and types of key parameters and the limit values to be used for the classification and/or the specification of the recovered fuel, with or without an explicit definition of the boundaries, e.g. the origin of the waste stream, the end use of the fuel.

For example, SFS 5875[43] was introduced in the past (year 2000) in Finland to regulate the production process and the quality of SRF. According to that standard, currently replaced by EN 15359, three classes of SRF (see Table B.1), based on a compliance with limit values for seven key parameters (operational parameters, mainly: Cl, S, N, K+Na, Hg and Cd), were defined.

In Italy, first (year 2004) two classes of solid recovered fuel, a “normal” (CDR) and a “high quality” (CDR-Q), legally permitted[15] as fuel substitutes in cement kilns and thermoelectric power plants), were introduced through the national standard UNI 9903,[14] based on a fuel complying with limit values for a set of physico-chemical properties (NCV, moisture, ash, Cl and S content) and eight trace elements (see Table B.3). UNI/TS 11553[19] which was then intended to provide a reference for the specification of the waste fuel named CSS, legally identified in Italy as a secondary solid fuel.[18] With the exception of the sum of heavy metals, limit values for the chemical properties assumed as obligatory parameters in EN 15359 are defined in that standard (see Table B.4).

In Germany, a quality assurance system for solid recovered fuels has been provided since the early 2000s through the RAL-GZ 724 standard.[8],[9],[10],[44],[45],[46],[47],[48],[49] The specification of the fuel quality takes into account properties assumed as relevant with respect to the economic and technological needs of the main domestic end users (co-incineration plants with high quality needs, such as cement kilns, coal-fired power plants), other than the environmental ones. Limit values are defined (see Table B.2) for a set of trace elements that include those it is obligatory to specify according to EN 15359 and Sn. Thus a clear difference was introduced in the country between a "qualified" SRF and selectively separated portions of MSW which in any case have a calorific value higher than the original waste mixture, but are less pre-treated and not submitted to the same quality assurance system (incineration is the main destination for the latter).

In Japan,[50],[51] the standard JIS Z 7311[52] regulates an SRF, known in the country as RPF, that is mainly utilized as an alternative fuel in industrial processes, e.g. the national cement, paper and steel industries.[36] According to the standard, four classes of RPF are defined (see Table B.5), one of which (RPF coke) identifies a high quality solid recovered fuel with a calorific value close to that of coal. The classification is based on the fuel complying with limit values for the key parameters NCV, moisture, ash and Cl content only. No requirements for the Hg content in RPF occur in the standard, due to the assumption that waste streams that are Hg-free are to be utilized for its production, according to the national legislation on waste management. As data reported in Annex D show, the previously mentioned properties are the main ones recorded to assess the quality of RPF, jointly with the content of Al, as a voluntarily chosen parameter.

Some countries have legal rules (see Clause B.2) to regulate the quality of the waste fuels utilized as waste in EfW plants and largely intended to ensure adequate compliance with the main goals of safeguarding human health and environmental protection according to existing regulations[42],[53]–[67] and reference limit values for industrial emissions[68],[69].

In Austria, limit values are legally defined[21] for a set of eight trace elements (Sb, As, Pb, Cd, Cr, Co, Ni and Hg) that apply to a "generic" waste fuel utilized in cement kilns, power plants or co-incineration facilities (see Table B.6). In France, quality requirements for Hg, Cl, Br and the sum of Br, Cl, F, I (see Table B.8) are now legally set[16] for non-hazardous wastes in the form of CSR to be used in relevant EfW facilities; this means in plants that produce heat or electricity falling into a specific class of the national nomenclature of plants relating to the protection of the environment.

In Italy, two ministerial decrees[13],[15] have been introduced in the past to specify the quality of CDR and CDR-Q that identified limit values for the trace elements Pb volatile, Cr, Cu soluble, Mn, Ni, As, Cd and Hg and the EfW plants permitted to use CDR and CDR-Q (see Table B.10).

The government of South Korea[26] has addressed the matter of waste fuels from the point of view of classification, quality and grade by changing the rules previously in force (see Table B.12). Since 2013 a *Solid Refuse Fuel*, produced and traded in pellet form or otherwise, is regulated in the country and distinguished as SRF and bio(mass) SRF, based on the type of waste stream it derives from. More restrictive requirements than in the past have been introduced for such SRFs e.g. in the case of the content of Cl, Hg, Pb, Cd, As, and Cr. The documentary source does not specify whether the quality requirements legally set apply to all the existing/planned EfW plants or to a specific end use of the RDF.

In India, central authorities[30],[31] recently moved to support the co-processing of wastes (SCF, RDF, plastic wastes) in domestic industrial sectors and, first of all, in the cement manufacturing industry, assumed to be technically ready to adopt higher rates of alternative fuels. A proposal for "standardization" was made in 2018 by MoHUA,[31] based on which the waste fuels are classified as SCF and RDF (three RDF grades) according to the maximum permissible values set for the above parameters (NCV, particle size; moisture, ash, Cl and S content) that substantially refer to technological and economic needs (see Table B.9)

A mention can also be made in respect of the end-of-waste classification for the recovered fuels. It is now legally permitted in some countries, e.g. Italy[20] and Austria[21] and regulated by binding rules that refer to the origin, the production process, the end use and the fuel quality (see Table B.7 and Table B.11).

Producers and end users of SRF/RDF can also be asked to comply with further or more restrictive provisions by local authorities. Only a few examples of local authority prescriptions have been collected that exclusively refer to quality requirements set in plant permits issued to cement kilns and power plants in some European countries (see B.3). A summary discussion on specifications in such plant permits is provided in Clauses 6 and 7.

An effort to provide a reference (not mandatory) for the specification of SRF/RDF has been made by national associations of end users/producers, national bodies or studies. The derived general guidelines (see B.4) can support: the end users, in the choice of the best performing fuel according to their own technological, economic and environmental needs; the producer, in making available a quality-controlled or a certified SRF (e.g.: the "*medium quality*" and "*premium quality*" SRFs produced in Austria and Croatia; the SRF protected under the trade marks *BPG*^{R} *and SBS*^{R} in Germany) suitable for an end use in cement kilns, lime kilns and coal power plants. A summary discussion on specifications in such guidelines is provided in Clauses 6, 7 and 8.

The above-mentioned rules for the specification of SRF/RDF, do not in any case exclude the creation of "plant-specific" requirements defined in a private commitment between the producer and the end user, which can take into account further relevant parameters and provide typical/limit values for fuel properties, according to the specific needs of the end user plant. A summary discussion of the collected voluntary specifications (see B.5), is provided in Clauses 6, 7 and 8. Indicative needs for the specification of SRF/RDF can also be derived from responses given by producers, end users and other stakeholders to some of the ISO/TC 300/WG 2 online surveys promoted in 2017, as summarized in B.6.

5.4 Market for SRF and other waste-derived fuels

A brief analysis of the production, domestic use and transboundary shipment of secondary fuels in different countries emphasises that*:*

- Secondary fuels (SRF/RDF/other combustible fractions) are currently produced from different waste streams (MSW, C&IW, C&DW), in sorting (MT) and mechanical-biological treatment (MBT) plants, with different shapes (e.g. fluff, pellets, briquettes, chips, crushed).

  The origin of SRF from urban wastes seems to be prevalent in most of the countries, followed by that from selected industrial/commercial fractions, such as paper and plastic wastes. Indicatively, an average SRF yield ranging from 35 % (input stream: MSW) to 15 % (input stream: C&IW, and C&DW) can be assumed[70].

  It is noted that the residues coming from domestic and industrial/commercial activities are submitted worldwide (e.g. Europe, China and Japan) to different regulations that apply to both their classification as waste and their management. This can have a spin-off on the composition of the input streams that the MBT/MT plants are locally allowed to treat for the production of SRF/RDF and other combustible fractions.

  The reprocessing of wastes into solid fuels such as SRF can play a role in meeting the objectives of the climate, energy and waste management policies, and the expected transition towards a circular economy, as policy choices adopted for example in Europe[71] clearly underline. Regarding the role in waste management and the circular economy, the complementary assumption mentioned in 5.1 according to which wastes not suitable for re-use, preparation for re-use or for efficient material recovery are intended to be used in MT/MBT plants for their production, is relevant. It can be noted that a new area of application for SRF/RDF could in the future be their use as feedstock for thermochemical recycling processes; these are aimed at producing liquid fuels or base chemicals that can be used to produce materials such as plastics. Nowadays the commercial facilities in this area are limited, but with the right incentives these technologies could develop further and become an important market for SRF/RDF.

- Secondary fuels enter the market with different names, as Table 1 shows, and a clear identification as a standardised (SRF) or non-standardised (RDF) fuel cannot always be made.

  The relevance of standardisation for the SRF/RDF market is now well recognized. Provisions for the classification and the specification of SRF are already available in international and national standards (see Annex B) as well as (specification) in national legislation and guidelines (see Annex B). India is now actively working on the development of national standards and guidelines for the production and the end use of SRF/RDF mainly in industrial sectors, and China is moving towards an alignment of its own standards to the international ones. The efforts put into ISO standardization will most probably lead to an increased trust in SRF as a secondary fuel. This in turn might also lead to a growing demand in countries that do not have an active market today, e.g. Pakistan, Egypt, Canada, and Australia, that have recently chosen to start undertaking standardization work or are in any case interested in exploiting energy recovery from waste.

— There is a lack of statistics for the global market in secondary fuels and, in some cases, of consolidated, homogeneous and updated assessments on a country basis.

The markets analyzed largely refer to countries (European countries, Japan and the USA) that were historically the first to start exploiting the potential of SRF/RDF in their energy and manufacturing sectors.

Regarding Europe, ERFO and Cembureau[70] highlighted cement kilns and incineration plants as the biggest customers, with a total consumption of about 12 Mt/y in the year 2015, to which cement kilns contributed 40 % (about 5 Mt/y), followed by other EfW plants (e.g. power plants, gasification/pyrolysis plants, dedicated industrial combustion plants, blast furnaces and lime kilns) with a reported consumption of about 1,5 Mt/y of SRF/RDF. A different extent of both yearly production and domestic consumption of SRF/RDF in EfW plants can be observed in European countries[2],[12],[17],[45],[78-85],[107],[108],[109],[110].

In the USA,[32],[33],[34],[86-89] a total consumption of about 0.72 Mt of RDF/y can be indicatively assumed in existing RDF facilities, designed to combust the waste fuel alone or in mixture with MSW. The refuse-derived fuels and other types of substitute fuels are currently utilized in about 73 % of all the US cement plants.

In Japan,[36],[37],[50],[51],[90] low-quality secondary fuels (RDF: about 300,000 tonnes produced in the year 2015) are essentially intended for use in urban EfW facilities (e.g. power generation plants, mainly along with district heating facilities to satisfy the local demand for electricity and heat). In the same year, production of about 1,25 Mt of RPF (SRF) is reported in Japan, mainly utilized as a substitute fuel in the paper, steel and cement manufacturing industries.

Other South-East Asian countries, such as Korea, Thailand, India and China that annually manage large amounts of wastes (MSW, mainly) and need to satisfy the internal demand for energy, have more recently started to implement their EfW systems (e.g. incineration plants, gasification plants and cement kilns) as well as waste pre-treatment systems to SRF, so as to support the planned increases in domestic consumption[26-28],[91-104].

China, in particular, could become a large producer and end user of SRF as it moves into a period of intense growth in the incineration industry with a major focus on the use of FBB technology and since it is also the largest cement producer in the world.

In India MSW-RDF is considered to be one of the most promising alternative fuels for the national cement industry, with an estimated potential availability for co-processing of about 1,37 Mt/y of MSW-RDF. The waste management policies adopted in Korea include a comprehensive plan for waste-to-energy, with an expected increase to 3,8 Mt in 2020 (1,8 Mt in 2013) of combustible fractions (e.g. paper, plastics and wood) of municipal/industrial wastes transformed into SRF, to be combusted or converted to energy in boilers and cogeneration plants.

In Thailand, various new RDF facilities, MSW/RDF-incineration plants and RDF gasification plants are planned or under construction in the country; a potential yearly production of 2,46 Mt of RDF is estimated, even while the expected increase to around 40 % of fossil fuel substitution in the cement industry could mean a need for around 2,7 Mt/y of RDF.

On the whole, incineration with recovery of electricity and thermal energy seems to be a typical end use of SRF/RDF in most countries and developments are taking place locally in the power and district heating sector. Over time, energy-intensive industrial sectors, such as the cement manufacturing industry and coal fired power plants in the energy sector, have become large consumers of SRF as a substitute fuel to reduce the need for fossil fuels and achieve benefits (plant environmental performance, e.g. reduction of GHG emissions).

The use as a fuel substitute in the steel/iron, pulp/paper, glass and chemical industries seems to be as yet unexplored in most countries. Industrial co-incineration plants are also exploiting the potential of SRF to satisfy their heat/electricity demand or (in some European countries, for example) to benefit economically from placing electricity on the national grid. Advanced conversion technologies, such as SRF/RDF gasification pyrolysis, are being explored e.g. in the UK, France, Norway, Japan, Korea, and Thailand.

— Active transboundary shipments of SRF/RDF can be observed in Europe, but also in South-East Asia, where the production of SRF/RDF is a way of tackling the management of very large volumes of urban wastes produced annually. India and China now seem to play a relevant role as recipient countries[90] and look with increasing interest to secondary fuels as a suitable feedstock to support the needs and the planned development of their national EfW systems (incineration and co-incineration plants).

As regards trade within Europe, an analysis performed by the Chartered Institution of Wastes Management (CIWM)[105] shows that the United Kingdom leads the export of SRF/RDF with 60 % of the total of 5,9 Mt exported by the European countries in 2016. 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. The Netherlands, Sweden and Germany top the list of importing countries. A scenario analysis carried out with the aim of forecasting the residual waste supply, (i.e. waste generation and waste recycling performance) and the internal demand (e.g. the capacity of operational and planned/proposed facilities) by 2030, resulted in a potential long term decrease of exports from both the UK and Ireland. It has also been evaluated[106] that the greatest treatment capacity surplus (1,3 Mt) could occur in future years in countries such as the Netherlands, Germany, Sweden, and Denmark, even if different factors (e.g. new national policies and legislation on waste, creation of new EfW capacity, decommissioning of existing EfW facilities and an increase in waste recycling) might have a significant upward or downward influence on the real capacity gap in these countries.

Different factors with an upward or downward trend exist locally that are able to determine a capacity gap for SRF/RDF. These include an internal supply (e.g. waste generation, waste management policies and waste recycling performance; strong local bureaucracy; public acceptance; treatment capacity of the local MT/MBT system) that is higher/lower than the internal demand (e.g. the number and treatment capacity of EfW facilities; strong local bureaucracy; public acceptance; low availability of end-user plants equipped with technologies that allow the use of SRF as feedstock).

Gasification of solid recovered fuel and the co-incineration of the syngas in a combustion plant to replace fossil fuels in the production of electricity and heat, co-incineration in the cement and lime manufacturing industry and incineration in dedicated facilities have been recently underlined as the most energy-efficient waste-to-energy techniques[71].

6 Coal co-combustion in the cement manufacturing industry

6.1 General

A brief description of the production process and the main technologies in the cement manufacturing industry is provided in C.1.

Mandatory requirements for the use of SRF/RDF and other waste fuels in cement kilns have been introduced in some national legislations, such as in Austria (see, Tables B.6 and B.7), India (see Table B.9), Italy (see Tables B.10 and B.11).

Some national standards give limit values for fuel properties to regulate the use of SRF/RDF or other waste fuels as suitable feedstock in cement kilns. Data reported in Annex B mainly refer to: the SRF specified, in Italy, CDR-Q and CSS and regulated according to UNI 9903:1 and UNI/TS 11553 (seeTable B.3 and Table B.4); the SRF that in Germany complies with RAL-GZ 724 (see Table B.2); and the solid recovered fuel known as RPF in Japan (see Table B.5).

With respect to the environmental performance, cement kilns comply with emission limits legally set for polluting substances. As an example, common legal rules have been introduced in Europe with the *Industrial Emissions Directive*[42] that give, in particular, specific provisions for trace elements (Hg, Cd+Tl, sum of As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V; dioxins and furans). Some European countries have already transposed these common rules into their own legislation, even if different and/or more restrictive provisions may be required e.g. by local authorities in plant permits. In Japan,[57] no emission limits for Hg are set in the *Air Pollution Control Act*[58]; furthermore, following the *Minamata Convention*,[61] an amendment of the Act was approved in the country (in force by the end of 2015) to limit mercury emissions[59] and special measures have also been legally introduced for dioxins.[59],[60] In China,[64] the standard GB 30485:2013 was issued to regulate the matter of air pollutants in the case of solid waste co-processing in cement kilns. Limit values for heavy metals and dioxins are defined in that standard. In India, new regulations and emission limits, (heavy metals, dioxins and furans) substantially aligned with the European IED Directive, were legally introduced in 2016 by the Central Government[30] for MSW and RDF co-processing in cement kilns. The matter of toxic air pollutants is regulated in the USA under the *Clean Air Act* and in the EPA CISWI standards[65],[66],[67]; the latter define specific limit values for the emission of Pb, Cd, Hg, dioxins and furans – from kilns that burn non-hazardous wastes; these emission limits do not apply in the case of cement kilns that burn tyres, used oil, biomass, and wood waste as these fuel feedstocks do not fall within the definition of “non-hazardous solid wastes”.

6.2 End use requirements of SRF and other waste derived fuels

6.2.1 Technical limitation of the technologies

The ongoing switch of cement kilns from conventional to alternative waste fuels, to a low extent on a global level but locally, e.g. in different European countries, at a very high level, includes the use of different kind of wastes, both totally biogenic (e.g. waste wood and sawdust) and partially so in nature, such as: discarded or shredded tyres; waste oils and solvents; sludge from water and wastewater treatment plants; pre-processed or raw industrial waste, including lime sludge from paper and similar industries; non-recyclable plastics, textiles and paper residues; fuels recovered from municipal solid waste such as SRF and RDF.

That switch presents different technical challenges, e.g. availability of a fuel with an adequate calorific value, selection of the right feeding point, poor heat distribution, unstable pre-calciner operations, blockages in the pre-heater cyclones, build-ups in the riser ducts and the formation of rings in kilns. But there are also some environmental challenges with regard to the emission of SO_2, NO_x, CO and of some heavy metals that can be affected not only by the composition of the raw meal (the natural or alternative raw materials utilized for the production of the cement clinker) but also of the combusted fuels. The raw material/fuel mass ratio for clinker production is approximately 10:1[68],[72],[107].

The volume, the origin and the properties of wastes are considered so to obtain appropriate quality assurance and compliance with plant requirements legally set or additional specifications from the end user that generally mainly refer, other than to the NCV, to the fuel particle size, the chlorine, sulfur, ash, water and biogenic carbon content as well as that of heavy metals (As, Sb, Pb, Cd, Cr, Co, Cu, Zn, Ni, Hg, Tl, V, Sn, Mn)[108],[109].

Cement kilns could utilize up to 100 % of alternative fuels. In practice, the calorific value of the waste fuel may be a limiting factor. For firing the main burn of the cement kiln, an average calorific value of at least 20 to 22 GJ/t is generally required; the pre-calciner section of the kiln system (up to 60 % of the fuel input) that works at a lower temperature, may be fed with low calorific value waste fuels. Different solid alternative fuels can offer a calorific value significantly lower than that of conventional fuels (coal, petroleum coke (pet-coke)). In the case of RDF/SRF, the NCV is not as high as in conventional fuel, generally around 20-25 MJ/Kg or lower. For example, NCV values in the range 12-18 MJ/kg and in the range 18-25 MJ/kg are reported[73] for what are called “SRF of medium quality” and “SRF of high quality”, respectively, produced in Austria and utilized in secondary firing systems of cement kilns and/or in special pre-combustion chambers for the former and in the primary firing systems of cement kilns for the latter.

Well-established technology allows the cement kilns to be fired with low-volatile fuels such as pet-coke, low-volatile bituminous coal, and anthracite, without problems. High volatile-low calorific value alternative fuels are used more in the pre-calciner firing (unless the NCV is about or >16,8 MJ/kg). The use of low-volatile fuels in a pre-calciner has required operational modifications of the pre-calciner, or specially designed pre-calciners[107].

The choice of *feeding point* is also relevant for cement kilns. It is selected according to the physical, chemical, and toxicological characteristics of the waste fuel. If containing stable toxic components, the waste fuels are fed to the main burner to ensure complete combustion due to the high temperature and the long retention time. Alternative fuels are always fed into the high-temperature combustion zones of the main kiln system[110]. Wastes, which are fed through the main burner, will be decomposed in the primary burning zone, at high temperatures of up to 2,000 °C. Multi-channel burners are designed for the use of different types of fuels including waste fuels. When fed to a secondary burner, pre-heater or pre-calciner, they are burned at lower temperatures, which is not always enough to decompose halogenated organic substances. Wastes containing volatile metals (mercury, cadmium, thallium) or volatile organic compounds can result in an increase in the emissions of mercury, cadmium, thallium or organic emissions (e.g. VOCs) when improperly used[68].

The lump size of the waste fuel also will be considered[38],[111]. Solid residues of municipal or commercial/industrial origin, or their high calorific fractions, are pre-processed and comminuted into finer particles of adequate size, according to the selected feeding point in the kiln system (Figure 3). A low particle size (d95 < 30 mm) is normally required when the feeding point is at the main burner; this can be increased up to < 80 mm when the wastes are utilized in a secondary firing point (calciner) and to < 250 mm in special pre-combustor chambers. The Step-Combustor mentioned in the figure refers to a combustion chamber (e.g. the Hotdisc solution) specifically developed to handle high feed rates of low calorific and large-sized alternative fuels for which a typical retention time of the suspension flow calciner can be quite insufficient (it can allow the retention time to be increased to up to 15 minutes).

Figure 3 — Waste treatment and objectives with respect to the requirements of the burning process (adapted from[111])

The scheme reported in Figure 4 highlights the relationship between the particle size and the calorific value of SRF, its suitability as an alternative fuel in cement kilns and the specific manner of use in the kiln system (feeding point). It refers to three types of SRF – low, medium and premium quality – currently produced in Austria (and in other European countries), of which the last two are a suitable and typical fuel feedstock for the local cement kilns.

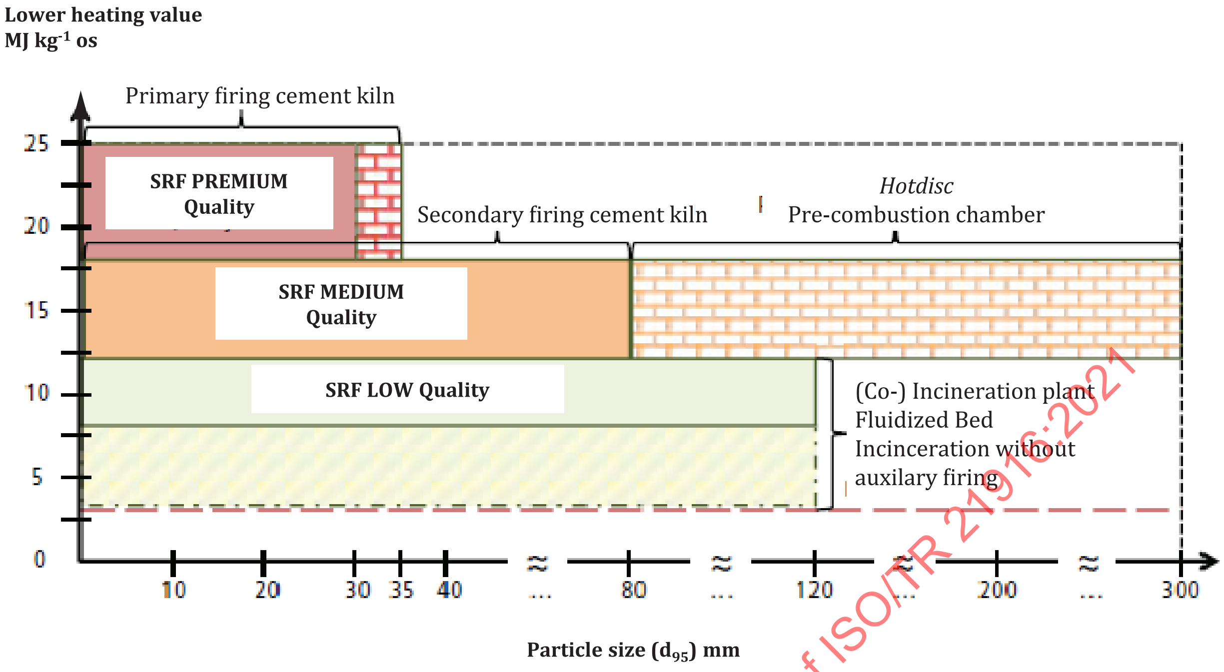


Figure 4 — Relationship between SRF particle size and lower heating value with regard to the energy recovery options (adapted from[38])

In cement manufacturing, constituents of the feedstock will be avoided that, even in small amounts (<1 %), may have adverse effects upon the performance of the product and/or the production process.

High levels of alkalis in cement can give rise to cracking in concretes and mortars and high levels of alkali sulfates in cements can affect their reactivity. From the point of view of kiln operation, it is better for alkalis (and sulfates) to be discharged from the system with the clinker, to avoid disruptive effects especially in kiln systems with highly efficient heat exchangers such as cyclones[107]. Sulfur levels in substitute fuels are generally lower than in conventional fossil fuels (0,1–0,2 % in RDF, 3–5 % in fossil fuels): negative effects of precipitation or clogging can be excluded, although issues of alkali sequestration and transfer in the clinker will be verified[112]. A sulfur content lower than 2,5 % is reported as a reference for the use of alternative fuels in the cement industry[113].

If chloride is introduced into the kiln system, either through the raw meal or the alternative fuel, sulfate–spurrite, stable within the temperature range 900–1,200 °C, can be formed, which is involved in the formation of rings in cement kilns. The requirement is to keep the chloride content low (as a reference, below 0,02 %) to avoid the formation of kiln rings and preheater deposits.[107] Fuels containing high levels of Cl (>0,7 %) can have an adverse effect on the performance of some types of electrostatic precipitators in wet process kilns. Clogging can occur in the cyclone pre-warmer, if the chlorine content of the fuel is higher than 0,2–0,5 percent[107]. Alternative waste fuels, such those enriched with polyvinylchloride (PVC) and chlorinated hydrocarbons, sewage sludge, meat and bone meal, can increase the amount of chlorine introduced into the kiln system[107]. A Cl content lower than 0,2 % is reported as a reference level for the use of alternative fuels in the cement industry[113].

The Cl content is less than 0,1 % in coke and, on average, around 0,3–0,5 % in RDF[112]. Chlorine content is also known to affect the quality of the final product: standards for Portland cements generally limit the amount of chloride to 0,10 % in the raw meal feedstock[107].

Problems can be created by high levels of circulating alkalis, chlorides and sulfur coming from the raw meal and/or the fuel, which can lead to build-ups in cyclones, blockages and stoppages of the kilns, due to the internal circulation between the kiln and the pre-heater that works as an enrichment cycle.

The use of a kiln gas bypass has been widely introduced to solve that problem and allow continuous kiln operation; typical bypass rates are of up to 15 % for a chlorine bypass and up to 70 % for a sulfur bypass[68].

The content of trace elements in alternative waste fuels can be quite different from that of conventional fossil fuels. In cement kilns, as well as in lime kilns, most of the heavy metals introduced with raw materials and fuels are trapped in the clinker (and the cement), with the main exception of volatile elements such as Hg and Tl that are relevant factors for air emission control in kiln systems.

Emission factors that give an indicative reference on the performance of modern dry kiln systems (rotary kiln systems with cyclone preheaters), equipped with the best available techniques for the abatement of inorganic and organic pollutants, are available[72] for the German cement industry, where widespread use of well upgraded kiln technologies and very high substitution rates (>60 %, on average) has been already reached, with extensive use of SRF, quantitatively the main component of the mix of alternative fuels. Low levels, below the legal requirements, have been observed in air emissions of some trace elements (e.g. As, Co, Sn, Be, Se, Tl, Zn), with most of the measured values above the detection limit. Very low or, sometimes, undetectable concentrations of dioxins and furans and of polychlorinated biphenyls (PCB), have been measured in the exhaust gas from German rotary kilns. The rotary kiln systems seem to ensure the virtually complete destruction of such organic pollutants.

An assessment of metal emissions[114] was recently carried out based on data from some Italian cement kilns fired with pet-coke and SRF, alone or in mixture with other alternative fuels such as meat and bone meal, plastics, waste oil, sewage sludge and end of life tyres. No substantial changes in the air emissions of trace pollutants (metals, dioxins and furans) were observed by enhancing the substitution rates, both when the kiln technology and the kind of alternative fuels are considered. When evaluated with respect to the kiln technology, better performance in term of both the total metal content in the flue gas and, particularly, of volatile (Hg, Tl) and semi-volatile (Cd) metals, has been observed in the case of pre-heater/calciner dry kilns.

It is noted that, for the control of air emissions of inorganic and organic pollutants, some innovative technologies have been developed and are locally applied such as the *Ex-mercury split preheater system* to reduce emissions of Hg, a typical volatile trace element, the *CTP-off-gas treatment system* for the reduction of both organic (CO, TOC, PCDD/F, odour) and inorganic (NO_X) emissions.

Transfer factors are commonly used to define the proportion of a metal occurring in the feedstock that is emitted in flue gases and can be a useful tool for managing the kiln feedstock. In the case of waste co-incineration in cement kilns, transfer factors for trace elements,[112] and specifically for Pb, Cd, Hg,[115] are reported, the latter calculated by modelling the clinker production process based on data from individual plants (e.g. some grate-type pre-heater and cyclone pre-heater plants). These calculations were based on some assumptions: trace elements, introduced by raw materials and fuels have the same incorporation rate in the electrostatic precipitator and the heat exchanger/rotary kiln of the plants; with respect to trace elements added by raw materials, those coming from the fuel feedstock have a much lower probability of entering the air emissions (high resistance in the heat exchanger/rotary kiln system). Transfer factors specifically related to SRF are reported in CEN/TR 15508[116] as derived from the operational data of wet and dry cement kilns (Belgium; Germany). According to these TFs, maximum possible concentrations in SRF have been proposed in the document, as orientation values (see Table B.16).

Regarding the impact of alternative fuels and SRF on the quality of the end product,[114],[115] metals in the cement produced are reported as being substantially due to the input coming from raw materials. The impact on their level in cement is reported as not being statistically significant. Only in the case of Zn, mainly introduced into the process through SRF and end-of-life tyres (ELT), an effectively higher content in the final product was observed when the share of fuel substitution was increased. These conclusions seem to agree with measured values published by the German Cement Works Association (VDZ) for some Portland cements.[117] With respect to Hg, the concentration in the main product, intermediate products (clinker) and by-products (bypass dust; filter dust) were analysed in a German study published in 2018.[118] A low level of heavy metals was observed in the produced cement, with a median value of 0,019 mg/kg d, (range: 0,005 to 0,200), for CEM I; 0,030 mg/kg d (range: 0,006 to 0,220), for CEM II; 0,010 mg/kg d (range 0,001 to < 0,060), for CEM III. The observed median value of Hg in clinker was of 0,005 mg/kg d (range: 0,001 to < 0,100). As for by-products, a median value of 0,012 mg/kg d (range: 0,002 to 1,100) is reported in the case of bypass dust, while the filter dust shows a higher level of Hg, with a median value of 1,785 mg/kg d (range: < 0,010 to 16).

6.2.2 Quality requirements in plant permits

Some examples of plant permits are provided in Annex B, which define the permitted content of trace elements in fuel feedstocks utilized in the European cement manufacturing industry. Limit values for a different alternative fuels (see Table B.15), a generic waste derived fuel (see Tables B.14 and B.15) or specifically for an SRF produced from high calorific fractions of MSW (see Table B.13), are defined.

With respect to SRF, the reported examples include requirements issued in Germany to cement kilns (and coal-power plants), according to rules established by the Environmental Ministry of North Rhine Westphalia and subsequently introduced in the country by other Länder[68],[110].

The chosen trace elements (see Table B.13) show a good alignment with requirements for SRF already established by the national RAL GZ 724 standard (see Table B.2). If compared with specifications set in the EN 15359 standard and today in the ISO 21640 standard (see Table 3), all the obligatory chemical properties are included, with the addition of Sn and Zn.

Limit values for trace elements are defined by mass, as both practical (typical value: to be compared with the 50th percentile value of one month) and maximum permitted value (to be compared with the 80th and 90th percentile value of one month). The reported "practical" values substantially coincide with limits (median value) set in RAL GZ 724: 2008 1), except for a lower value being required in the case of Co.

6.2.3 Quality requirements in general guidelines

General provisions are outlined by national guidelines, some examples of which are given in Annex B. Aimed at supporting and driving the end use of waste fuels, these guidelines do not always uniquely refer to SRF or to a specific type of waste recovered fuel.

Desirable values for physico-chemical properties of RDF, co-processed in cement kilns and in other industrial activities, are defined in a guideline provided in India[30],[31] by the national Ministry of Housing and Urban Affairs of India and by the Central Public Health and Environmental Engineering Organisation (see Table B.19). In summary, RDF are assumed to be suitable with:

- Size (mm) falling in the range < 70-120;
- Chlorine content (%in mass ar) <0,7;
- Moisture content (%in mass ar) <20;
- NCV (MJ/kg ar) >12,6.

The guideline of the Swiss Federal Department for the Environment, Forests and Landscape (BUWAL) provides limit values for trace elements in a "generic" waste fuel utilized in cement kilns (see Table B.18). The list of chemicals covers all the obligatory properties now required by the existing standards for SRF (see EN 15359 and ISO 21640) and Sn, for which the limit values are detailed in Table B.18. In particular, the guideline provides a requirement for a fuel not exceeding a mean value by energy, of:

- Hg (mg/MJ d) 0,02;
- Tl (mg/MJ d) 0,12;
- Cd (mg/MJ d) 0,08.

---

1) The RAL GZ 724:2008 has been replaced by RAL GZ 274:2012, which defines the quality requirements in relation to energy

Valuable orientation values for trace elements in SRF have been proposed in CEN/TR 15508,[116] as maximum possible concentrations in the case of the use of SRF in wet and dry kiln processes (see Table B.16). The following limit values (by energy) are defined in CEN/TR 15508:

- Hg (mg/MJ ar) 0,17 (wet kiln) – 0,082 to 0,33 (dry kiln);
- Sum of Cd and Tl (mg/MJ ar) 6,9 (both kilns);
- Sum of As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V (mg/MJ ar) 1,650 (both kilns).

Fuel specifications that have been defined in Germany to approve a solid recovered fuel, (the BPG ^{R} 2 and the SBS ^{R} 2 in Table B.20) suitable for an end use in cement kilns, could be considered as further general guidance.

For the physico-chemical properties of traded SRFs (BPG® 2 and SBS® 2) the following reference values are assumed:

- NCV (MJ/kg ar) in the range 18 -24;
- Chlorine (% in mass d) <1,0;
- Ash content (mg/kg d) in the range < 15 - < 20.

Limit values by mass (BPG®) are detailed for all the trace elements assumed as relevant in CEN/TR 15508 (see Table B.20). If assessed by energy, the following indicative limit values on a dry basis can be derived:

- Hg (mg/MJ d) < 0,03 to < 0,04;
- Sum of Cd and Tl (mg/MJ d) < 0,27 to < 0,39;
- Sum of heavy metals as previously (mg/MJ d) < 30 to < 82.

The set of chemical properties includes other trace elements (Se, Sn, Be, Te) whose limit values by mass are detailed in Table B.20.

6.2.4 Quality requirements in voluntary end user specifications

A valuable statistical assessment of statements in private agreements among European producers and end users, (Belgium, Germany and France), was provided in CEN/TR 15508. Properties that are relevant for the classification of SRF, (NCV and chlorine), are considered in that document (see Table B.24), for which the reported mean/maximum values fall in the range:

- NCV (MJ/kg ar) 5/10 to 12/22 (mean);
- Chlorine (wt% ar) 0,5 to 1 (mean) – 1 to 3 (maximum).

The requirement for Cl depends on the composition of the input stream. At high substitution rates, a maximum limit of around 3 % is highlighted in cement kilns equipped with a salt bypass system and in the range 0,5 %-1 % without that system. In the case of a wet process cement kiln, a maximum limit of 6 % is reported.

The same geographical origin characterizes further references to voluntary requirements given in Annex B, such as local specifications derived from literature or provided by personal communications of producers/end users (see Tables B.26 to B.29) and the profile of properties relevant for the fuel specification (see Table B.35) made available by the ISO survey among producers.

By taking the classification and specification system in the EN 15359 standard as a general reference, these data highlight a requirement for an SRF:

— NCV classed from 1 to 3, (more frequently classed as 1-2), based on the ISO survey.

  Requirements in local voluntary specifications (see Annex B) show values < 15-16 (MJ/kg ar);

— Chlorine classed from 2 to 4 (more frequently classed as 2-3), based on the ISO survey.

  Limit values < 1-1,5 (% in mass d) occur in local voluntary specifications (see Annex B);

— Hg classed as 1, based on the ISO survey.

  Maximum allowable concentrations in the range 1 – 1,7 (mg/kg d) can be found in local voluntary specifications (see Annex B).

The moisture and ash content of SRF are generally identified as relevant physico-chemical properties. Other than NCV, Cl and, to some extent, Hg, these are the only two parameters that seem to be the properties of main interest in the case of the solid recovered fuel RPF produced and utilized in Japan, as borne out by both the ISO survey and the statistical assessment of measured values (D.2). The local voluntary specifications in Annex B set maximum levels that fall in the range:

— Moisture (% in mass ar)	< 25 – 30;
— Ash content (% in mass d)	< 15 – 30.

General agreement with the set of obligatory chemical properties defined in the EN 15359 standard can be observed in the case of responses to the ISO survey and in the local voluntary specifications reported in Annex B. The former includes Sn as an additional parameter for the fuel specification. Some of the latter set specifications for further chemical properties (e.g. Zn, Be, Ba, Se, Te).

All the voluntary specifications in Annex B provide limit values by mass. The following indicative limit values by energy can be derived for SRF:

— Hg (mg/MJ d)	< 0,044 to < 0,068;
— Sum of Cd and Tl (mg/MJ d)	< 0,497 to < 1,10;
— Sum of heavy metals (as previously) (mg/MJ d)	< 61 to < 73.

6.3 Typical values for SRF

A valuable statistical assessment of typical values for SRF combusted in cement kilns was produced for the purposes of CEN/TR 15508, based on measured values from national sets of data from several European countries. Typical values for properties that are relevant for the classification of SRF (NCV, Cl, Hg and the sum of Cd and Tl) are given as a general reference (see Table D.1) and specifically for SRF with a low or high ash content (see Table D.2), as secondary fuels may take part in the substitution of raw materials in the cement industry and the ash composition is intended to meet the requirements dealing with the quality of the product.

The median values provided by energy, generally fall into the range:

— NCV (MJ/kg ar)	3,2 – 25,5;
— Chlorine (% in mass ar)	0.07 -1,7;
— Hg (mg/MJ ar)	< 0,02 – 0,406;
— Sum of Cd and Tl (mg/MJ ar)	< 0,12 - < 0,93.

Based on the ash content of the fuel, the derived range of medians are as follows:

- in the case of low-ash fuels
  - NCV (MJ/kg ar) 11,7 – 25,5;
  - Chlorine (% in mass ar) 0,04 - 1,7;
  - Hg (mg/MJ ar) 0,004 – 0,042;
  - Sum of Cd and Tl (mg/MJ ar) 0,008 – 0,121;
- in the case of high-ash fuels
  - NCV (MJ/kg ar) 3,2 – 10,0;
  - Chlorine (% in mass ar) 0,07 – 0,77;
  - Hg (mg/MJ ar) < 0,05 – 0,406;
  - sum of Cd and Tl (mg/MJ ar) 0,26 - < 0,93.

Reference ranges of average values for physico-chemical and trace elements measured locally are provided in Annex D, some of which (see Tables D.3 to D.5) also give a comparative view of values occurring in the hard coal or the pet-coke utilized in European cement kilns.

For the purposes of this document, a search for measured values for SRF utilized in cement kilns was carried out. The derived dataset covers quite many physico-chemical and chemical properties that characterize solid recovered fuels utilized in the cement industry of different European countries and Japan. The collected measured values characterize European SRF (a total of 74 assays) produced mainly from MSW (70 %) and from mixed waste streams, while all the analysed data for RPF (a total of 166 assays) refer to a solid recovered fuel that originates from industrial and commercial waste (ICW) streams only, essentially plastic and paper wastes, and with an end use in cement kilns and other co-incineration industrial facilities (paper and steel industry).

The monitored physico-chemical parameters show a generally good compliance with requirements for the fuel classification and specification in existing standards.

About 98 % of the assays provide a characterization of the ash content in SRF, a parameter monitored by all the assays in the case of the RPF.

Differences occur in the fuel specification for trace elements, especially for mercury (see Annex D, Figure D.1 and D.2). That heavy metal falls within the parameters required for the fuel classification according to EN 15359, while in the case of the RPF it is not a required parameter (only two of the collected assays really provide a measured value). Data provided by the Japanese producers of RPF show that the aluminium content of the fuel is assumed to be a relevant property for its end users.

Summary statistics (median and 80th percentile values) have been produced by processing the whole dataset of measured values (see Table D.15) and, individually, the subsets within it that specifically refer to a European SRF (see Table D.17) or to the Japanese RPF (see Table D.16). Moreover, measured values for SRF have been selected according to the fuel origin (MSW, ICW streams) and statistically processed (see Tables D.18 and D.19). The lack of sufficient information in the dataset about the end-user plant (technology and feeding point) did not allow for a statistical analysis of measured values based on that criterion. Further details of the main statistical outcomes per fuel property are provided in Annex D (Tables D.20 to D.21-a, b).

In summary, according to the available data sets of Annex D, the following typical values can be derived for SRF produced and utilized in the European cement industry (median value):

— NCV (MJ/kg ar - MJ/kg d)	18,3 – 21,7;
— Ash (% in mass d)	15,1;
— Chlorine (% in mass ar)	0,58;
— Hg (mg/kg d - mg/MJ d – mg/MJ ar)	0,268 – 0,014 – 0,023;
— Cd (mg/kg d - mg/MJ d – mg/MJ ar)	0,750 – 0,031 – 0,057;
— Tl (mg/kg d - mg/MJ d – mg/MJ ar)	0,217 – 0,010 – 0,020.

Futher informations are available in Annex D.

Depending on the origin of the European SRF, the following references for typical values have been obtained:

- in the case of MSW-SRF

— NCV (MJ/kg ar - MJ/kg d)	16,6 – 21,2;
— Ash (% in mass d)	17,1;
— Chlorine (% in mass ar)	1,27;
— Hg (mg/kg d - mg/MJ d – mg/MJ ar)	0,723 – 0,036 – 0,050;
— Cd (mg/kg d - mg/MJ d – mg/MJ ar)	1,060 – 0,050 – 0,078;
— Tl (mg/kg d - mg/MJ d – mg/MJ ar)	0,215 – 0,010 – 0,019;

- in the case of mixed-SRF

— NCV (MJ/kg ar - MJ/kg d)	21,4 – 23,7;
— Ash (% in mass d)	14,0;
— Chlorine (% in mass ar)	0,53;
— Hg (mg/kg d - mg/MJ d – mg/MJ ar)	0,200 – 0,009 – 0,010;
— Cd (mg/kg d - mg/MJ d – mg/MJ ar)	0,180 – 0,007 – 0,008.

Regarding the solid recovered fuel RPF, the measured values made available by Japanese producers provided the following references for typical values:

— NCV (MJ/kg ar - MJ/kg d)	26,6 – 23,1;
— Ash (% in mass d)	5,1;
— Chlorine (% in mass ar)	0,13;
— Al (mg/kg d - mg/MJ d– mg/MJ ar)	1 600 – 61,4 – 63,8.

7 Coal co-combustion in power plants

7.1 General

A brief description of the main technologies adopted in coal combustion power plants is given in C.2.

Mandatory requirements for the use of SRF/RDF and other waste fuels in coal combustion power plants have been introduced in some national legislation. In Austria for example, (see Table B.6), limit values for trace elements legally apply to boilers employing predominantly hard coal or lignite and used for the generation of electricity and district heating. The Austrian legislation also limits the proportion of thermal output from the incineration of waste relative to the total thermal output to a maximum of 15 %. Mandatory requirements have also been legally set in Italy that apply to the use in well-defined power plants of the SRF referred to in the country as CDR-Q and CSS end-of waste (see Tables B.10 and B.11).

Some national standards provide specifications for solid recovered fuels that apply to their use in coal co-combustion power plants. This happens for example in the case of: the CDR-Q (see Table B.3) and the CSS (see Table B.4) produced in Italy according to UNI 9903-01 and UNI/TS 11553; the SRFs that comply in Germany with the RAL-GZ 724 standard (see Table B.2) and, as already discussed, are largely produced and traded under the brand mark SBS^{R} 1 and SBS^{R} 2 for co-combustion with lignite in the former and with hard coal in the latter.

Regarding the environmental performance, coal co-combustion power plants should comply with emission limits legally set for polluting substances. As an example, common legal rules have been introduced in Europe through the *Industrial Emissions Directive*[42] that gives, in particular, specific provisions for the emission of trace elements (Hg, Cd+Tl, sum of As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V; dioxins and furans) in such large combustion plants. Common rules have already been transposed by some European countries in their own legislation, even if different and/or more restrictive provisions may be required e.g. by local authorities in plant permits. In the USA, a federal law, the *Clean Air Act* , and the EPA CISWI standards[65],[66],[67] regulate the emission of toxic air pollutants (Pb, Cd, Hg, dioxins, furans) from energy recovery units combusting solid waste or designed to burn solid (coal, biomass, waste)/liquid (waste)/gas.

7.2 End use requirements for SRF and other waste derived fuels

7.2.1 Technical limitations of the technologies

Wastes generally contribute to the fuel feedstock of coal co-combustion power plants at a rate lower than 10 % on a thermal basis; higher rates are usually associated with fluidized bed boilers or the co-incineration of separately pulverized wood waste in pulverized coal-fired boilers.[69] The substitution of conventional fuels with solid recovered fuels depends on the compatibility of properties of the RDF/SRF with the thermal recovery process, typically designed for fossil fuels.

Requirements can vary according to the plant design and the type of coal but are generally higher than alternative options for RDF/SRF thermal recovery, e.g. their incineration especially in grate boilers.

The easiest way to introduce waste into the combustion process is by mixing it with the main fuel and burning it in the combustion chamber or boiler. This may lead to technical and/or environmental constraints in the combustion plant related to the milling and drying capacity of existing solid fuel mills (if the waste is dried and pulverized together with the main fuel) and to the feeding of the waste. In a solid-fuel-fired boiler, fuel/waste mixing is possible in the following locations: on the fuel conveyor belt; in the fuel bunker; in the fuel feeder; at the fuel mill; on the pulverized fuel lines. In the first three cases, the waste is spread over the main solid fuel to achieve adequate mixing of the fuel/waste streams. This results in grinding of the waste together with the main fuel in the coal mill. Due to grinding behaviour constraints, this technique is usually only associated with dried sludge. It is only possible to apply this technique when the grinding behaviour of both fuel and waste are more or less the same or when the amount of waste is very small compared with the main fuel flow.

Wastes that are shredded separately from the main fuel can be injected into the fuel mill or into the pulverized coal pipelines between the coal mill and the boiler. Liquid wastes are typically blended with liquid fuels before the mix is used. Separate lances or modified existing burners (separate feeding of the waste to the burners) are required to handle waste that cannot or is not intended to be mixed with the main fuel or to increase the percentage of waste. This occurs when the waste has different physical properties (e.g. viscosity, particle size) or may cause health risks (sewage sludge).

The burners are specially designed for the fuel/waste in order to achieve good ignition, a stable flame, and good mixing with the main fuel flame in the boiler. The location of these burners in relation to the main burners is important for good burnout of the fuel.

General references for some properties of interest from a technical and environmental point of view, when SRF is co-combusted in power plants with different boiler technologies, are summarized in Table 5[119].

In *pulverized coal combustion plants* (DBB and WBB), the raw coal and other solid fuels utilized as feedstock are properly prepared to ensure optimal performance of the process and pulverized (or the liquid fuels atomized) before combustion.

Solid fuels are dried to reduce the moisture content, where high; that step is typically required in the case of a sewage sludge with moisture contents exceeding 50 %. The waste fuels are also grounded (lignite particles are typically reduced to less than 90 µm, for example). Fine grinding ensures rapid ignition and complete combustion to achieve maximum efficiency and minimize ash and particulate deposits on heat-exchanger surfaces. Waste milling to less than 75 µm is typically required in pulverized fuel-fired boilers[69].

Pulverized hard coal-fired plants with wet-bottom boiler types (WBB) are considered more tolerant to the shape and dimensions of SRF, in comparison to plants with dry-bottom boilers (DBB)[119].

Table 5 — Reference data for the quality of SRF utilized in coal fired power plants and in other fluidized bed combustion plants [data from[119]]

Parameter (Unit)	Pulverized coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FBC
Form	Soft pellets Hard pellets			Soft pellets	Fluff Soft pellets Hard pellets
Bulk density (Mg/m^3)	0,35	range 0,24 - 0,35	range 0,24 - 0,35	0,35	
Particle size (mm)	range 10-25 median 20 < 25	range 10 - 25 median 20 < 25 < 20	range 10 - 25 median 20 < 25 < 20	range 10 - 25 median 20 < 25	range 10 - 150 median 50
Cl content (% in mass d)		< 1 (depending on the S content) mean 0,6 max 1,3	< 1 (depending on the S content) mean 1,1 max 2,5	< 1 (depending on the S content) mean 0,5 max 0,6/1,0	mean 0,4 (ar) max 0,5/0,8/1,4
Hg (EN 15359 class)		class 1 to 2	class 1 to 2	class 1 to 3	class 1 class 1 to 4, when with activated carbon equipment

KEY

- DBB: dry-bottom boiler
- WBB: wet-bottom boiler
- FBC: fluidized bed combustion plant

Table 5 *(continued)*

Parameter (Unit)	Pulverized coal power plant	Hard coal DBB power plant	Hard coal WBB power plant	Brown coal (lignite) power plant	FBC
NCV, (MJ/kg, ar)	range 16 - 19 range 11 - 17 median 17 min 14	> 20 mean 13,5 range 11 - 18 range 16 - 19 range 11 - 17 median 17 median 14	> 20 mean 17 range 13 - 22 range 16 - 19 range 11 - 17 median 17 median 14	> 11 mean 13,5 range 11 - 18 range 16 - 19 range 11 - 17 median 17 median 14	mean 13,5 range 11 - 18 range 6 - 18 median 14,5
Ash		Low	Low	Can be high	
Contrary materials		Fe and non Fe free 3D particle free	Fe and non Fe free 3D particle free	Fe and non Fe free	

KEY

- DBB: dry-bottom boiler
- WBB: wet-bottom boiler
- FBC: fluidized bed combustion plant

In the case of *fluidized bed combustion*, fuels are not necessarily pulverized or dried when used. Due to the combustion temperatures and the long residence time, the burnout of the fuel is very high and therefore the related emissions of combustion products are relatively low.

Fluidized bed combustion plants need waste fuels to be crushed: based on fuel properties, maximum grain sizes of between 3 mm and 20 mm are reported as suitable. On a general basis, fluidized bed boilers require mechanical milling (size reduction) of the solid waste so as to facilitate feeding into the bed and ensure good performance of the process. In that respect, a need for a particle size typically no larger than 100 mm is reported[69].

That type of boiler can tolerate fuels with a high moisture content (stabilizing effect of the bed) but not fuels with a low ash melting point (as the fluidization can be quickly disturbed by the accumulation of melted ash; plastic foils, for example, have a lower melting point and can melt in the coal mill, which leads to technical issues) and fuels with heavy physical impurities such as metal particles which can occur in domestic, commercial or industrial wastes if not well pre-treated (they disturb fluidization and are difficult to remove from the furnace).

Metallic particles in the fuel feedstock are to be avoided to prevent mechanical damage or obstruction.

Bubbling fluidized bed combustion boilers are considered highly suitable for the combustion of non-homogeneous biofuels. A particle size distribution in the fluidizing bed that falls in the range 0.5–1.5 mm typically occurs, with smaller particles being carried out with the fluidizing gas flow, while larger particles go down to the distribution plate[69].

Waste co-incineration can have an impact on plant energy efficiency and performance, emissions to air and water and the quality of the combustion residues. The main potential effects can be associated with the size, the moisture and the ash content of the waste fuel, the sulfur and chlorine content, the heavy metals content and the alkali content. A suitable choice, pre-treatment or pre-conversion of the waste, or a limited degree of waste co-incineration, can help to prevent these effects.

The conversion efficiency of wastes can be influenced by their calorific value, ash and moisture content and reactivity, as well as by the grindability and the efficiency of the required waste pre-treatment process. The waste can also influence the energy conversion of the main fuel, e.g. due to excess air being required to ensure proper combustion, a change in the flue-gas temperature and flow in the boiler or increased unburnt carbon in the fly ash. A decrease in the nominal load or the load control speed of the power plant, corrosion and erosion of boiler parts due to the sulfur and chlorine content of the waste, slagging and fouling due to the alkali content and the melting trajectory of the ash, are issues that can affect the plant performance. The designed capacity of the combustion units, the combustion properties of the waste – e.g. ignition, flame stability, flame temperature, NO_X formation and burnout, that may differ from those of the main fossil fuel – disruptions induced by waste (e.g. corrosion and erosion, slagging and fouling) and the thermal behaviour of the boiler can affect both the energy efficiency and the performance of the power plant.

With respect to technological issues, operational experiences in several power plants in Germany[120],[121] seem to emphasize that a failure of the co-firing of SRF (from both MSW and ICW-SRF) can occur in pulverized power plants, mainly due to an incomplete burnout or collapse of combustion and to chlorine corrosion. These items are possible final exclusion factors for the use of SRF in pulverized power plants.

Again, fouling and slagging induced by SRF/RDF are assumed to be a possible permanent limiting factor, and the same is true for the potential increase in the chlorine load of the flue gas (due to the need for economic investment; retrofitting of emission control systems, mainly at CFB plants). Other problems experienced – e.g. fuel dosing, mechanical damage due to metallic contaminants in the fuel, chemical and thermal problems due to the aluminium content in CFB boilers, erosion of boilers and ash formation are, on the other hand, regarded as manageable issues, through optimization of SRF production so as to increase its quality and/or an improvement of plant components.

On the matter of the emission of air pollutants, the content of Hg in wastes is one of the most critical factors because of its high volatility. Due to the limitation of the waste input (only a few per cent of the total thermal input of a power plant generally come from wastes), the raw gas concentration of Hg is reported not to change significantly with respect to pure coal-fired power plants.[69] The emitted loads can, however, increase by means of the higher flue-gas volumes. For other metals, such as Pb, Co, Tl, and Se, a potential increase of air emissions is reported[69].

Transfer factors from SRF to the waste gas (TFs for Hg, sum of Cd and Tl, sum of heavy metals) have been provided in CEN/TR 15508,[116] based on data from Dutch plants. These TFs refer to SRF utilized in hard/brown coal fired power plants with a dry bottom (DBB) or a wet bottom (WBB) boiler. Based on such TFs, maximum possible concentrations in SRF have been proposed in the document, as orientation values (see Table B.17).

The air emissions from coal-fired plants of volatile organic compounds such as dioxins and furans is typically low; it is due to the specific combustion characteristics and the sulfur content of fuels which impedes the formation of these compounds, even when wastes (urban, commercial, industrial or solid recovered fuels) that contain these pollutants or their precursors and have a quite high chlorine content are co-combusted[69].

Regarding combustion residues from waste co-incineration, their utilization or disposal is an important economic factor; power plants control their quality by limiting the input of waste into the firing system and by monitoring waste parameters such as the content of alkalis, sulfates, chlorides, silicates, unburnt carbon and metals. Technical quality is considered: it is defined by various parameters (e.g. stiffness, porosity, particle size, moisture content, chloride, phosphorus, sulfate and carbon content) that determines their usability as a by-product. Environmental quality is considered too, that is related to how pollutants can leach from the product in which residues are utilized.

The impact of co-incineration on the quality of residues and by-products has been investigated in some countries. Due to the high removal rates of the dust control techniques applied in large combustion plants, more than 99 % of elements are found in the ashes. Generally, changes in the composition of the fuel can result in equivalent changes in the composition of the ashes; based on their volatility, a redistribution of elements can take place, resulting in a different concentration in the fly ash and in the bottom ash.[69] The ash composition can therefore change according to the waste composition.

Metals present a risk of leaching into the environment. This is less significant in relation to the fly ash when used in immobilized applications, e.g. in the cement and concrete industry. Bottom ash, utilized for example as a layer under a road, can leach trace elements in the long term: a shift in composition and leaching may be a constraint on the application of bottom ash from waste co-incineration. The immobilization and stabilization of metals in residues are taken into account, as well as the calculation of the total content. Comparative data on the effect on combustion residues of waste co-incineration, (specifically, co-firing of sewage sludge at a share of 10 %) and of the combustion of conventional fuels (coal) alone,[69] highlighted a relatively low risk of mobilization in the residues for metals. An increase of the content of Hg, Pb and Cd in the fly ash dry sorption residue and of Pb, Zn, Cu and Cr in the coarse was observed, while the leaching behaviour result was not significantly influenced, in particular when the residues had been stabilized.

Gypsum is a by-product that can be affected by a change in the composition of the fuel. The leaching risk is assumed to be small,[69] due to its main use being inside buildings, where contact with water does not occur.

7.2.2 Quality requirements in plant permits

An example of SRF specifications issued in plant permits, not properly updated (year 2005), was found (see Table B.13). As already mentioned for cement kilns (6.2.2), it shows requirements set for the use of an SRF produced from high calorific fractions of MSW in both power plants and cement kilns in Germany[68],[110].

The chosen trace elements are well aligned with the requirements for SRF established at that time by the national RAL GZ 724 standard (see Table B.2). If compared with specifications set in EN 15359, and today in ISO 21640 (see Table 3), all the obligatory chemical properties are included, with the addition of Sn and Zn. Limit values for trace elements are defined by mass, as both a practical (typical value: to be compared with 50th percentile value for a defined lot) and a maximum permitted value (to be compared with the 80th and 90th percentile values for a defined lot). The reported “practical” values substantially coincide with the limits (median) set in RAL GZ 724: 2008[2], with the exception of a lower value being required in the case of Co.

7.2.3 Quality requirements in general guidelines

Valuable orientation values for trace elements in SRF have been proposed in CEN/TR 15508, as maximum possible concentrations by energy for DBB and WBB coal fired power plants (see Table B.17). These values have been derived according to the evaluated transfer factors and take into account the type of fossil fuel (hard coal, in WBB plants; hard and brown coal, in the case of DBB plants).

On the whole, the proposed maximum possible concentrations, expressed by energy, are:

— Hg (mg/MJ ar)	0,034/0,65 (hard coal) - 0,085 (brown coal);
— Sum of Cd and Tl (mg/MJ ar)	0,25/1,21 (hard coal) - 1,21 (brown coal);
— Sum of As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V (mg/MJ ar)	34/106 (hard coal) - 170 (brown coal).

As discussed in 7.2.4, CEN/TR 15508 also provides general references on the net calorific value and the chlorine content of SRF utilized in brown and hard coal power plants that are based on data from voluntary specifications.

Specifications defined in Germany to approve a trade mark SRF suitable for an end use in lignite power plants, (the SBS ^{R} 1), and in hard coal power plants, (the SBS ^{R} 2), could be considered as further general guidance (see Table B.20). Regarding the physico-chemical properties of that traded SRF, the following specifications are given:

— NCV (MJ/kg ar)	in the range 13 - 18 (lignite power plants),
	in the range 18 - 23 (hard coal power plants);
— Chlorine (% in mass d)	<0,7 (lignite power plants),

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[2] The RAL GZ: 2008 has been replaced by RAL GZ 274:2012, which defines the quality requirements in relation to energy.

<1,0 (hard coal power plants);

for both the fuel properties, the quoted values fit well with the reference values mentioned in CEN/TR 15508;

- Ash content (mg/kg d) <20 (lignite power plants),

  <15 (hard coal power plants).

Limit values by mass are then detailed for all the trace elements assumed as relevant in CEN/TR 15508. If assessed by energy on a dry basis, the following indicative limit value can be derived:

- Hg (mg/MJ d) < 0,04 to < 0,03 (hard coal power plants),

  < 0,05 to < 0,03 (lignite power plants);
- Sum of Cd and Tl (mg/MJ d) < 0,35 to < 0,27 (hard coal plants),

  < 0,47to < 0,35 (lignite power plants);
- Sum of heavy metals (as previously) (mg/MJ d) < 82 to < 65 (hard coal power plants),

  < 112 to < 82 (lignite power plants).

Other trace elements are considered (Se, Sn, Be, Te), for which the limit values provided by mass are detailed in Table B.20.

7.2.4 Quality requirements in voluntary end user specifications

Valuable summary data are reported in CEN/TR 15508 for the net calorific value and the chlorine content of SRFs utilized in hard and brown coal DBB plants and in hard coal WBB plants (see Table B.25). That assessment was based on the voluntary specifications of European end users (Germany and the Netherlands).

In the case of hard coal power plants these requirements are for:

- NCV (MJ/kg ar) mean value from 11-13 to 18-22;
- Chlorine (% in mass d) maximum allowable content from 1,3 to 2,5;

and in the case of brown coal power plants, for:

- NCV (MJ/kg ar) mean value in the range 11-18;
- Chlorine (% in mass d) maximum allowable content from 0,6 to 1,0, depending on the plant design and the fuel mix.

The same geographical origin characterizes further references on voluntary requirements, such as the specification provided by an Italian producer (see Tables B.29 and B.30) and the profiles of properties relevant for the SRF specification (see Table B.35), which the ISO survey among producers provided.

Based on the latter and according to the key parameters and the classification system adopted in the EN 15359 standard (see Table 2), a voluntary requirement seems to occur for:

- NCV that falls into classes 1 to 4 (most requirements are for NCV of class 1 and 2). The local specification reported in Table B.29 requires an NCV from class 1 to class 3, while that in Table B.30 specifies class 3;
- Chlorine that falls into classes 2 to 4. The local specification in Table B.29 sets a Cl content ranging from class 1 to class 3, the latter is assumed to be a voluntary requirement by the specification in Table B.30;

- Hg in class 1. Higher contents of the heavy metal are allowable, e.g. in the case of the local specification reported in table B.5.8 of Annex B.

The collected response of producers to the ISO survey (see Table B.35) highlights the moisture and ash content as relevant key properties for SRFs.

On that subject, local specifications provided by an Italian producer/end user (see Tables B.29 and Tables B.30) show a requirement for:

- Moisture (% in mass ar) generally ≤15 with higher values (up to 30) permitted in one case;
- Ash content (% in mass d) <20; a maximum value of 30 seems allowable in one case.

Regarding trace elements, a general agreement with the set of obligatory properties (As, Cd, Tl, Co, Cu, Cr, Ni, Sb, Pb, Mn, V) in EN 15359 (as well as ISO 21640), can be derived by both the ISO survey and the local specifications mentioned above. The following indicative limit values by energy can be derived from the latter:

- Hg (mg/MJ d) <0,04 or compliance with limits for class 3 in EN 15359;
- Sum of Cd and Tl (mg/MJ d) < 1,1 to < 1,3;
- Sum of heavy metals (as previously) (mg/MJ d) < 73 to < 288.

7.3 Typical values for SRF

General and complete valuable references for typical values for SRF with an end use in coal power plants have not be found. The source for measured values used for the purposes of this document (Annex D) provided a limited number of analytical assays (21 in all), most of which (16) refer to MSW-SRFs utilized in one European country only.

When statistically processed (details in D.2.3.2), in summary these measured values depict an SRF with the following typical values for the monitored physico-chemical SRF properties, expressed as a median and 80th percentile value:

- NCV (MJ/kg, ar) median 17 80th percentile 17,8;
- moisture content (% in mass, ar) median 17,8 80th percentile 20,4;
- ash content (% in mass, d) median 15,9 80th percentile 17,1;
- chlorine content (% in mass d) median 0,89 80th percentile 1,0.

Such results seem to confirm a good alignment of the fuels analyzed with the guidance values discussed in 7.2.3 and 7.2.4.

The collected measured values offer an adequate degree of coverage (see Annex D, Figure D.3) for the chemical properties of SRF that it is obligatory to specify according to existing standards (e.g. EN 15359 and ISO 21640), with the exception of Tl, Sb, Co and V. The derived statistical outcomes are detailed in Tables D.22 to D.24.

With respect to the mercury content, the following typical values by energy have been derived from the collected measured values:

- Hg (mg/MJ d) median 0,024 80th percentile 0,027.

When the derived values as mg/MJ, ar are considered, the statistical outcomes reported below seem to fit well with the guidance values provided in CEN/TR 15508:2008 (7.2.3):

— Hg (mg/MJ ar) median 0,034 80th percentile 0,043.

8 Gasification

8.1 General

Background references on the gasification process and the main available technologies are given in C.3.

Mandatory requirements in national legislation and standards that explicitly refer to the use of SRF/RDF in gasification plants have not been found.

With respect to the environmental performance of gasification facilities, compliance with legally set limit values is generally required. In Europe, for example, the limit values issued in the *Industrial Emissions Directive*[42] for trace elements (Hg, As, Sb, Pb, Cr, Co, Cu, Mn, Ni, V, Tl, dioxins, furans) in the case of waste incineration/co-incineration plants also apply to waste gasification facilities. Again, in the European reference document on the best available techniques for large combustion plants,[69] emission limits associated with the best available techniques (BAT-AELs) are defined and assumed to be generally applicable to all gasification plants directly associated with combustion plants and to IGCC plants. Air emission limits are also in place in other countries, such as Japan[122].

8.2 End use requirements for SRF and other waste derived fuels

8.2.1 Technical limitations of the technologies

In gasification based EfW units, relevant operational parameters[122] are:

- the *equivalence ratio* ER (the ratio between the oxygen content in the oxidant supply and that required for complete stoichiometric combustion) that can strongly affect the gas composition (including tar content) and its chemical energy. Values of ER around 0,25–0,35 appear to maximize char conversion and are typically assumed in large-scale commercial plants, even if values as high as 0.5 can be used, in particular with moving grate gasifiers and fluidized bed gasifiers operated with wet fuels. With lower values of ER, unconverted char and higher tar content can result, while higher values can result in the oxidation of part of the syngas and a reduction of the syngas heating value;
- the *temperature profile along the reactor* that can also determine the state of bottom ash and the content of tar in the syngas;
- the *residence time of gases and waste* in the reactor (this depends on the reactor type and design);
- the *composition and the inlet temperature of the gasifying medium* (this can affect the mass and energy balances of the reactor);
- the *waste feedstock* (composition and characteristics). Wastes (especially unsorted wastes) show a large variability in composition and properties (e.g. size), containing combustible and non-combustible (e.g. ash) materials, the latter at a higher extent if compared to a typical biomass feedstock, also after a high-grade pre-treatment of the waste.

Kilns, grates and shaft furnaces are considered very suitable solutions to manage a variable composition and size of the waste feedstock. In the case of fluidized bed systems, shredding of the waste feedstock is needed to ensure that the fuel particles are not too coarse to fluidize and to remove most of the non-combustible fractions (e.g. metals, glass) that can create bed-related problems. Gasifiers for waste that operate at 400-600 °C (lower than the 800-900 °C of biomass gasifiers) allow the recovery of metals and avoid operational issues (melting of glass contained in the fuel); a low temperature operation could have a negative effect on the gas quality by increasing tar formation, but a close-coupled combustion stage or a high-temperature gas treatment stage downstream of the gasifier help to limit the impact[123].

The main properties of interest for waste gasification can be identified in the lower heating value (LHV), the bulk density and size, the ash content and composition, the moisture content, the volatile matter content and the presence of other contaminants, such as N, S, Cl, alkalis, heavy metals, etc.

In the case of a *fixed bed gasifier gasification process*, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- a uniform morphology (both updraft and downdraft gasifier);
- a particle size up to 100 mm (both updraft and downdraft gasifier);
- a moisture content <20 % in mass ar (downdraft gasifier) and <50 % (updraft gasifier);
- an ash content <5 % in mass d (downdraft gasifier) and <15 % d (updraft gasifier);
- an ash melting point >1,250 °C (downdraft gasifier) and >1,000 °C (updraft gasifier);
- a bulk density >500 kg/m^3 (downdraft gasifier) and >400 kg/m^3 (updraft gasifier).

Combined with the generally low capacity (below 1 MW), *downdraft reactors* are reported to be rarely used for MSW or other wastes, as they show a sensitivity to a variable composition, shape and particle size of the waste fuel. *Updraft reactors* (traditionally utilized for capacities of 10 MW thermal or less) have also been deployed for the gasification of MSW and RDF and for co-gasification of wastes with coal[123].

In the case of the *fluidized bed gasification process*es, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- a uniform morphology (both BFB and CFB gasifier);
- a particle size <150 mm (BFB gasifier) and <100 mm (CFB gasifier);
- a bed particle diameter between 0,08-0,3 mm (BFB gasifier) and 0,05-0,5 mm (CFB gasifier);
- a moisture content <55 % in mass ar (both BFB and CFB gasifier);
- an ash content <25 % in mass d (both BFB and CFB gasifier);
- an ash melting point >1,000 °C (both BFB and CFB gasifier);
- a bulk density >100 kg/m^3 (both BFB and CFB gasifier).

Entrained flow reactors seem to show a strict requirement for the waste feedstocks: high or moderate energy content liquid wastes (e.g. waste oils) are reported as a feasible feedstock while some streams of solid wastes (e.g. plastic wastes) are not feasible.[123] As a general reference, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- a uniform morphology;
- fine fuel particles (< 1 mm), added to water to produce a slurry with a solid concentration > 60 %, fed to the gasifier;
- a moisture content < 15 % in mass ar;
- an ash content < 20 % in mass d;
- an ash melting point > 1,250 °C;

In the case of r*otary kiln gasifiers*, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- any particle size (from fine to large lumps), morphology, moisture content, ash melting point;
- an ash content < 40 % in mass d;

- a bulk density > 100 kg/m^3.

In the case of *moving grate gasifiers*, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- any morphology;
- a particle size <200 mm;
- a moisture content <60 % in mass ar;
- an ash content <40 % in mass d;
- an ash melting point >1,200 °C;
- a bulk density 250-350 kg/m^3.

In the case of *plasma gasification*, wastes characterized by the following main properties can be assumed[122] to be a suitable feedstock:

- any particle size, morphology, moisture content, ash content, melting point;
- a bulk density > 100 kg/m^3.

In Table 6, typical requirements of the main type of gasification reactors are summarized[123],[124].

Table 6 — A comparison of qualitative and quantitative requirements for different gasification options (adapted from[124])

Characteristics	Downdraft gasifier	Updraft gasifier	Fluidized bed gasifier	Entrained flow gasifier	Plasma gasifier	Plasma enhanced downdraft gasifier
Operating energy requirement	low	low	moderate	low	high	moderate
Ability to handle different wastes	moderate	low	very low	low	very high	high
Permissible fuel particle size (mm)	<4 (<100)	<2 (<50)	<1/4 (<10)	<1/25 (<1)	n/a	<4 (<100)
Maximum moisture content	~ 40 % in mass ar	~ 50 % in mass ar	~ 10 % in mass ar	~ 10 % in mass ar	>50 % in mass ar	>50 % in mass ar
Dust content	medium	low	high	high	low	low

KEY

— n/a: value not reported

As regards the *coal/multi-fuel gasification combined cycles (IGCC plants),* significant amounts (5–25 t/h) of biomass and wastes can be added to the feed in coal gasifiers without compromising the operation or quality of the slag. Limitations in use are mainly due to the syngas clean-up systems and the specific composition of the biomasses used. A high alkali content in biomass/waste ashes can result in an increase of fouling and result in increased slag leaching properties[69].

Different performance parameters are normally considered in gasification based EfW units.[122] Other than those related to the syngas produced [e.g. syngas heating value (kJ/Nm^3); specific syngas flow rate (Nm^3/kg waste); specific energy production (kJ/kg waste); syngas quality], relevant indicators are:

- the *cold gas efficiency* (CGE), the ratio between the chemical energy of the syngas produced and the chemical energy of the waste fed to the plant;
- the *hot gas efficiency* (HGE), the ratio between the sum of chemical energy and sensible heat of the syngas produced and the sum of chemical energy and sensible heat of the fed waste;

- the *carbon conversion efficiency* (CCE), the ratio between the carbon flow rate converted to gaseous products and that fed to the reactor with the solid waste (this provides an assessment of the amount of unconverted material that is treated with other techniques or sent for disposal, and a measure of the chemical efficiency of the process);
- the *tar content* and the *tar composition*, relevant as tars can reduce the overall efficiency of the gasification process and of the devices for the end-use of the syngas produced (e.g. slagging, blockages and corrosion, adverse effects on reforming catalysts, sulfur removal systems, ceramic filters).

Tar is a typical challenge for biomass and waste gasifiers and has a significant effect on the overall gas cleaning process of the plant, especially in low-temperature gasifiers (fixed-bed and fluidized bed).[69] Condensable or non-condensable organic materials (tar) are a mixture of aromatic compounds whose quantitative production (also at a significant amount, between 0,1 % and 10 % of the gas product) and composition largely depend on the fuel feedstocks. If condensed, (at temperatures between 200 °C–600 °C), tar can cause coke formation on fuel reforming catalysts, deactivate sulfur removal systems and damage compressors, heat exchangers, ceramic filters, gas turbines and engines. Also, non-condensable tars can cause problems for advanced power conversion devices. The amount and composition of tars are dependent on the fuel, the operating conditions and the secondary gas phase reactions.

Physical and chemical treatment processes can reduce the presence of tar in the gas produced. Wet or wet/dry scrubbing processes are commercially available. Cyclones, cooling towers, venturis, baghouse filters, electrostatic precipitators, and wet/dry scrubbers are some of the tools used. Dry tar removal using ceramic, metallic, or fabric filters is an alternative to wet tar removal processes. Chemical tar treatment processes (thermal, steam, partially oxidative, and catalytic processes (dolomite is a very widely used tar cracking catalyst) are those most widely used in the gasification industry[125].

The gas resulting from waste gasification contains various tars, particulates, halogens, heavy metals and alkaline compounds, depending on the fuel composition and the gasification process[125].

SRF/RDF can be characterized by a high moisture and volatile content, and a porous-fragile structure, that reflect their propensity to give rise to significant amounts of tar and fine fragments of carbon and fly ash particles. Char and tars are converted mostly through thermal cracking and direct combustion, thermodynamically favoured by high temperatures. To reduce the tar content, the use of catalysts (e.g. dolomite) in situ (as fluidized bed additives) is reported to be helpful, even though the extent of reduction can be limited by the high level of ash in RDF, lowering the performance of the catalyst added[126].

When the air gasification of a mainly paper/plastics-RDF and of sewage sludge was experimentally tested in a bubbling fluidized bed (at 800 °C and atmospheric pressure),[127] the gas produced resulted in high levels of tar precursors (e.g.: ethylene and benzene, 4,6 mg/m^3 and 9,309 mg/m^3, respectively) as well as tar (26,4 mg/m^3).

Studies on the gasification of tyre waste and its co-gasification with coal (steam air gasification process in a fixed bed reactor) are reported in the literature.[128] Gasification of the tyre waste resulted in a tar yield of 40,5 %, while when processing coal the yield was 17,5 % and co-gasification of the two fuels resulted in a reduction of tar formation (tar formation not significantly higher compared to coal gasification only was observed when 10 % of tyre waste was added in the fuel feedstock).

The formation of large quantities of tar seems to occur when sewage sludge[131],[132],[133] or biomass wastes containing fats (e.g. bagasse, plant oil, bonemeal)[129],[130] are used as feedstock in gasification plants; wastes containing fats can be co-processed with conventional fuels in appropriate proportions (e.g. a share not exceeding 40 % in case of bagasse; and 1 % in case of bone meal).

Air pollutants can be generated by gasification reactors. Different abatement solutions are already available, whose choice and application largely depend on the plant configuration and the gas quality requirements of the specific energy-conversion device. Certified emission data,[122] that refer to six MSW plants (Japan, Norway and Canada) in operation with different gasification technologies, seem to confirm compliance with the emission limits set in national legislation (Table 7).

Table 7 — Certified data on air emissions in MSW gasifiers (adapted from[122]).

	Plant 1 [a]	Plant 2 [b]	Plant 3 [c]	Plant 4 [d]	Plant 5 [e]	Plant 6 [f]
	Japan	Japan	Japan	Japan	Norway	Canada
Treatment capacity (tonnes/day)						
Waste	200	300	420	400	100	110
Energy Production						
Power	2,3 MWe	8 MWe	5,5 MWe	8,7 MWe	10,2 MWth	n/a
Emissions (mg/Nm^3, at 11 % O_2)						
Particulates	10,1	<3,4	<1	<0,71	0,24	9,1
HCl	<8,9	8,3	<2	39,9	3,61	2,2
NOx	22,3	n/a	29	59,1	42	107
SOx	<15,6	n/a	<2,9	18,5	19,8	19
Hg	n/a	n/a	<0,005	n/a	0,0026	0,0001
Emissions (ng-TEQ/Nm^3)[g]						
Dioxins/furans	0,032	0,018	0,000051	0,0032	0,0008	0,006

KEY

- n/a : value not reported

NOTE

(a) Fixed bed downdraft air high temperature air gasifier

(b) Fixed bed downdraft air high temperature oxygen gasifier

(c) Internally circulating fluidized bed low+high temperature air gasifier

(d) Rotary kiln low temperature air gasifier

(e) Moving grate low temperature gasifier

(f) Plasma high temperature gasifier

(g) Toxic equivalent nanogram per standard cubic meter

With respect to direct combustion, the waste gasification process seems to offer advantages due to the low levels of oxygen that, for example, allow the prevention of sulfur and nitrogen compounds from oxidizing, favour the conversion of fuel-bound nitrogen/sulfur to gaseous H_2S, N_2 or ammonia, rather than SO_x and NO_x[69],[125] and inhibit the formation of dioxins and furans[122].

The concentration of hydrogen chloride in the syngas can create problems when the main product of the gasifier is used to feed combustion units for heat or power generation.

As regards metals, whose content can also be significantly higher in waste than in a conventional fuel such as coal, their presence in plant gaseous emissions is basically related to the metal properties e.g., volatility, mechanical strength and solubility in water. During the gasification process metals can follow different pathways[134]: non-volatile metals are reported as generally distributed in ash (and slag) like the semi-volatile metals, but the latter can also be volatilized in the gas phase.[134],[135] Studies on the behaviour and partitioning of heavy metals in by-products of MSW gasifiers showed that around 90 % of the heavy metals with a low melting point (e.g.: 95,2 % lead; 92,0 % zinc) occur in the fly ash[136].

The use of fuels with a high content of sulfur and chlorine (e.g.: sewage sludge, waste plastics, some types of biomass, petroleum coke) can lead to an increase in the volatility of some elements.

The formation of volatile chlorides was observed for thallium, tin, zinc, cadmium, antimony and arsenic[137].

Other studies on co-gasification,[138] seem to demonstrate that the migration of metals – such as copper, germanium, molybdenum, nickel, lead, arsenic, antimony, thallium, boron and zinc – to the fly ashes could be reduced by means of the addition of biomass fuels in the feedstock (up to 6 % by mass), as a result of an increase of elements, including heavy metals, in the slag.

Tests carried out by processing plastic fractions of MSW and post-consumer plastic films,[134] demonstrate that the process can result in a relatively high content of metals in the waste gas, and specifically of Pb (about 44,19 µg/m^3 in the case of MSW plastics; about 35,27 µg/m^3 in the case of plastic films), Cr (about 20,08 µg/m^3 in the case of plastic films) and also Hg (about 3,82 µg/m^3).

8.2.2 Quality requirements in plant permits

The literature search carried out for the purposes of the Report as well as the survey among producers/end users promoted by ISO/TC 300/WG 2, did not provide references on specifications occurring in authorization permits issued locally.

8.2.3 Quality requirements in general guidelines

As regards the use of SRF/RDF in gasification plants, three general guidelines have been found, all based on experiences in European countries.

A study recently promoted by IEA Bioenergy provides references for the specification of SRF in terms of minimum and maximum limit values for both the physico-chemical properties and the content of trace elements (see Table B.23), that have been derived from representative data of SRF utilized in a fairly limited number (6) of gasification and co-gasification plants (in operation in Spain, Poland, the Netherlands, Germany, Italy and Finland). The WRAP guideline (see Table B.21) developed in the UK, provides a classification and specification system for *Waste Derived Fuels* (WDF: see Annex A) suitable also for end uses with advanced technologies, such as gasification and pyrolysis (other than grate and fluidized bed combustion plants). It is specifically designed for plants with a treatment capacity of less than 100,000 tonnes/year; the assumption is that in the case of small scale plants, rules set in EN 15359 (the main reference for EfW plants processing higher amounts of solid wastes) are not appropriate for ensuring an economically sustainable use of waste fuels that is able to comply with the authorization permits. A reference for the specification of RDF has also been found in a Finnish guideline (see Table B.22).

In respect of the physico-chemical properties of the fuel, a general conclusion of the IEA study is that an SRF falling in the classes from 1.2.1 to 3.3.3, as defined in EN 15359 complies well with its use in gasification and co-gasification plants. It can be noted that an SRF of class 1.2.1 also seems to be confirmed as suitable for gasification plants by the only suggestion made available by the ISO survey among producers (see Table B.35).

The following reference limits (range of values mainly) for properties of SRF are assumed in the IEA study:

— Particle size (mm)	range 10 - 25;
— Moisture (% in mass ar)	range 2,5 - 15;
— Ash content (% in mass d)	range 6,3 - 21,2;
— Volatile matter content (% in mas d)	range 76 - 86;
— Bulk density (kg/m$^{3)}$	600;
— NCV (MJ/kg ar)	range 15,4 - > 29;
— Chlorine (% in mass d)	range 0,26 - 0,65;
— Hg (mg/MJ ar)	range 0,02 - 0,04.

With respect to the specification of other chemical properties of SFR, the IEA study provides as general guidance the following maximum values, expressed by mass (mg/kg d), for:

— As (1,5) - Cd (2) - Cr (70) - Cu (250) - Ni (25) - Pb (350) - Zn (500), and a definite “limit” value is defined in the case of:

— Co (1,5) - Tl (< 0.05) - Na (1190) - K (670) - F (43) - Br (< 3).

The conclusions of the IEA study seem to be in generally good agreement with specifications suggested in the Finnish guideline for RDF:

— Particle size (mm)	range 10 - 15;
— Moisture (% in mass ar)	range 6 - 10;
— NCV (MJ/kg ar)	range 16 - 18;
— Volatile matter content (% in mass d)	71,1;
— Bulk density (kg/m^3)	range 500 -700,

and in the WRAP guideline, where the proposed class limits (mean value) for the first three classes of WDF show a requirement for:

— NCV (mg/MJ ar)	≥ 25 (class1)	≥ 20 (class 2)	≥ 15 (class 3);
— Moisture (% in mass ar)	≤ 10 (class1)	≤ 15 (class2)	≤ 20 (class3);
— Ash content % in mass d)	≤ 10 (class1)	≤ 20 (class2)	≤ 30 (class3);
— Bulk density (kg/m^3)	≥ 650 (class1)	≥ 650 (class1)	≥ 350 (class3);
— Chlorine (% in mass d)	≤ 0,2 (class1)	≤ 0,6 (class2)	≤ 0,8 (class3);
— Hg (mg/MJ ar)	≤ 0,02 (class1)	≤ 0,03 (class 2)	≤ 0,06 (class 3);
— Cd (mg/MJ ar)	≤ 0,1 (class1)	≤ 0,3 (class 2)	≤ 1,0 (class 3);
— Sum of heavy metals (mg/MJ ar)	≤ 15 (class1)	≤ 30 (class2)	≤ 50 (class3).

8.2.4 Quality requirements in voluntary end user specifications

A few specifications have been collected that refer to European CFB gasification plants (see Tables B.31, B.32, B.33). This applies to RDF that originate from municipal wastes, from a mix of sorted household waste, demolition wood and industrial waste wood or generically to a mix of alternative fuels, such as plastic and paper wastes, SRF/RDF, tar sludge, roofing paper, utilized as feedstock in a gasification plant with lignite as the main conventional fuel.

All the specifications mainly emphasize requirements for physico-chemical parameters:

— Size (mm)	<50 (MSW-RDF)
	<100 (mix of alternative fuels);
— NCV (MJ/kg d)	10 - 20 (MSW-RDF)
	18 - 24 (mixed-RDF)
	1 - 35 (mix of alternative fuels);
— Moisture (% in mass ar)	<30/35 (MSW-RDF/mixed-RDF)
	< 50 (mix of alternative fuels);
— Ash content (% in mass d)	<25 (MSW-RDF)

< 15 (mixed-RDF)

limited by the energy balance in the case of a gasification plant fed with a mix of alternative fuels;

- Bulk density (kg/m^3) 250 (MSW-RDF)

  300 (mix of alternative fuels);

- Chlorine (% in mass d) < 0,6 (mixed-RDF)

  < 2 (MSW-RDF).

As regards heavy metals, specifications are reported for Hg only, with a required content in the mixed RDF <0,1 mg/kg d (in the case of the MSW-RDF, the reported value, <1,5 mg/kg, does not specify whether it is on a dry basis or as received).

8.3 Typical values for SRF

It has not been possible to find valuable data, supported by consistent statistics, for typical values of SRF/RDF utilized in gasification plants.

A search for measured values was carried out for the purposes of the Technical Report (Annex D), that provided a dataset characterized by low consistency (27 assays, in total). Data are for European recovered fuels only, of which 18 refer to an SRF and nine to a secondary fuel identified as RDF. In regard to technology, it is specified for few assays only that refer to the use of SRF/RDF in a circulating fluidised bed gasifier (CFB), a bubbling fluidized bed gasifier (BFBG), a down-draft fixed bed gasification plant or a two-stage fluid bed gasification–plasma process.

Therefore, the derived statistics (see Tables D.25 and D.26) can offer only an indicative reference for typical values for SRF.

All the assays provide a characterization of the ash content, while other physical parameters, such as the form, size and bulk density of the fuel, were covered by measured values.

The derived median and 80th percentile values, assumed to be properly representative for a typical value, seem to suggest as suitable the use of an SRF with:

- NCV (MJ/mg d) from 25 (median) to 33 (80th perc.);
- Moisture (% in mass ar) from 3,5 (median) to 6,3 (80th perc.);
- Chlorine (% in mass d) from 0,6 (median) to 0,9 (80th perc.);
- Ash content (% in mass d) from 10,5 (median) to 13,2 (80th perc.).

As for the trace elements, Hg, Cd, Pb, Cr, Cu and Ni are the most widely monitored parameters, followed by As, Tl, Sb, Co, Mn and V (see Figure D.4).

In that case, due to the limited number of data available (generally < 10 for each parameter), the following range of values (minimum/maximum), can be used to derive an indicative reference achievable from the statistical analysis of measured values:

—	Hg	0,002/0,019	mg/MJ d	0,100/0,300	mg/kg d;
—	Cd	0,006/0,200	mg/MJ d	0,100/4,4	mg/kg d;
—	Pb	0,835/25,9	mg/MJ d	4,3/871	mg/kg d;
—	Cr	0,225/16,4	mg/MJ d	6,1/368	mg/kg d;

—	Cu	0,380/39,6	mg/MJ d	16/1333	mg/kg d;
—	Ni	0,027/4,73	mg/MJ d	1,10/159	mg/kg d;
—	As	0,002/0,330	mg/MJ d	0,100/6,6	mg/kg d;
—	Tl	0,003/0,025	mg/MJ d	0,050/0,500	mg/kg d;
—	Co	0,012/0,152	mg/MJ d	0,510/3,6	mg/kg d;
—	Mn	0,006/3,4	mg/MJ d	0,250/79	mg/kg d;
—	V	0,004/0,565	mg/MJ d	0,150/19	mg/kg d.

The statistical results for the main physico-chemical properties of SRF and most of the trace elements summarized above seem to be in good agreement with the average values reported in the literature for individual gasification plants (see Table D.8).

9 Conclusions and guidance

All the secondary fuels produced from waste streams are assumed in the Report to fall under the generic and common name of Refuse Derived Fuels (RDFs). The SRFs are identified as a subset of that large family, including only fuels that meet the requirements for quality (e.g. classification and specification provisions) defined by a national or international standard. In other words, only a regulated RDF is assumed to be an SRF. A complementary assumption is that wastes not suitable for re-use, preparation for re-use or for efficient material recovery are intended to be used for their production.

The national markets for waste fuels clearly show that secondary fuels can take on different names locally and, above all, a broad use of the term RDF occurs that does not always allow a clear identification as a generic, non-standardized, or a standardized solid recovered fuel (an SRF).

SRF/RDF are locally produced in MT and MBT plants from individual or mixed streams of municipal (MSW), commercial (CW), industrial (IW) and construction and demolition (CDW) wastes, that can differ in their share of residual fractions and, based on this, also in elemental composition. As the background data given in the Report show, solid recovered fuels with a different degree of quality are produced, more or less suitable for the end use in the coal co-combustion and gasification plants of interest, based on the input waste stream and the type and intensity of the pre-treatment process.

Residues coming from domestic and industrial/commercial activities are submitted worldwide (e.g. Europe, China and Japan) to different regulations that apply to both their classification as waste and their management. This can have a spin-off on the composition of the input streams from which SRF/RDF and other combustible fractions are produced locally.

A summary view of the limitations of the end-user plants is provided in Clauses 5 to 7. This underlines the main physical and chemical properties of the fuel feedstock which can represent a relevant challenge or can result in a limiting factor for the waste-to-energy plant. Technological impacts can occur (e.g. build-ups in cyclones, blockages, formation of kiln rings and preheater deposits in cement kilns; fouling, slagging, mechanical damage due to metallic contaminants in the fuel, chemical and thermal problems due to the aluminium content, erosion of boilers, ash formation in power plants; tar formation in gasification plants). The fuel feedstock can potentially also have an impact on the environmental performance of the plant (e.g. pollutant emissions, quality of process products and by-products). Indicative references for limit values in SRF/RDF or other waste utilized as feedstock are provided for each of the end users studied, which can be a useful reference for the specification of a suitable fuel feedstock.

It is noted that the specific characteristics of the production process (e.g. cement kilns), the availability and the use of the effectively upgraded or innovative technologies (processes; emission control), as well as the specific behaviour of fuel contaminants and/or their relationship with the process conditions, can actually assist the EfW plant in managing such challenges.

For the end uses considered (e.g. cement kilns and power plants), provisions for the fuel specification are legally in place in different countries. Mandatory rules are also issued in local plant permits, some local examples of which are provided in the Report. Such provisions are mainly intended to ensure adequate compliance with the relevant general goals of safeguarding human health and environmental protection.

Rules for fuel classification and the specification of SRF occur in international and national standards that substantially mediate the technological, economic and environmental constraints on their use in waste-to-energy plants. Those provisions can have a general relevance for the waste-to energy system or refer to a defined boundary of end uses for the waste fuel (e.g. plant meeting specific capacity requirements in terms of clinker production for cement kilns or thermal output for power plants).

, Some properties (NCV, chlorine and Hg) are assumed to be relevant to the fuel classification from an environmental, economic and technological perspective in both the EN 15359 and the ISO 21640 standard on SRF. Limit values per class are defined, to which voluntary specifications also explicitly refer (e.g. that collected for SRF utilized in a coal power plant). As regards the fuel specification, a choice is made in the standards quoted for a "qualitative" provision only (without any mention of limit values); a list of general and physico-chemical properties is provided, that is intended to (in respect of obligatory properties) or can be voluntarily utilised to provide a suitable definition of the fuel quality.

Moving from national standards to general guidelines, from the opinions of producers provided by the ISO survey, the few collected examples of plant permits and voluntary end user specifications, to the measured values themselves, data provided in the Report clearly show that the obligatory physical and chemical properties chosen are largely adopted for the specification of SRF as fuel feedstock in the end-user plants examined.

It is noted that in the case of a specific solid recovered fuel such as the Japanese RPF, rules set in the national standard give a classification system only, by leaving the fuel specification on a voluntary basis. Other than NCV and chlorine, properties such as the moisture and the ash content are assumed to be key parameters for the classification, while Hg, quite a relevant parameter to define the quality of SRF in other countries, is not considered a requirement for either the classification or the specification of the RPF, as the collected measured values seem to confirm. The latter also seem to highlight Al as a property of relevance, from a technological point of view, for the typical end user of that fuel (the cement, paper and steel manufacturing industries).

The efforts made by national associations of end users/producers, national bodies or specific studies in providing a guide for the end uses studied, are more balanced on plant needs and can be considered to be a useful reference for the specification of SRF (typical/limit values). This happens in particular in the case of SRF utilized in cement kilns and coal fired power plants, for which valuable orientation values can be considered to be those provided by CEN/TR 15508 or by the specifications defined in Germany for the production of high-quality trade mark SRFs suitable for use in such plants. Even though they have a lower consistency due to the limited dataset they are based on, the guidelines found for the use of SRF in gasification plants are in any case able to help in defining the boundaries for the relevant properties.

The number of voluntarily chosen parameters, as well as the defined quantitative reference for typical or limit values – a few local examples are provided in the Report for each technology – reasonably reflect specific needs that come from technological limitations and/or restrictive requirements locally set in plant permits. A valuable reference for the choice of limit values can be derived, even if for a few parameters only, from CEN/TR 15508 mainly for coal power plants and cement kilns.

For the choice of relevant properties and practical or limit values that the fuel specification specifies, the consolidated assessments of typical values for SRF that provide an indicative profile of the recovered fuels utilized as feedstock in the EfW plants of interest are also useful references. On this matter, the Report provides valuable summary results derived from the literature (coal power plants and cement kilns) and the outcomes of a dedicated statistical analysis that takes into account all the end users studied.

Finally, it is necessary to comment on how typical/limit values for fuel properties are expressed, with respect to their chemical properties (trace elements). Original data reported in *Annexes* or in the body of the Report clearly show that different units (by mass or by energy) are currently used in legislation, standards, plant permits, guidance and voluntary specifications.

An effort was made in Clauses 6 to 8, (mainly in the case of general and voluntary specifications), and in Annex D, (outcomes of the dedicated statistical assessment of measured values), to provide a more homogeneous reference, in terms of the value expressed by energy, so as to facilitate a better comparative reading of the reported data.

Annex A
(informative)

Background references on the production of SRF and other waste derived fuels

A.1 Input waste streams, processes, general references on the properties of SRF

SRFs are locally produced from individual or mixed streams of municipal (MSW), commercial (CW), industrial (IW) and construction and demolition (CDW) wastes or from mixed waste streams. These streams include different shares of residual fractions and show different elemental compositions.

In respect of differences in composition and physico-chemical properties among the input and output waste streams, indicative references are provided for SRFs produced in MT plants from municipal (Table A.1), industrial and commercial (Table A.2) and construction and demolition (Table A.3) waste streams[5],[6],[7].

With respect to some properties, CEN/TR 15508[116] gives typical values for SRF according to the fuel origin (Table A.4), as derived through a statistical analysis of a series of measured values collected in European countries (mainly Austria, Germany, Belgium, the Netherlands, Italy, Norway and Sweden,).

A database of measured values was built for the purposes of this Technical Report (see Annex D). It allowed a similar statistical assessment to be applied by means of the input waste stream the SRF is produced from. Results for the main monitored properties, in terms of median and 80th percentile values are summarized in: Table A.5 (MSW-SRF); Table A.6 (Mixed waste-SRF); Table A.7 (ICW-SRF), in the case of waste fuels named SRF in the source document, almost all produced in European countries;Table A.8, with respect to the refuse-derived paper and plastics densified fuels (RPF) produced mainly in Japan, but also in South Korea.

Different types and degrees of treatment are applied by the producers in their MT and MBT plants, which modify to some extent the properties of the input waste streams and determine the achievable yield in waste-derived fuels, in both a quantitative and a qualitative sense.

Schematically, in mechanical treatment plants (MT) various unit operations/sorting techniques, such as primary shredding, screening, magnetic and eddy current separation, pneumatic separation, optical sorting and near-infrared (NIR) sorting and secondary shredding, are applied to produce SRF and other waste fractions. The purpose is to selectively separate inert material, metals and highly chlorinated/pollutant waste components from the input waste into small streams so as to obtain a high yield of a quality controlled SRF. Based on the extent and intensity of the treatment process, SRF with a different level of quality can be obtained. As an example, typical values for the properties of a low, medium and a high quality SRF are provided in Tables A.9 and A.10. Data refers to SRF produced in a TM multi-stage system by processing commercial waste, packaging waste, industrial waste and pre-processed household waste to low, medium and high quality SRF[39],[139].

The mechanical-biological treatment process (MBT) includes a bio-stabilization step aimed at guaranteeing de-humidification through a biological process (no energy or fuel consumption for heating), sanitation, stabilization of organic compounds and to obtain a waste fuel with stable moisture (e.g. 10-15 % max), mass reduction (e.g. 30 % by weight,) and increases in the calorific value (e.g. 35 % with respect to the MSW input stream).[140],[141] Multistage processing schemes based on a "single flow process" or a "two-path process" are adopted in MBT plants. An example of typical values for the SRF produced is provided in Table A.11[141].

Table A.1 — SRF produced from MSW in a MT plant. Differences in composition (top table) and physico-chemical properties (bottom table) between the input waste streams and the output SRF and processed waste fractions (adapted from[5])

Component	Unit	INPUT	OUTPUT					
		MSW	SRF	Reject material	Separated Fe-metals	Separated Non-Fe metals	Heavy fraction	Fine Fraction
Paper Cardboard	% in mass	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
Textiles		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

Property	Unit	INPUT	OUTPUT			
		MSW	SRF	Reject material	Fine fraction	Heavy fraction
Moisture	% in mass ar	13,5	15,0	26,8	33,0	8,9
Ash 550 °C	% in mass d	22,4	9,8	32,5	50,3	96,0
Volatile matter	% in mass d	n/a	79,4	n/a	n/a	n/a
Biogenic content	% C	n/a	50,8	n/a	n/a	n/a
C	% in mass d	47,0	53,0	40,3	28,0	8,3
H	% in mass d	6,2	7,4	5,2	3,6	1,1
N	% in mass d	0,5	0,6	0,9	0,9	0,2
S	% in mass d	0,2	0,2	0,5	1,0	0,1
O	% in mass d	19,6	28,0	16,3	14,8	4,0
NCV	MJ/kg ar	16,7	20,2	12,0	7,3	2,5
	MJ/kg d	19,6	22,4	16,8	12,0	3,0

- n/a: value not reported

Table A.2 — SRF produced from IW & IC streams in a MT plant. Differences in composition (top table) and physico-chemical properties (bottom table) between the input waste stream and the output SRF and processed waste fractions (adapted from[6])

Component	Unit	INPUT	OUTPUT					
		C&I W	SRF	Reject material	Separated Fe-metals	Separated Non-Fe metals	Heavy fraction	Fine Fraction
Paper Cardboard	% in mass	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	-	5,8
Textiles		9,0	8,5	9,2	1,4	1,4	-	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	16,8	0,8
Foam		1,0	1,2	0,2	-	0,6	-	4,5
Glass		3,6	-	10,0	-	1,4	1,4	16,8
Stone		3,0	-	18,5	-	-	66,2	28,2
Fines		5,0	6,0	17,0	-	-	1,8	26,6

Property	Unit	INPUT	OUTPUT		
		I&C W	SRF	Reject material	Fine Fraction
Moisture	% in mass ar	26,5	25,0	26,0	44,5
Ash 550 °C	% in mass d	16,6	12,5	23,0	48,0
C	% in mass d	48,0	57,4	41,0	29,6
H	% in mass d	7,0	8,0	5,8	4,0
N	% in mass d	0,6	0,5	1,0	1,2
S	% in mass d	0,2	0,3	0,3	0,8
O	% in mass d	18,0	17,8	20,8	16,0
NCV	MJ/kg ar	13,0	18,0	11,6	5,5
	MJ/kg d	18,5	25,0	16,6	12,0

Table A.3 — SRF produced from C&D waste streams in a MT plant. Differences in composition (top table) and physico-chemical properties (bottom table) between the input waste stream and the output SRF and processed waste fractions (adapted from[7])

Component[a]	Unit	INPUT	OUTPUT					
		C&D W	SRF	Reject material	Separated-Fe-metals	Separated non-Fe metals	Heavy fraction	Fine fraction
Paper Cardboard	% in mass	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
Textiles		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 materials[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

NOTE 1: The composition of the ICW stream was determined after primary shredding.

NOTE 2: Stone/rock, concrete, gypsum etc.

Property	Unit	INPUT	OUTPUT			
		C&D W	SRF	Reject materials	Fine fraction	Heavy fraction
Moisture	% in mass ar	14,0	16,5	12,0	23,6	10,4
Ash 550 °C	% in mass d	46,8	9,0	47,2	78,8	65,6
Volatile matter	% in mass d	n/a	76,6	n/a	n/a	n/a
Biogenic content	%C	n/a	66,7	n/a	n/a	n/a
C	% in mass d	30,0	50,0	31,2	12,0	20,0
H	% in mass d	4,0	6,4	3,8	1,3	2,6
N	% in mass d	0,5	1,0	0,6	0,4	0,5
S	% in mass d	0,7	0,3	0,7	2,8	0,3
O	% in mass d	17,0	31,6	16,2	4,8	13,2
NCV	MJ/kg ar	9,8	18,0	10,0	2,5	6,5
	MJ/kg d	11,0	20,0	12,0	4,0	7,6

- n/a: value not reported

Table A.4 — Reference values for physico-chemical properties of SRF produced from municipal solid wastes (MSW), and from commercial waste streams, statistically derived from measured values collected in several European countries (adapted from[116])

Waste stream	Statistic	NCV	Cl	Hg	Cd + Tl
		MJ/kg ar	% in mass ar	mg/MJ ar	mg/MJ ar
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

Table A.5 — SRF produced from MSW streams. Statistical analysis of the collected dataset of measured values: summary results for the physico-chemical properties monitored (top table) and the content of trace elements it is compulsory to specify according to EN 15359 and ISO 21640 (bottom table)

Parameter	**Moisture**	**NCV**		**Ash**	**Cl**
Unit	% in mass ar	MJ/kg ar	MJ/kg d	% in mass% d	% in mass ar
Qty of data	*215*	*215*	*215*	*214*	*164*
Median	19,00	16,80	21,17	14,30	0,381
80th perc.	27,52	19,26	23,77	18,30	0,738

Parameter	**Hg**	**Sb**	**Tl**	**As**	**Cd**	**Sn**	**Pb**	**Co**	**Cr**	**Cu**	**Ni**	**V**	**Mn**
Unit	mg/kg d												
Qty of data	*179*	*101*	*58*	*205*	*184*	*28*	*134*	*100*	*209*	*128*	*209*	*48*	*157*
Median	0,305	21,33	0,350	1,280	0,995	7,650	90,63	4,420	48,00	83,71	16,44	3,070	78,100
80th perc.	0,996	57,25	0,500	2,500	2,179	28,64	188,60	6,984	90,99	206,08	28,49	5,844	113,94
Unit	mg/MJ d												
Qty of data	*179*	*101*	*58*	*205*	*184*	*28*	*134*	*100*	*209*	*128*	*209*	*48*	*157*
Median	0,015	1,000	0,016	0,063	0,044	0,323	4,410	0,200	2,305	3,935	0,792	0,137	3,707
80th perc.	0,045	2,800	0,026	0,100	0,092	1,419	8,143	0,320	4,202	9,103	1,358	0,302	5,600

Table A.6 — SRF produced from mixed waste streams. Statistical analysis of the collected dataset of measured values: summary results for the physico-chemical properties monitored (top table) and the content of trace elements it is compulsory to specify according to EN 15359 and ISO 21640 (bottom table)

Parameter	**Moisture**	**NCV**		**Ash**	**Cl**
Unit	% in mass ar	MJ/kg ar	MJ/kg d	% in mass d	% in mass ar
Qty of data	*94*	*95*	*95*	*94*	*93*
Median	10,90	18,80	22,44	15,80	0,470
80th perc.	21,58	21,90	23,87	18,96	0,614

Parameter	**Hg**	**Sb**	**Tl**	**As**	**Cd**	**Sn**	**Pb**	**Co**	**Cr**	**Cu**	**Ni**	**V**	**Mn**
Unit	mg/kg d												
Qty of data	*63*	*7*	*6*	*73*	*64*	*1*	*56*	*7*	*84*	*66*	*87*	*5*	*85*
Median	0,350	nd	nd	1,000	1,000	nd	76,00	nd	42,75	10,60	15,20	nd	95,00
80th perc.	1,100	nd	nd	2,726	1,182	nd	149,00	nd	68,40	85,60	30,00	nd	148,40
Unit	mg/MJ d												
Qty of data	*63*	*7*	*6*	*73*	*64*	*1*	*53*	*7*	*84*	*65*	*87*	*5*	*85*
Median	0,018	nd	nd	0,046	0,039	nd	3,186	nd	1,927	0,504	0,732	nd	4,132
80th perc.	0,050	nd	nd	0,127	0,051	nd	6,145	nd	3,159	3,708	1,300	nd	6,500

- nd: value not derived due to the low consistency of the dataset

Table A.7 — SRF from ICW streams. Statistical analysis of the collected dataset of measured values: summary results for the physico-chemical properties monitored (top table) and the content of trace elements it is compulsory to specify according to EN 15359 and ISO 21640 (bottom table)

Parameter	**Moisture**	**NCV**		**Ash**	**Cl**
Unit	% in mass ar	MJ/kg ar	MJ/kg d	% in mass d	% in mass ar
Qty of data	*24*	*24*	*24*	*24*	*17*
Median	10,25	18,10	23,88	12,50	0,45
80th perc.	18,72	30,31	31,04	27,18	1,04

Parameter	**Hg**	**Sb**	**Tl**	**As**	**Cd**	**Sn**	**Pb**	**Co**	**Cr**	**Cu**	**Ni**	**V**	**Mn**
Unit	mg/kg d												
Qty of data	*22*	*20*	*19*	*21*	*22*	*4*	*21*	*20*	*21*	*21*	*20*	*20*	*20*
Median	0,100	51,000	5,000	1,800	0,795	nd	82,00	1,235	50,00	350,00	24,65	4,885	86,15
80th perc.	0,340	87,60	5,000	6,140	6,720	nd	575,00	4,200	100,00	1,333,0	53,08	11,680	195,60
Unit	mg/MJ d												
Qty of data	*22*	*20*	*19*	*21*	*22*	*4*	*21*	*20*	*21*	*21*	*20*	*20*	*20*
Median	0,006	1,991	0,183	0,125	0,044	nd	4,234	0,089	2,046	17,500	1,234	0,230	4,137
80th perc.	0,020	4,254	0,292	0,306	0,300	nd	25,910	0,178	5,859	56,230	3,173	0,618	11,865
- nd: value not derived due to the low consistency of the dataset													

Table A.8 — RPF produced in Asian countries (Japan, South Korea) from IC (paper and plastic) waste streams. Statistical analysis of the collected dataset of measured values: summary results for the fuel properties monitored

Parameter	**Moisture**	**NCV**		**Ash**	**Cl**	**Al** [a]	
Unit	% in mass ar	MJ/kg ar	MJ/kg d	% in mass d	% in mass ar	mg/kg d	mg/MJ d
Qty of data	*174*	*144*	*144*	*174*	*166*	*78*	*75*
Median	2,60	26,75	27,34	5,10	0,13	1600	61,40
80th perc.	4,00	34,13	34,28	6,92	0,23	3380	136,12
NOTE 1: Typical values for Al refer to RPF produced in Japan only, Aluminium is a voluntarily chosen parameter.							

Table A.9 — Composition (top table: results of manual sorting analysis) and physico-chemical properties (bottom table) of low, medium and premium quality SRF produced in a MT facility in Austria (adapted from[38])

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

Parameter	**Unit**	**SRF low quality**		**SRF medium quality**		**SRF premium quality**	
		median	**80th perc**	**median**	**80th perc**	**median**	**80th perc**
Moisture	% in mass ar	26,5	31,4	25,0	29,1	15,1	29,3
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

Parameter	Unit	SRF low quality		SRF medium quality		SRF premium quality	
		median	80th perc	median	80th perc	median	80th perc
Ash	% in mass 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	% in mass d	-	-	46,9	48,6	52,8	58,3

Table A.10 — Yearly characterizations of medium and premium quality SRF produced in a MT facility in Austria (adapted from[139])

Parameter	Unit	Premium Quality SRF						Medium Quality SRF					
		Median			80th percentile			Median			80th percentile		
		2014	2016	2018	2014	2016	2018	2014	2016	2018	2014	2016	2018
NCV	MJ/kg ar	19,3	17,2	17,7	22,8	27,5	22,7	15,5	13,9	15,5	16,8	15,5	19,1
	MJ/kg d	25,0	21,3	22,0	26,6	29,9	23,1	21,2	18,4	22,1	21,4	20,8	26,4
Tot C	% in mass d	52,8	36,6	51,1	58,3	39,2	54,1	46,9	33,4	51,4	48,6	36,4	61,1
DM[a]	% in mass	84,9	84,3	82,6	89,1	92,4	85,8	75,0	75,1	68,5	81,2	85,1	77,1
Ash	% in mas d	14,2	17,6	15,6	16,6	22,1	19,4	17,2	20,2	16,2	19,5	24,1	23,8
Cl	g/kg d	13,8	12,2	6,8	17,1	16,7	11,6	10,8	9,5	12,5	22,2	11,5	15,5
S	g/kg d	3,3	4,2	3,0	4,5	6,4	3,9	3,4	5,4	4,4	4,6	6,1	17,1
Sb	mg/MJ d	4,5	2,0	1,6	5,9	4,3	2,5	1,1	1,7	1,5	3,6	2,8	4,2
As	mg/MJ d	0,1	< 0,1	0,1	0,2	< 0,1	0,2	< 0,1	0,1	0,1	0,3	0,2	0,4
Pb	mg/MJ d	8,0	3,3	4,9	11,7	6,1	7,4	4,3	6,3	5,0	9,5	24,5	33,0
Cd	mg/MJ d	0,06	0,08	0,02	0,25	0,15	0,04	0,05	0,05	0,06	0,28	0,20	0,10
Cr	mg/MJ d	4,8	6,9	2,6	7,7	9,0	3,1	4,5	3,9	3,4	8,5	10,1	7,4
Co	mg/MJ d	0,2	0,3	0,3	0,4	0,5	0,4	0,2	0,3	0,4	0,4	0,4	0,8
Ni	mg/MJ d	0,7	0,7	0,8	1,2	2,3	0,8	0,8	1,2	1,8	1,9	1,6	2,7
Hg	mg/MJ d	0,040	< 0,011	0,012	0,072	< 0,012	0,014	0,047	0,015	0,012	0,052	0,015	0,054

Table A.11 — Properties of premium quality SRFs produced in MBT plants in Croatia and utilized as fuel feedstock in the national cement manufacturing industry (adapted from[141])

Key parameter	Unit	Measured values (Median)		
		SRF # 1	*SRF # 2*	*SRF # 3*
NCV	MJ/kg ar	16,6	14,4	23,8
	MJ/kg d	20,6	18,3	28,1
Total C	% in mass d	49,6	46,6	62,9
Biomass content[a]	% in mass d	34,7	52,4	20,7
Non-biomass content[a]	% in mass d	65,3	47,6	79,3
Biomass content	% in mass d	38,4	55,2	25,5
Non-biomass content	% in mass d	35,3	22,6	63,1
Dry matter	% in mass d	82,5	81,3	85,8

NOTE: Relative to the total C content.

Table A.11 *(continued)*

Key parameter	**Unit**	**Measured values (Median)**		
		SRF # 1	***SRF # 2***	***SRF # 3***
Ash (815 °C)	% in mass 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
NOTE: Relative to the total C content.				

Annex B
(informative)

Fuel specification: Provisions in national standards, legislation, plant permits. General and national guidelines. Voluntary specification by the end user

B.1 Provisions in national standards

The key parameters and the limit values adopted in some national standards for the classification and specification of solid recovered fuels are detailed in Tables B.1 to B.5.

Table B.1 — FINLAND. Rules for the classification and specification (limit values) of SRF utilized in incineration and co-incineration plants set in national standard SFS 5875 (adapted from[43])

Parameter	Unit	Class 1	Class 2	Class 3
		Limit value	Limit value	Limit value
Cl	% in mass	< 0,15	< 0,5	< 1,5
S	% in mass	< 0,2	< 0,3	< 0,5
N	% in mass	< 1,0	< 1,5	< 2,5
K + Na	% in mass	< 0,2	< 0,4	< 0,5
Hg	mg/kg d	< 0,1	< 0,2	< 0,5
Cd	mg/kg d	< 1,0	< 0,4	< 5,0

Table B.2 — GERMANY. Rules for the specification (limit values for trace elements) of SRF utilized in co-incineration and co-combustion plants set in the national standard RAL-GZ 724 (c) (adapted from[9,44,46,47])

Parameter	RAL-GZ 724: 2008			RAL-GZ 724: 2012		
	Limit value (median)	Limit value (80th percentile)	Unit	Limit value (median)	Limit value (80th percentile)	Unit
As	5,0	13,0	mg/kg d	0,31	0,81	mg/MJ d
Cd	4,0	9,0	mg/kg d	0,25	0,56	mg/MJ d
Co	6,0	12,0	mg/kg d	0,38	0,75	mg/MJ d
Cr	40[a] 125[b]	120[a] 250[b]	mg/kg d	7,8	16	mg/MJ d
Hg	0,60	1,20	mg/kg d	0,038	0,075	mg/MJ d
Mn	50[a] 250[b]	100[a] 500[b]	mg/kg d	16	31	mg/MJ d
Ni	25[a] 80[b]	50,0[a] 160[b]	mg/kg d	5	10	mg/MJ d
Pb	70[a] 190[b]	200[a] 400[b]	mg/kg d	12	25	mg/MJ d
Sb	50	120	mg/kg d	3,1	7,5	mg/MJ d
Sn	30	70	mg/kg d	1,9	4,4	mg/MJ d

- nd: limit value not reported

[a] For solid recovered fuel that originates from production-specific waste.

[b] For solid recovered fuel that originates from high calorific fractions of municipal waste.

[c] In addition, chlorine, water, ash and copper contents are reported regularly.

Table B.2 *(continued)*

Parameter	RAL-GZ 724: 2008			RAL-GZ 724: 2012		
	Limit value (median)	Limit value (80th percentile)	Unit	Limit value (median)	Limit value (80th percentile)	Unit
Tl	1,00	2,00	mg/kg d	0,063	0,13	mg/MJ d
V	10	25	mg/kg d	0,63	1,6	mg/MJ d
Cu	200[a] 400[b]	500[a] 1000[b]	mg/kg d	nd	nd	mg/MJ d

- nd: limit value not reported

[a] For solid recovered fuel that originates from production-specific waste.

[b] For solid recovered fuel that originates from high calorific fractions of municipal waste.

[c] In addition, chlorine, water, ash and copper contents are reported regularly.

Table B.3 — ITALY. Rules for the classification and specification of the solid recovered fuels CDR and CDR-Q set in the national standard UNI 9903-1 (adapted from[14])

Key parameter	Unit	Statistic	CDR	CDR-Q
			Limit value	Limit value
Moisture	% in mass ar	mean	< 25	< 15
Ash	% in mass d	mean	< 20	< 15
NCV	kJ/kg ar	mean	> 15,000	> 20,000
Cl (total)	% in mass ar	mean	0,9	< 0,7
As	mg/kg d	mean	< 9	< 5
Cd	mg/kg d	mean	< 7	< 7
Hg	mg/kg d	mean	< 3	< 1
Cr	mg/kg d	mean	< 100	< 70
Cu (soluble)	mg/kg d	mean	< 300	< 50
Mn	mg/kg d	mean	< 400	< 200
Ni	mg/kg d	mean	< 40	< 30
Pb (volatile)	mg/kg d	mean	< 200	< 100
S	mg/kg d	mean	< 0,6	< 0,3

Table B.4 — ITALY. Quality requirements (specification) set in the national standard UNI/TS 11553 for the solid recovered fuel CSS utilized in incineration, co-incineration and co-combustion plants (adapted from[19])

Parameter	Unit	Statistic	CSS Limit value
Cd	mg/kg d	median	10
Tl	mg/kg d	median	10
As	mg/kg d	median	15
Co	mg/kg d	median	20
Cr	mg/kg d	median	500
Cu	mg/kg d	median	2,000
Mn	mg/kg d	median	600
Ni	mg/kg d	median	200
Pb	mg/kg d	median	600
Sb	mg/kg d	median	150

Table B.4 *(continued)*

Parameter	Unit	Statistic	CSS Limit value
V	mg/kg d	median	150
Hg	MJ/kg ar	median - 80th percentile	EN 15359 - values for classes 1 and 2
Cl	% in mass d	mean	EN 15359 - values for classes 1, 2 and 3

Table B.5 — JAPAN. Rules (limit values) for the classification of the SRF referred to in the country as RPF set in the national standard JIS Z 7311 (adapted from[50,25])

Parameter	Unit	Statistic	RPF coke	RPF class A	RPF class B	RPF class C
NCV	MJ/kg ar	mean	≥ 33	≥ 25	≥ 25	≥ 25
Moisture	% in mass ar	mean	≤ 3	≤ 5	≤ 5	≤ 5
Ash	% in mass d	mean	≤ 5	≤ 10	≤ 10	≤ 10
Cl (residual)	% in mass ar	mean	≤ 0,6	≤ 0,3	> 0,3 - ≤ 0,6	>0,6 - ≤ 2,0

B.2 Provisions in national legislations

The following Tables B.6 to B.12 provide references for the quality requirements specified in some national legislation for the use of SRF/RDF and other combustible wastes in EfW plants, as waste or as a fuel product (end-of-waste).

Table B.6 — AUSTRIA. Quality requirements (specification: limit values) legally defined for secondary fuels to be utilized as waste in co-incineration and coal co-combustion plants (adapted from[21])

Parameter	Unit	Statistic	Coal co-combustion in cement kilns [a]	Coal co-combustion in power plants [c]		Co-incineration
			Waste fuels as waste			
			Limit value	Limit value proportion of thermal output ≤ 10%	Limit value proportion of thermal output ≤ 15%	Limit value
Sb	mg/MJ d	Median	7	7	7	7
	mg/MJ d	80th Perc.	10	10	10	10
As	mg/MJ d	Median	2	2	2	1
	mg/MJ d	80th Perc.	3	3	3	1,5
Pb	mg/MJ d	Median	20	23	15	15
	mg/MJ d	80th Perc.	36	41	27	27
Cd	mg/MJ d	Median	0,23 [b]	0,27	0,17	0,17
	mg/MJ d	80th Perc.	0,46 [b]	0,54	0,34	0,34

[a] According to the Austrian legal act (Annex 8, (1.1)), the limit values apply to those parts of cement production plants in which cement clinker is burned (furnace system in accordance with Art. 2(1) (c) of the Cement Regulation (ZemetV) 2007, BGBI II No. 60/2007, consisting of the rotary furnace, the cyclone or grate preheater and the calciner.

[b] For quality-assured waste fuels (code number 91108 in accordance with the List of Waste Ordinance, BGB1 No. 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.

[c] According to the Austrian legal act (Annex 8, (1.2)), the limit values apply to boilers predominantly using hard coal or lignite for the generation of electricity and district heating. The proportion of the thermal output from the incineration of waste relative to the total thermal output is limited to a maximum of 15 %.

Table B.6 *(continued)*

Parameter	Unit	Statistic	Coal co-combustion in cement kilns [a]	Coal co-combustion in power plants [c]		Co-incineration
			Waste fuels as waste			
			Limit value	**Limit value** proportion of thermal output ≤ 10%	**Limit value** proportion of thermal output ≤ 15%	**Limit value**
Cr	mg/MJ d	Median	25	31	19	19
	mg/MJ d	80th Perc.	37	46	28	28
Co	mg/MJ d	Median	1,5	1,4	0,9	0,9
	mg/MJ d	80th Perc.	2,7	2,5	1,6	1,6
Ni	mg/MJ d	Median	10	11	7	7
	mg/MJ d	80th Perc.	18	19	12	12
Hg	mg/MJ d	Median	0,075	0,075	0,075	0,075
	mg/MJ d	80th Perc.	0,15	0,15	0,15	0,15

[a] According to the Austrian legal act (Annex 8, (1.1)), the limit values apply to those parts of cement production plants in which cement clinker is burned (furnace system in accordance with Art. 2(1) (c) of the Cement Regulation (ZemetV) 2007, BGBI II No. 60/2007, consisting of the rotary furnace, the cyclone or grate preheater and the calciner.

[b] For quality-assured waste fuels (code number 91108 in accordance with the List of Waste Ordinance, BGB1 No. 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.

[c] According to the Austrian legal act (Annex 8, (1.2)), the limit values apply to boilers predominantly using hard coal or lignite for the generation of electricity and district heating. The proportion of the thermal output from the incineration of waste relative to the total thermal output is limited to a maximum of 15 %.

Table B.7 — AUSTRIA. Quality requirements (specification: limit values) legally set for the fuel product (end-of-waste of secondary fuels) to be used in the legally permitted EfW plants (adapted from[21])

Parameter	Unit	Statistic	Waste fuel as fuel product
			Limit value[a]
Sb	mg/MJ d	Median	0,5
	mg/MJ d	80th Perc.	0,75
As	mg/MJ d	Median	0,8
	mg/MJ d	80th Perc.	1,2
Pb	mg/MJ d	Median	4
	mg/MJ d	80th Perc.	6
Cd	mg/MJ d	Median	0,05
	mg/MJ d	80th Perc.	0,075
Cr	mg/MJ d	Median	1
	mg/MJ d	80th Perc.	2,1
Co	mg/MJ d	Median	0,7
	mg/MJ d	80th Perc.	1,05
Ni	mg/MJ d	Median	1,6
	mg/MJ d	80th Perc.	2,4

NOTE According to the Austrian Ordinance (Annex 9) the waste fuel products may be incinerated only in plants with a rated thermal output of ≥ 50 kW that comply with a limit value for dust amounting to 20 mg/m^3 (ha-hourly-value) or in plants falling under the scope of Art. 2(1) of the Ordinance.

Table B.7 *(continued)*

Parameter	Unit	Statistic	Waste fuel as fuel product
			Limit value[a]
Hg	mg/MJ d	Median	0,02
	mg/MJ d	80th Perc.	0,03
S	mg/MJ d	Median	200
	mg/MJ d	80th Perc.	300
Cl	mg/MJ d	Median	100
	mg/MJ d	80th Perc.	150

NOTE According to the Austrian Ordinance (Annex 9) the waste fuel products may be incinerated only in plants with a rated thermal output of ≥ 50 kW that comply with a limit value for dust amounting to 20 mg/m^3 (ha-hourly-value) or in plants falling under the scope of Art. 2(1) of the Ordinance.

Table B.8 — FRANCE. Quality requirements (specification: limit values) legally set for the use of the SRF known as CSR as waste in the relevant EfW plants[a] (adapted from[16])

Parameter	Unit	Statistic	CSR
			Limit value
NCV	MJ/kg ar	nd	> 12
Hg	mg/kg d	nd	< 3
Cl	mg/kg d	nd	< 15,000
Br	mg/kg d	nd	< 15,000
Sum of Br, Cl, F, I	mg/kg d	nd	< 20,000

- nd: statistic not reported.

[a] The relevant EfW plants are those that fall into the class 2971 of the national nomenclature of plants for the protection of the environment. This means plants that produce heat or electricity from NHW in the form of CSR prepared in an associated pre-treatment facility, alone or mixed with other fuels.

Table B.9 — INDIA. Rules (maximum permissible values) for the classification and specification of SCF (segregated combustible fraction) and MSW-RDF to be used in cement kilns, according to the proposal of the Ministry of Housing and Urban Affairs, MoHUA of India (adapted from[30])

Parameter	Unit	SCF[a]	RDF Grade III[b]	RDF Grade II[c]	RDF Grade I[c]
		Mean value			
NCV	kcal/kg	> 1,500	> 3,000	> 3,750	> 4,500
		Maximum permissible value			
Ash	% in mass	< 20	< 15	< 10	< 10
Moisture	% in mass	< 35	< 20	< 15	< 10
Cl	% in mass	< 1,0	< 1,0	< 0,7	< 0,5
S	% in mass	< 1,5	< 1,5	< 1,5	< 1,5
Particle size	mm	< 400	< 50, if ILC plant[d] — < 20, if SLC plants[e]		

[a] Segregated combustible fractions as input material for the Waste to Energy plant (incineration plants) or RDF pre-processing facility.

[b] Refuse derived fuel for co-processing directly or after processing with other waste materials in cement kilns.

[c] Refuse derived fuel for direct co-processing in cement kilns.

[d] In Line Calciner.

[e] Separate Line Calciner.

Table B.10 — ITALY. Quality requirements (specification: limit values) legally set for the SRF known as CDR and CDR-Q to be utilized as waste in the permitted incineration and co-incineration, plants, power plants and cement kilns (adapted from[13-15])

Parameter	Unit	Statistic	CDR [a b]	CDR-Q [c d]
			Limit value	Limit value
NCV	MJ/kg ar	mean	> 15	> 20
Moisture	% in mass ar	mean	< 25	< 18
Cl	% in mass ar	mean	< 0,9	< 0,7
Ash	% in mass d	mean	< 20	< 15
Pb (volatile)	mg/kg d	mean	< 200	< 100
Cr	mg/kg d	mean	< 100	< 70
Cu (soluble)	mg/kg d	mean	< 300	< 50
Mn	mg/kg d	mean	< 400	< 200
Ni	mg/kg d	mean	< 40	< 30
As	mg/kg d	mean	< 9	< 5
Cd+Hg	mg/kg d	mean	< 7	nd
Cd	mg/kg d	mean	nd	< 3
Hg	mg/kg d	mean	nd	< 1

\- nd: limit value not legally defined

NOTE

[a] The use of CDR is permitted in authorized incineration/co-incineration plant > 10 MW.

[b] The use of CDR is permitted in authorized co-combustion plants > 20 MW.

[c] The use of CDR-Q is authorized in authorized cement kilns with a clinker production > 500 t/d.

[d] The use of CDR-Q is permitted in authorized power plants > 50 MW.

Table B.11 — ITALY. Quality requirements (specification: limit values) legally set for the fuel product *CSS-combustibile* (end-of-waste of the SRF known as CSS in the country) to be used in the legally permitted cement kilns[a] and power plants[b] (adapted from[20])

Parameter	Unit	Statistic	*CSS- combustibile*
			Limit value
NCV	MJ/kg ar	mean	EN 15359 - Values for classes 1, 2 and 3
Cl	% in mass d	mean	EN 15359 - Values for classes 1, 2 and 3
Hg	mg/MJ ar	median	EN 15359 - Values for classes 1 and 2
	mg/MJ ar	80th perc.	EN 15359 - Values for classes 1 and 2
Sb	mg/kg d	median	50
As	mg/kg d	median	5
Cd	mg/kg d	median	4
Cr	mg/kg d	median	100
Co	mg/kg d	median	18
Mn	mg/kg d	median	250

NOTE

[a] The use of the *CSS-Combustibile* is permitted only in authorized cement kilns with a clinker production > 500 tonne/d, that apply a quality management system according to UNI EN ISO 14001 or EMAS.

[b] The use of the *CSS-Combustibile* is permitted only in authorized thermo-electrical power plants with a rated thermal output > 50 MW, that apply a quality management system according to UNI EN ISO 14001 or EMAS.

Table B.11 *(continued)*

Parameter	Unit	Statistic	*CSS- combustibile* Limit value
Ni	mg/kg d	median	30
Pb	mg/kg d	median	240
Cu	mg/kg d	median	500
Tl	mg/kg d	median	5
V	mg/kg d	median	10

NOTE

[a] The use of the *CSS-Combustibile* is permitted only in authorized cement kilns with a clinker production > 500 tonne/d, that apply a quality management system according to UNI EN ISO 14001 or EMAS.

[b] The use of the *CSS-Combustibile* is permitted only in authorized thermo-electrical power plants with a rated thermal output > 50 MW, that apply a quality management system according to UNI EN ISO 14001 or EMAS.

Table B.12 — SOUTH KOREA. Quality requirements (limit values) legally set for the classification and specification of the waste derived fuels produced in the country (adapted from[26])

Parameter	Unit	Until 2012 – Solid Fuel					Since 2013 – SRF			
		RDF		RPF	TDF	WCP	SRF		Bio-SRF	
		pellet	non pellet	pellet	--	--	pellet	non pellet	pellet	non pellet
Diameter	mm	≤ 30	--	≤ 50	--	--	≤ 50	≤ 50	≤ 50	≤ 120
Length	mm	≤ 100	passing rate ≥ 95 %	≤ 100	≤ 120	≤ 100	≤ 100	≤ 50	≤ 100	≤ 120
Moisture	% in mass ar	≤ 10	≤ 25	≤ 10			≤ 10	≤ 25	≤ 10	≤ 25
NCV	kcal/kg	≥ 3,500		≥ 6,500		≥ 3,500	≥ 3,500	≥ 3,500	≥ 3,000	≥ 3,000
Ash	% in mass d	≤ 20			≤ 4	≤ 8	≤ 20		≤ 15	
Cl	% in mass d	≤ 2				≤ 0,3	≤ 2		≤ 0,5	
S	% in mass d	≤ 0,6			≤ 2	≤ 1,2	≤ 0,6		≤ 0,6	
Hg	mg/kg d	≤ 1,2				≤ 1,0	≤ 1,0		≤ 0,6	
Cd	mg/kg d	≤ 9,0				≤ 2,0	≤ 5,0		≤ 5,0	
Pb	mg/kg d	≤ 200,0				≤ 30,0	≤ 150		≤ 100,0	
As	mg/kg d	≤ 13,0				≤ 2,0	≤ 13,0		≤ 5,0	
Cr	mg/kg d	--				≤ 30,0	--		≤ 70,0	

B.3 Provisions in local plant permits

Some examples of provisions for the quality of SRF/RDF and other combustible wastes provided locally in plant permits are reported in Tables B.13 to B.15. The data found refer exclusively to plant permits issued for end use in cement kilns and power plants in European countries.

Table B.13 — End use: CEMENT KILNS AND COAL FIRED POWER PLANTS. Specification for SRF from high calorific fractions of MSW (limit values for trace elements) in plant permits issued in Germany, based on regulations of the Environmental Ministry of North Rhine Westphalia (NRW), September 2005 (adapted from[68],[110])

Parameter	Unit	SRF - Limit value[a b] (practical value)	SRF - Limit value[a c] (maximum value)
As	mg/kg d	5	13
Sb	mg/kg d	50	120
Pb	mg/kg d	190	400
Cd	mg/kg d	4	9
Cr	mg/kg d	125	250
Cu	mg/kg d	350 [d]	700 [d]
Co	mg/kg d	6	12
Ni	mg/kg d	50	100
Hg	mg/kg d	0,6	1,2
Mn	mg/kg d	250	500
Tl	mg/kg d	1	2
V	mg/kg d	10	25
Zn	mg/kg d	nd	nd
Sn	mg/kg d	30	70

KEY

- nd: value not defined.

[a] These limit values of NRW have subsequently been introduced by other federal states in Germany.

[b] Limit value to be compared with 50th percentile over one month.

[c] Limit value to be compared with 80th and 90th percentiles over one month.

[d] Higher Cu-values as a result of non-homogeneities in individual cases acceptable.

Table B.14 — End use: CEMENT KILN. Specifications (limit values for trace elements) for waste fuels in plant permits issued by local authorities in Spain, Belgium and France (adapted from[68],[110])

Parameter	Unit	Spain	Belgium	France
		Waste fuels		
		Limit value	Limit value	Limit value
Cl	% in mass	2	2	2
F	% in mass	0,20	nd	nd
S	% in mass	3	3	3
Br+I	mg/kg d	nd	2,000	nd
Cyanide	mg/kg d	nd	100	nd
Hg	mg/kg d	10	5	10
Cd	mg/kg d	50/100	70	nd
Tl	mg/kg d	50/100	30	nd
Sum of Hg, Cd, Tl	mg/kg d	100	nd	100
Sum of Sb, As, Co, Ni, Pb, Sn, V, Cr	mg/kg d	5,000/10,000	2,500	2,500
Sb	mg/kg d	nd	200	nd
As	mg/kg d	nd	200	nd

- nd: value not defined.

Table B.14 *(continued)*

Parameter	Unit	Spain	Belgium	France
		Waste fuels		
		Limit value	Limit value	Limit value
Co	mg/kg d	nd	200	nd
Ni	mg/kg d	nd	1,000	nd
Cu	mg/kg d	nd	1,000	nd
Cr	mg/kg d	nd	1,000	nd
V	mg/kg d	nd	1,000	nd
Pb	mg/kg d	nd	1,000	nd
Sn	mg/kg d	nd	nd	nd
Mn	mg/kg d	nd	2,000	nd
Be	mg/kg d	nd	50	nd
Se	mg/kg d	nd	50	nd
Te	mg/kg d	nd	50	nd
Zn	mg/kg d	nd	5,000	nd
PCBs	mg/kg d	30	30	25
PCDD/PCDF	mg/kg d	nd	nd	nd

- nd: value not defined.

Table B.15 — End use: CEMENT KILN. Specification (maximum values) for alternative fuels in plant permits issued by local authorities in Austria (adapted from[68])

Parameter	Unit	Waste fuels[a]	Paper sewage sludge	Waste oil solvents varnish waste	Plastics and high calorific fractions	Waste wood	Used tyres	Paper	Rubber	Animal meal
Limit value (maximum value)										
As	mg/kg d	15	5 - 10	10 - 20	15	15	nd	0,5	36	0,3
Sb	mg/kg d	200	20,00	10 - 100	20 - 30 (800 [b])	20	nd	0,5	8,4	1
Pb	mg/kg d	150	100 - 500	250– 800	500	300–800	nd	500	33,8	2
Cd	mg/kg d	5	3 - 5	1 – 20	25 – 27	10– 15	nd	5	8	0,1
Cr	mg/kg d	150	100 - 500	50 – 300	300	70	nd	300	97	5
Co	mg/kg d	50	50 - 60	3 – 25	20 – 100	14	nd	60	128	1
Cu	mg/kg d	700	350 - 600	500	500	100 – 400	nd	600	748	15
Mn	mg/kg d	500	700	70 - 100	nd	150	nd	300	4,250	30
Ni	mg/kg d	100	60	40 – 100	200	100	nd	80	200	1,5
Hg	mg/kg d	0,5	2 - 3	1 – 2	0,86 – 2	1	nd	1	0	0,2
Tl	mg/kg d	3	3	1 – 5	3 – 10	2,0	nd	5,0	1,0	0,6
V	mg/kg d	100	100	10 – 100	70	60	nd	15	40	1

- nd: value not defined.

[a] Waste fuel except sewage sludge; NCV: 5 MJ/kg.

[b] Maximum value required for PET (Polyethylene terephthalate) wastes only.

Table B.15 *(continued)*

Parameter	Unit	Waste fuels[a]	Paper sewage sludge	Waste oil solvents varnish waste	Plastics and high calorific fractions	Waste wood	Used tyres	Paper	Rubber	Animal meal
Zn	mg/kg d	na	1,000 – 2,000	300 – 3,000	nd	1,000	20,000	2,000	11,400	150
Sn	mg/kg d	50	10 - 50	nd	70	nd	nd	10	20	1,5
Cl	% in mass	1	0,8	nd	2	0,5	nd	nd	nd	nd
S	% in mass	3	nd	nd	nd	nd	nd	nd	nd	nd

- nd: value not defined.

[a] Waste fuel except sewage sludge; NCV: 5 MJ/kg.

[b] Maximum value required for PET (Polyethylene terephthalate) wastes only.

B.4 Orientation values in general or national guidelines

Orientation values for the specification of SRF to be used in cement kilns (Table B.16) and coal fired power plants (Table B.17) have been proposed in CEN/TR 15508,[116] with respect to Hg, the sum of Cd and Tl and the sum of heavy metals.

The maximum possible concentrations (Cmax) in tables have been calculated according to transfer factor values to waste gas based on practical data from some European plants (cement kilns: mainly Belgium and Germany; coal fired power plants: Germany).

Table B.16 — End use: CEMENT KILN. Transfer factors (TF) to waste gas for Hg, Cd+Tl, sum of heavy metals and calculated maximum possible concentrations (Cmax) in SRF, proposed as orientation values for the use of SRF in wet and dry cement kiln processes (adapted from[116])

Parameter	Wet process kiln		Dry process kiln	
	TF	C max mg/MJ ar	TF	C max mg/MJ ar
Hg	0,2	0,17	0,1 to 0,4	0,082 to 0,33
Cd+Tl	0,0048	6,90	0,0048	6,90
Sum of heavy metals	0,0002	1,650	0,0002	1,650

Table B.17 — End use: COAL FIRED POWER PLANTS. Transfer factors (TF) for Hg, Cd+Tl, sum of heavy metals and calculated maximum possible concentration (Cmax) in SRF, proposed as orientation values for the use of SRF in DBB and WBB coal fired power plants (data from[116])

Parameter	DBB hard coal		DBB brown coal		WBB hard coal	
	TF	C max mg/MJ ar	TF	C max mg/MJ ar	TF	C max mg/MJ ar
Hg	0,26	0,065	0,2	0,085	0,5	0,034
Cd+Tl	0,014	1,21	0,04	0,43	0,067	0,25
Sum of heavy metals	0,0016	106	0,001	170	0,005	34,00

- DBB: dry-bottom boiler.
- WBB: wet-bottom boiler.

The collected examples of quality requirements for the specification of SRF/RDF and other combustible wastes that occur in national guidelines are reported in Tables B.18 to B.23.

Table B.18 — End use: CEMENT KILN. Specification for trace elements provided in Switzerland in the BUWAL Guideline for the disposal of waste in cement plants (adapted from[44])

Parameter	Unit	Waste fuel
		Mean value
As	mg/MJ d	0,6
Cd	mg/MJ d	0,08
Co	mg/MJ d	0,8
Cr	mg/MJ d	4
Cu	mg/MJ d	4
Hg	mg/MJ d	0,02
Ni	mg/MJ d	4
Pb	mg/MJ d	8
Sb	mg/MJ d	0,2
Sn	mg/MJ d	0,4
Tl	mg/MJ d	0,12
V	mg/MJ d	4

Table B.19 — End use: CEMENT KILN. Desirable characteristics of RDF for co-processing in cement kilns provided in the Municipal Solid Waste Management Manual, PART II (2016) by the national Central Public Health and Environmental Engineering Organisation (CPHEEO) - (adapted from[30])

Parameter	Unit	RDF
		Desiderable value
NCV	kcal/kg	> 3,000
Moisture	% in mass	< 20
Cl	% in mass	< 0,7
S	% in mass	< 2
Size	mm	< 70 - 120

Table B.20 — End use: CEMENT KILNS, LIME KILNS, COAL FIRED POWER PLANTS. Guideline for the specification of SRF protected under the trade marks BPG® and SBS® that are produced in Germany according to RAL GZ 724 and according to the end use (adapted from[8],[43],[45])

Parameter	Unit	BPG^{R} 1	BPG^{R} 2	BPG^{R} 3	SBS^{R} 1	SBS^{R} 2
NCV	MJ/kg ar	16 - 20	20 - 24	23 - 27	13 - 18	18 - 23
Moisture	wt in mass ar	< 35	< 20	< 12,5	< 35	< 20
Ash	mg/kg d	< 20	< 15	< 9	< 20	< 15
Cl	% in mass d	< 1,0	< 1,0	< 1,0	< 0,7	< 1,0
F	% in mass d	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05
S	% in mass d	< 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

Table B.20 *(continued)*

Parameter	**Unit**	BPG^{R} 1	BPG^{R} 2	BPG^{R} 3	SBS^{R} 1	SBS^{R} 2
Cu	mg/kg d	< 400	< 400	< 400	< 1,000	< 1,000
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
End use		power plant	cement kiln	lime kiln	lignite power plant	hard coal power plant cement kiln
Origin		residues of paper industry rejects, punching, photographic paper, blocks wet-strength paper, cellulose cloths, etc.	paper wastes as BPG 1, plastics (resins, polyacrylic, polyester, polyolefine, PUR), fibre fabrics, carpets, etc.	low ash plastics (resins, polyacrylic, polyester, polyolefine, PUR)	different high calorific fractions from MSW demolition wastes	as SBS 1

Table B.21 — End use: ADVANCED THERMAL TREATMENT (GASIFICATION AND PYROLYSIS) AND FLUIDIZED BED AND MOVING GRATE COMBUSTION PLANTS. A guideline for the classification and specification of WDF (waste derived fuel) proposed in the UK by WRAP (adapted from[41])

Parameter	**Unit (statistic)**	**WDF classification system – Limit values**				
		Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Biomass content	% in mass ar (mean)	≥ 90	≥ 80	≥ 60	≥ 50	< 50
NCV	MJ/kg ar (mean)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 6,5
Moisture	% in mass ar (mean)	≤ 10	≤ 15	≤ 20	≤ 30	< 40
Ash	% in mass d (mean	≤ 10	≤ 20	≤ 30	≤ 40	< 50
Bulk density	kg/m^3 (mean)	> 650	≥ 450	≥ 350	≥ 250	≥ 100
Cl	% in mass d (mean)	≤ 0,2	≤ 0,6	≤ 0,8	nd	nd
Hg	mg/MJ ar (median)	≤ 0,02	≤ 0,03	≤ 0,06	nd	nd
	mg/MJ ar (80th percentile)	≤ 0,04	≤ 0,06	≤ 0,12	nd	nd

- nd: value not defined.

[a] Sum of Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni) and Vanadium (V).

Table B.21 *(continued)*

Parameter	Unit (statistic)	WDF classification system – Limit values				
		Class 1	Class 2	Class 3	Class 4	Class 5
Cd	mg/MJ ar (median)	≤ 0,1	≤ 0,3	≤ 1,0	≤ 5,0	≤ 7,5
	mg/MJ ar (80th percentile)	≤ 0,2	≤ 0,6	≤ 2,0	≤ 10	≤ 15
sum of Heavy metals[a]	mg/MJ ar (median)	≤ 15	≤ 30	≤ 50	≤ 100	≤ 190
	mg/MJ ar (80th percentile)	≤ 30	≤ 60	≤ 100	≤ 200	≤ 380

- nd: value not defined.

[a] Sum of Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni) and Vanadium (V).

Table B.22 — End use: GASIFICATION PLANT. A general guideline for the specification of RDF (adapted from[127])

Parameter	Unit	RDF Reference Value
Diameter	mm	10 - 15
Length	mm	50 - 150
Bulk density	kg/m^3	500 - 700
NCV	MJ/kg	16 - 18
Moisture	% in mass	6 - 10
Volatile matter	% in mass	71,1
Fixed carbon	% in mass	11,4
S	% in mass	0,5
Cl	% in mass	4 - 6
Total non-combustibles	% in mass	11

Table B.23 — End use: GASIFICATION PLANT. Specifications of SRF suggested by the IEA Study (adapted from[142,143])

Parameter	Unit	SRF Minimum value	SRF Maximum value
Particle size	mm	10	25
Maximum diameter	mm	25	150
Moisture	% in mass ar	2,5	15
Volatile matter	% in mass d	76	86
Ash	% in mass d	6,3	21,2
Ash melting point	°C	1,225	
NCV	MJ/kg ar	15,4	< 25
Sulfur	% in mass d	0,08	0,53
Chlorine	% in mass d	0,26	0,65
Ash sulfur content	% in mass d	0,31	
Fixed carbon	% in mass d	12,2	

Table B.23 *(continued)*

Parameter	Unit	SRF Minimum value	SRF Maximum value
Bulk density	kg/m^3 ar	600	
Hg	mg/MJ ar	0,02	0,04
	mg/kg	0,3	0,7
C	% in mass d	41	49
H	% in mass d	6,1	7,6
N	% in mass d	0,28	1,5
O	% in mass d	22	39
As	mg/kg d	1,4	1,5
Cd	mg/kg d	0,1	2
Co	mg/kg d	1,5	
Cr	mg/kg d	21	70
Cu	mg/kg d	20	250
Ni	mg/kg d	8,5	25
Pb	mg/kg d	4,3	350
Zn	mg/kg d	74	500
Na	mg/kg d	1,190	
K	mg/kg d	670	
Br	mg/kg d	< 3	
F	mg/kg d	43	
Tl	mg/kg d	< 0,05	

B.5 Voluntary end user specifications

A summary of specifications from cement kiln and coal fired power end-user plants was provided in CEN/TR 15508[116] for properties (NCV; Cl content) that are relevant to the classification of SRF. The provided data, re-stated in B.24 and Table B.25, refer to specifications from European end users only, e.g. Belgium, Germany, France (cement kilns) and Germany and the Netherlands (coal fired power plants).

Table B.24 — End user: CEMENT KILN. Summary of specifications for NCV and chlorine in SRF from end-user plants of European countries (adapted from[116])

Parameter	Unit	SRF specification
NCV	MJ/kg ar	5 - 10 to 12 - 22 (mean values)
Cl	% in mass ar	0,5 to 1,0 (mean value) - 1 to 3,0 (maximum value) a

[a] Cl specification depends on the composition of the input. At high substitution rates, the maximum limits are around 3 % in the case of a cement kiln equipped with a salt bypass system and in the range 0,5 % - 1 % in kilns without that system. For a wet process cement kiln a maximum limit of 6 % is reported.

Table B.25 — End user: COAL FIRED POWER PLANT. Summary of specifications for NCV and chlorine in SRF from end-user plants in European countries – (adapted from[116])

Parameter	Unit	Statistic	Hard coal DBB	Hard coal WBB	Brown coal DBB
NCV	MJ/kg ar	mean value	13,5	17	13,5
		range of values	11 - 18	13 - 22	11 - 18
Cl[a]	% in mass d	mean value	0,6	1,1	0,5
		maximum value	1,3	2,5	0,6[b a] 1,0[b]

- DBB: dry-bottom boiler;
- WBB: wet-bottom boiler

[a] The Cl concentration of the total fuel mix is kept < 0,2 % to 0,4 % to prevent high temperature corrosion. The maximum allowable Cl % depends on the design and materials chosen. In the Netherlands the maximum is usually 0,2 %. In the UK the maximum is higher (0,4 %) as the plants are designed for coal with a high Cl content.

[b] The maximum values vary for different companies.

Examples of specifications for SRF/RDF and other combustible wastes that occur in voluntary commitments between the producer and the user have been collected for the purposes of this Report and are reported in the following Tables B.26 to B.33.

Table B.26 — End user: CEMENT KILN. Summary view of specifications (typical values) of waste fuels adopted in German cement kilns (adapted from[68])

Waste fuels Typical value[a]			Waste fuels Typical value[b]		
Parameter	**Unit**	**Range**	**Parameter**	**Unit**	**Value**
Pb	mg/MJ	0,09 - 25	Pb	mg/kg d	400
Cd	mg/MJ	0,01 - 0,7	Cd	mg/kg d	9
Cr	mg/MJ	0,09 - 21	Cr	mg/kg d	250
Ni	mg/MJ	0,1 - 25	Ni	mg/kg d	100
Hg	mg/MJ	0,01 - 0,1	Hg	mg/kg d	0,5 – 1
Tl	mg/MJ	< 0,01 - 0,1	Tl	mg/kg d	1 - 2
Zn	mg/MJ	0,5 - 625	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.

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

Table B.27 — End user: CEMENT KILN. Specification of the solid recovered fuel CSS in a private agreement between a producer and a local cement kiln in Italy, year 2016 (adapted from[144])

Parameter	Unit	CSS Limit value
NCV	MJ/kg ar	≥ 15
Cl	% in mass d	1
Hg	mg/kg d	1

Table B.27 *(continued)*

Parameter	Unit	CSS Limit value
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 B.28 — End user: CEMENT KILN. Specification of RDF (limit values) in a private agreement between a producer and a local cement kiln in Latvia (data from[146])

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

Table B.29 — End user: CEMENT KILN, POWER PLANT, INCINERATION PLANT. Specification of the solid recovered fuel CSS: range of limit values defined in private agreements between a producer and local end-users in Italy, year 2016 - (adapted from[145],[147])

Parameter	Unit	Limit value defined as	CSS Range of Limit value (minimum and maximum)	
NCV	MJ/kg ar	minimum value	15	39
Moisture	% in mass ar	maximum value	10	30
Ash	% in mass d	maximum value	15	30
Cl	% in mass d	maximum value	0,6	1,5
S	% in mass d	maximum value	0,3	0,8
Hg	mg/kg d	maximum value	1,0	1,7
Cd + Hg	mg/kg d	maximum value	7	

Table B.29 *(continued)*

Parameter	Unit	Limit value defined as	CSS Range of Limit value (minimum and maximum)	
Pb volatile	mg/kg d	maximum value	100	200
Cr	mg/kg d	maximum value	70	833
Cu soluble	mg/kg d	maximum value	300	500
Mn	mg/kg d	maximum value	217	500
Ni	mg/kg d	maximum value	40	333
As	mg/kg d	maximum value	9	15
Co	mg/kg d	maximum value	67	100
Sb	mg/kg d	maximum value	20	267
Tl	mg/kg d	maximum value	3,3	10
V	mg/kg d	maximum value	20	100
Zn	mg/kg d	maximum value	500	1,000
F	mg/kg d	maximum value	1,000	
Be	mg/kg d	maximum value	50	
Ba	mg/kg d	maximum value	200	
Se	mg/kg d	maximum value	10	
Sn	mg/kg d	maximum value	70	100
Te	mg/kg d	maximum value	5	

Table B.30 — End user: COAL FIRED POWER PLANT, Specification for the solid recovered fuel CDR/CSS in a voluntary commitment between a producer and an end user in Italy, year 2016 (adapted from[148])

Parameter	Unit	CDR/CSS	
		Typical value[a]	Limit value[a]
Ash	% in mass d	≤ 20	≤ 20
Moisture	% in mass ar	≤ 15	≤ 15
NCV	MJ/kg ar	EN 15359 value for class 3	EN 15359 value for class 3
	MJ/kg d	≥ 15	≥ 15
Cl	% in mass d	EN 15359 value for class 3	EN 15359 value for class 3
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	≤ 1,300	≤ 2,000
Pb	mg/kg d	≤ 200	≤ 600
Mn	mg/kg d	≤ 400	≤ 600
Hg	mg/kg d	EN 15359 value for class 3	EN 15359 value for class 3
Ni	mg/kg d	≤ 40	≤ 200
Tl	mg/kg d	≤ 1	≤ 10
V	mg/kg d	≤ 7,5	≤ 150

[a] This agreed specification requires that SRF complies with EN 15359 and the Italian UNI TR 11581.

Table B.31 — End user: GASIFICATION PLANT. Specification of an MSW-RDF to be used in a (100 MW) circulating fluidized bed gasifier aiming to produce a dust-free syngas for application in cement kilns (data from[142])

Parameter	Unit	MSW-RDF Reference value
Maximum diameter	mm	50
Moisture	% in mass	≤ 35
Volatile matter	% in mass	≤ 75
Ash	% in mass	≤ 25
S	% in mass	< 1
Cl	% in mass	< 2
Mercury	mg/kg	< 1,5
Ash melting point	°C	≥ 960
NCV	MJ/kg	10 - 20
Bulk density	t/m^3	0,25

Table B.32 — End user: GASIFICATION PLANT. Specification of RDF (produced from sorted household waste, demolition wood and industrial waste wood) utilized in the Lahti CFB plant[a] in Finland (adapted from[123,149])

Parameter	Unit	RDF Required value
NCV	MJ/kg d	18 – 24
Moisture	% in mass ar	< 30
Ash	% in mass d	< 15
Cl	% in mass d	< 0,6
Na + K	% in mass d	< 0,3
Hg	mg/kg d	< 0,1

[a] The plant consists of two 80 MW gasification systems feeding a common gas boiler. It can process 250,000 tons of RDF per year, with a production of 50 MW of electricity and 90 MW of district heat.

Table B.33 — End user: GASIFICATION PLANT. Reference data on type and properties of the mix of alternative fuels to be utilized in the CEMEX Rudersdorf CFB gasification plant and main process conditions (data from[123])

	Parameter	Unit	Plant data
Mix of alternative fuels Plastic and paper wastes, SRF/RDF, tar sludge, roofing paper	Particle size	mm	< 100
	Fines size	mm	< 0,5
	Moisture	%	< 50
	NCV	MJ/kg	1-35
	Ash		limited by energy balance
	Bulk density	kg/m^3	> 300
Conventional fuel Lignite (high carbon lignite ash residues)	Particle size	mm	< 6
	Fines size	mm	< 0,5
	NCV	MJ/kg	< 6

Table B.33 *(continued)*

	Parameter	Unit	Plant data
Gasification reactor	Diameter	m	3,5
	Total height	m	23,5
	Grate area	m^2	2,3
	Gas pipe length	m	50
Gasification process	Gasification agent	MW	air
	Thermal capacity	t/h	100
	Feed flow	°C	20-30
	Temperature gasifier	Nm^3/h	900-960
	Gas flow	MJ/m^3	62,000
	Gas NCV	°C	3-5
	Gas temperature	s	900-950
	Gas residence time		4

B.6 Outcomes from the ISO surveys on the specification of solid recovered fuels

A survey was circulated by ISO/TC 300/WG 2 to producers of SRF/RDF from which indicative references on fuel specification can be derived. A total of 25 responses were received: results are summarized in Table B.34 (general fuel profile) and Table B.35 (specification profile).

The survey provided only a qualitative view of fuel specifications (list of the key parameters monitored, without typical or limit values), with the exception of properties (NCV; Cl and Hg content) that are required for the classification of solid recovered fuel according to EN 15359. In that case, the class number that in Table B.35 defines the degree of quality the producer is asking for, identifies the assumed limit value according to the classification system used in EN 15359 (Table 2).

Table B.34 — Survey ISO/TC 300/WG2 N45 survey among producers. General profile of SRF used in the cement and paper industry, in power plants, in gasification/pyrolysis plants, in dedicated SRF combustion plants and other plants

Country	ID Producer	Fuel name	End use	Shape category	Diameter
Italy	IT 1	CSS	DCP	Pellet/briquette/chips	25-30 mm
	IT 2	CSS	CK - PP	Fluff	< 30 mm
	IT 3	CSS	DCP	Fluff	nd
	IT 4	CSS	CK	Fluff	30 mm
	IT 5	CSS	PP	Fluff	35 mm
	IT6	CSS	PP	Fluff	60 mm
	IT 7	CSS	DCP	Fluff	< 60 mm
	IT8	CSS	DCP	nd	nd
Spain	SP 1	nd	CK	crushed	30 mm
	SP2	nd	CK - GP	fluff	25 mm
Sweden	SW 1	Grovkross, RB, BKR	PP	crushed	nd
Germany	D 1	BGS-SBS®	CK - PP	fluff	< 20 mm
	D 2	BGS-SBS®, SBS1-SBS2	CK - PP	fluff	< 50 mm
	D 3	BGS-SBS®	CK - PP	fluff	< 20 mm
	D 4	BGS-SBS®	CK - PP	fluff	< 20 mm
	D 5	BGS-SBS®	CK - PP	fluff	< 30 mm
	D 6	BGS-SBS®	CK - PP	fluff	< 30 mm
	D 7	BGS-SBS®	CK - PP	fluff	< 50 mm
	D 8	BGS-SBS®	CK - PP	fluff	< 50 mm
	D 9	BGS-SBS®	CK - PP	fluff	< 25 mm
	D 10	BGS-SBS®	CK - PP	fluff	< 50 mm
	D 11	BGS-SBS®	CK - PP	fluff	< 16 mm
Japan	J 1	RPF	PI	Pellet/briquette/chips	15-35 mm
	J 2	RPF	PI - CK	Pellet/briquette/chips	30 mm
	J 3	RDF	DCP	Pellet/briquette/chips	15,3 mm

KEY

- nd: fuel name not specified
- CK: end use in the cement industry
- PI: end use in the paper industry
- PP: end use in power plants
- GP: end use in gasification/pyrolysis plants
- DCP: end use in dedicated SRF combustion plants
- CHP: end use in CHP plants for waste combustion

Table B.35 — ISO/TC 300/WG 2 survey among producers. Specification profile of SRF

ID. Producer	End use	NCV [a]	Cl [a]	Hg [a]	Moisture	Ash	S	Cd	As	Tl	Co	Ni	Sb	Pb	Cr	Cu	Mn	V	Sn	Biogenic share	Fossil share	Total C	Fossil C	Biogenic C
IT 1	DCP	3; 4	2; 3	1; 2	•	•		•	•															
IT 2	CK - PP	1	3	1	•	•		•	•															
IT 3	DCP	1- 4	1- 4	1- 4	•	•		•	•															
IT 4	CK	3	3	1	•	•		•	•	•	•	•	•	•	•	•	•	•						
IT 5	PP	4	3	1	•	•		•	•	•	•	•	•	•	•	•	•	•						
IT 6	PP	4	3	3		•		•	•	•	•	•	•	•	•	•	•	•						
IT 7	DCP	3	3	1		•		•	•	•	•	•	•	•	•	•	•	•						
IT 8	DCP	3	4	1	•	•		•	•															
SP 1	CK	2	2	1	•																			
SP2	CK - GP	1	2	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
SW 1	PP	3; 4	2; 3	1- 3	•	•	•	•	•															
D 1	CK - PP	1- 3	3	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
D 2	CK - PP	2; 3	2; 3	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
D 3	CK - PP	1	2; 4	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
D 4	CK - PP	1	2; 4	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
D 5	CK - PP	2	2; 3	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
D 6	CK - PP	1; 2	3; 4	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
D 7	CK - PP	1; 2	3; 4	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
D 8	CK - PP	2	3	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
D 9	CK - PP	1; 2	2- 4	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
D 10	CK - PP	2; 3	2	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
D 11	CK - PP	1; 2	2; 3	1	•	•		•	•	•	•	•	•	•	•	•	•	•	•					
J 1	PI	2	2	1	•	•																		
J 2	PI - CK	2	2	1	•	•																		
J 3	DCP	3	3	2	•	•		•	•															

KEY

- -- : profile not provided
- CK: end use in the cement industry
- PI: end use in the paper industry
- PP: end use in power plants
- GP: end use in gasification/pyrolysis plants
- DCP: end use in dedicated SRF combustion plants

[a] The number reported in the table for the parameters NCV, Cl, Hg identify the class of the SRF according to standard EN 15359: the limit values per class are specified in Table 2.

Annex C
(informative)

Background reference on technologies

C.1 Coal co-combustion in cement kilns

Cement production is an energy-intensive industrial activity for which the background reference on country markets proposed in Annex A clearly shows a progressive shift over time towards the use of alternative fuels, as well as of alternative raw materials, to satisfy the specific need to achieve economic and environmental benefits.

The production of cement involves the heating, calcination and sintering of blended and ground raw materials (e.g. limestone and other materials containing calcium, silicon oxides, aluminium and iron oxides) to form clinker. An overview of a typical cement production process is given by the flow diagram, from quarry to dispatch, provided in Figure C.1[72].

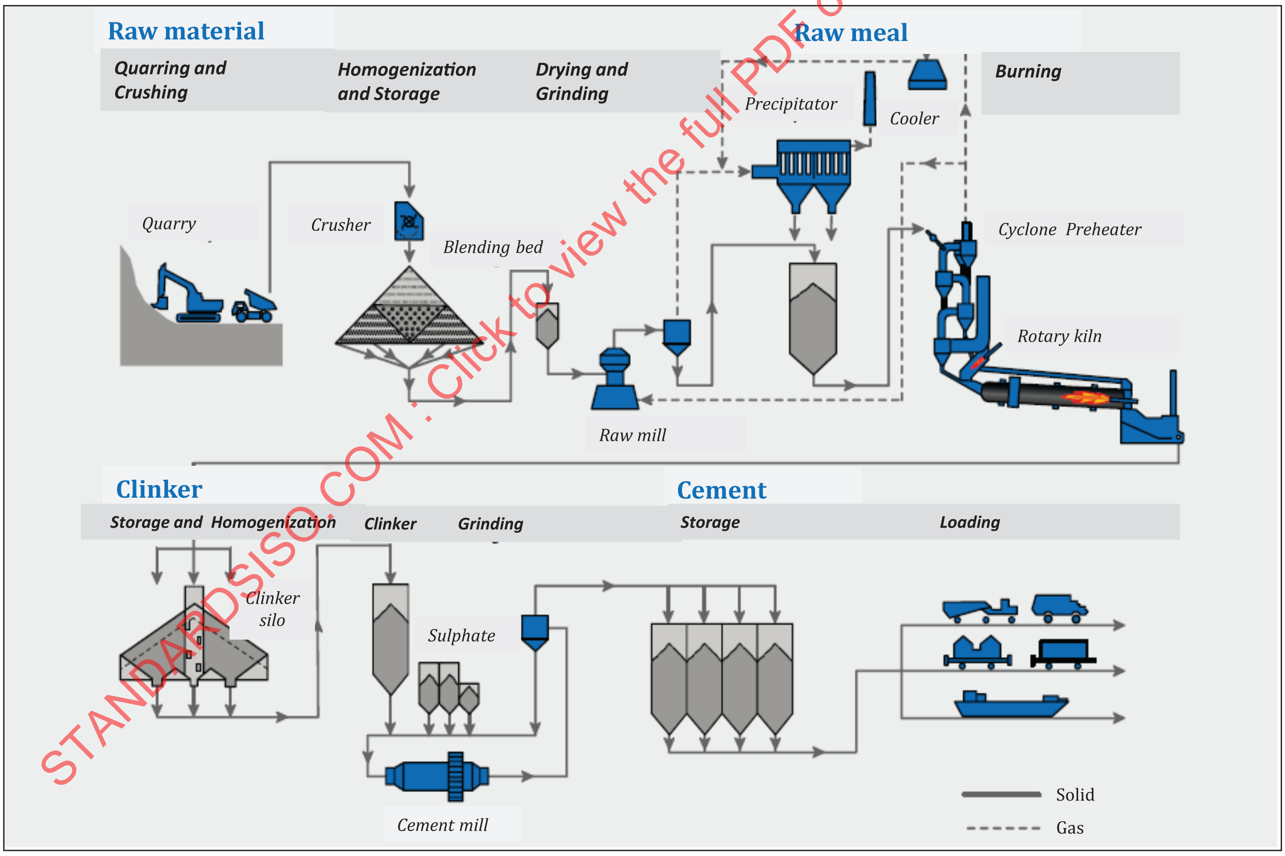
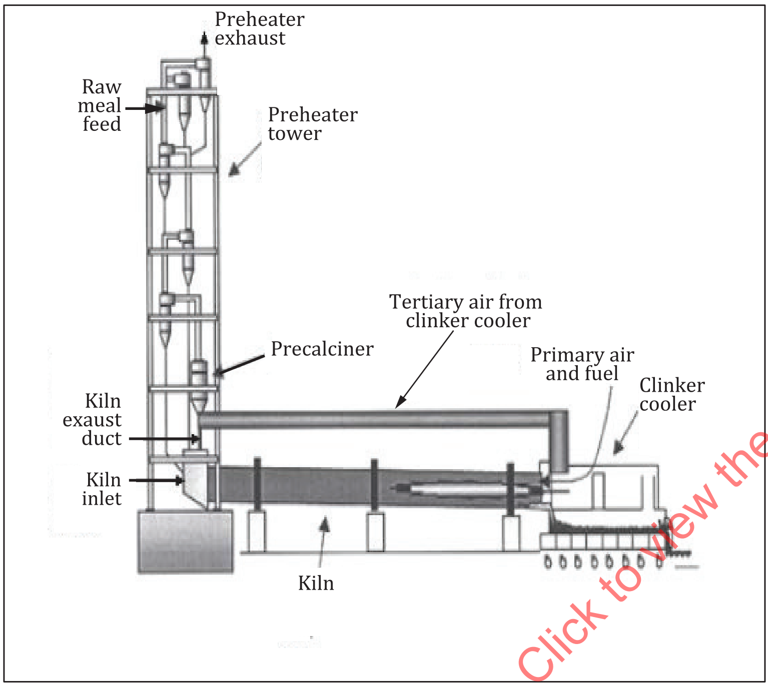


Figure C.1 — Schematic representation of the cement manufacturing process from quarry to dispatch (figure from[72])

The process basically begins with the calcination process, the decomposition of calcium carbonate ($CaCO_3$) at about 900 °C to calcium oxide (CaO, lime), with the release of CO_2 as a by-product, which occurs in the upper, cooler end of the kiln, or, as in most modern cement kiln systems, in a special combustion chamber (pre-calciner) of the preheating tower. In the clinkering process, the calcium oxide reacts at a high temperature (typical range: 1,400–1,500 °C) under oxidising conditions with silica, alumina, and ferrous oxide to form the silicates, aluminates, and ferrites of calcium which comprise the clinker. The clinker is finally ground or milled together with calcium sulfate (natural gypsum, anhydrite or gypsum from flue gas desulfurisation, to adjust the setting behaviour of the cement in order to obtain optimum workability of the product during concrete production) and, if necessary, with further constituents to produce cement[68],[72],[107].

The development and optimization of technologies over time has led to a solution, dry kiln with pre-heater and pre-calciner (Figure C.2), widely adopted in modern cement plants, even if worldwide part of the clinker production still takes place through the wet process. The pre-calcination technique allows, apart from the primary fuel combustion in the kiln burning zone, further burning in a special combustion chamber, installed between the rotary kiln and the preheater system. In that chamber up to 65 % of the total fuel can be burned in a typical pre-calciner kiln (energy is used to calcine the raw meal; calcination levels of about 90 % can be achieved).



Characteristics	Temperature and time
Temperate at main burner	>1 450 °C : material >1 800 °C : flametemperature
Residence time at main burner	>12-15 sec and >1 200 °C >5-6 sec and >1 800 °C
Temperature at precalciner	>850°C : material >1 000 °C : flame temperature
Residence time at precalciner	>2-6 sec and >800 °C

Figure C.2 — Schematic view of a kiln system: preheater tower with pre-calciner and main burner (kiln) (figures from[107,110])

Technologies moved from rotary kilns equipped with *grate preheaters* to kilns equipped with a *suspension preheater* that can work with four to six cyclone stages, arranged one above the other in a tower.[68] The *four-stage cyclone pre-heater kiln system* was first adopted as standard technology for cement kilns with a capacity in the range of 1,000 to 3,000 tonnes/day. Kiln systems equipped with up to five/six cyclone preheater stages and a pre-calciner have also been built. According to the reference documents on the best available techniques for the production of cement,[68] dry process kilns with a multistage (with up to six stages) of pre-heating and pre-calcination, can be assumed to be the state-of-the-art for new plants and upgrades (the wet kilns, as well as the semi-dry/semi-wet kilns are therefore expected to convert to the dry process, if renovated), in order to comply with the aim of reducing/minimizing the plant's thermal energy consumption. More than 90 % of European clinker production is now obtained using a dry process.[150] In Germany,[72] for example, most of the cement clinker is now produced in rotary kilns with cyclone pre-heaters, based on a dry process (39 out of a total of 53 kilns). The same choice has been made in other countries. In the USA,[151] cement production achieved through 91 cement plants is reported with 128 kilns, of which 118 work according to a dry process (long dryer, preheater, preheater/pre-calciner) and only 10 with a wet process. In Japan[152] large-scale replacement of old kiln systems by suspension pre-heater kilns (SP kiln) or suspension pre-heater kilns with a pre-calciner (NSP kiln) was completed by 1997.

Cement production is an energy-intensive industrial activity with a high consumption of electricity and, mainly, fuels to satisfy the thermal energy requirement of the main burner and the pre-calciner. Some references on the specific thermal energy demand according to the kiln technology are provided in Table C.1. In modern plants about 40 % of the thermal heat demand is covered by the main burner, with 60 % by one or more firing points at the calciner. The following can be assumed to be relevant factors determining the specific fuel energy: the chemical (moisture content, elemental composition) and mineralogical (type, burnability) characteristics of the raw materials, the production capacity of the cement kiln and its technology; the availability and nature of the fuel mix and its properties (calorific value, reactivity)[153].

Table C.1 — Specific thermal energy consumption in different kiln processes (data from[113])

Kiln process	**Specific thermal energy demand[a]**
	GJ/ton clinker
Wet process	5,86 - 6,28
Long dry process	4,60
1-stage cyclone pre-heater	4,18
2-stage cyclone pre-heater	3,77
4-stage cyclone pre-heater	3,55
4-stage cyclone pre-heater plus calciner	3,14
5-stage pre-heater plus calciner plus high efficiency cooler	3,01
6-stage pre-heater plus calciner plus high efficiency cooler	< 2,93

NOTE

(a) Data sources reported in[113]: GERIAP, Company Toolkit for Energy Efficiency, Industry Sectors – Cement, 2005. http://www.energyefficiencyasia.org/docs/IndustrySectorsCement_draftMay05.pdf, viewed on 10th May 2012.

The process of clinker production creates suitable conditions for a switch from conventional to alternative waste fuels, such as:

- high temperatures,
- long residence times,
- an oxidizing atmosphere,
- an alkaline environment and sorption of gaseous components such as HF, HCl, SO_2 on alkaline reactants,
- ash retention in clinker,
- destruction of organic pollutants due to the high temperatures at sufficiently long retention times;
- high retention capacity for particle-bound heavy metals,
- short retention times of exhaust gases in the temperature range known to lead to ‘de novo-synthesis’ of PCDD/F,
- chemical-mineralogical incorporation of non-volatile heavy metals into the clinker matrix (high thermal inertia) for a switch from conventional to alternative waste fuels.

Well-established technology allows the cement kilns to be fired with low-volatile fuels such as pet-coke, low-volatile bituminous coal and anthracite, without problems. High volatile-low calorific value alternative fuels are utilized more in the pre-calciner firing (unless an NCV about or > 16,8 MJ/kg is available). The use of low-volatile fuels in the pre-calciner has required operational modifications to the pre-calciner, or specially designed pre-calciners[107].

In the cement industry, several type of wastes (e.g. fly ash, blast furnace slag, silica fume, iron slag, paper sludge, pyrite ash, spent foundry sand, soil containing oil[68]) are utilized, in a relatively large amount, to replace the raw materials (e.g. limestone, chalk, marl and shale or clay, extracted from quarries) required for clinker production. Alternative raw materials are generally fed to the kiln system in the same way as traditional raw materials (via the normal raw meal supply).[68],[110] Wastes to be used as raw materials will consist primarily of the clinker components, will ensure a low volatile heavy metal content (e.g. mercury, thallium) and will require a regular monitoring of the input streams[68].

In many countries a high substitution rate of fossil fuels – solid, e.g. coal as well as pet-coke and lignite mainly, in some cases also oil shale; liquid, e.g. fuel oil, also highly viscous fuel oil; gaseous, e.g. natural gas – has already been reached. Plastic fractions, used tyres, solvents, used oil, waste wood, sludge and SRF are frequently added to the mix of alternative fuels treated in cement kilns. This means that a mix of fuels, differing in origin, composition and properties, are now added in the combustion process in cement kilns. Wastes accepted as alternative fuels give an added value to the cement kiln in term of calorific value and material value.

The switch from conventional to alternative fuels presents different technical challenges such as selection of the right feeding point, a poor heat distribution, possible unstable pre-calciner operations, blockages in the preheater cyclones, build-ups in the riser ducts, formation of rings in kilns.

Environmental challenges are also considered. Air emissions in cement kilns derive from the physico-chemical reactions involving the raw materials and the fuels. The raw material/fuel mass ratio for clinker production is approximately 10:1.[68],[72],[107] In all the kiln systems, the solid material moves counter-currently to the hot combustion gases. This flow affects the emissions of pollutants, since it acts as a built-in circulating fluidized bed[68]. Typical kiln exhaust gas volumes are between 1,700 and 2,500 (m^3/tonne of clinker dry gas, 101,3 kPa, 273 K), for all types of kilns. Suspension pre-heater and pre-calciner kiln systems have exhaust gas volumes of around 2,300 m^3/tonne of clinker. Channelled emissions of dust from other sources, such as grinding (milling) and handling operations, raw materials, solid fuels and products also exist in the kiln system[68]. As the raw material/fuel mass ratio for clinker production is approximately 10:1, the raw material-related inputs have an influence on emissions to air.

Refractory or non-volatile metals (e.g.: Ba, Be, Cr, As, Ni, V, Al, Ti, Ca, Fe, Mn, Cu and Ag) are completely absorbed by the clinker and discharged with it, and do not circulate in the kiln system. In the exhaust gas, the only emissions are with the dust, and this depends on the input and the efficiency of dust segregation equipment. Therefore, these elements remain within the process and exit the kiln as part of the cement clinker composition (> 99,9 %). Semi-volatile metals (e.g. Sb, Cd, Pb, Se, Zn, K and Na) condense as sulfates or chlorides at temperatures of between 700 and 900 °C. An inner circulation effect (kiln/preheater cycle) occurs within the system: metals are largely condensed in the preheater area, returned to the kiln with the kiln charge and remain almost completely trapped in the clinker. Cadmium, lead, and selenium can form low volatility compounds (with excess of chlorides and sulfates in the section between the rotary kiln and the preheater) that can condense on the feed particles (at 700 and 900 °C) and enter into an internal cycle. Most of the Cd (and the Pb) is substantially trapped in the clinker.

Thallium condenses in the upper area of the cyclone preheater between 450 and 550 °C and is largely retained in the preheater; an inner circulation of the metal occurs between preheater, raw material drying and exhaust gas purification.

Mercury is a relevant pollutant due to its volatility and behaviour in the kiln process. Some references[69],[118],[153] on the Hg content in both fossil (coke, pet-coke, lignite) and alternative fuels largely used in the cement industry are given in Table C.2. Hg that enters the process through raw materials and fuels is not precipitated in the kiln and the preheater. It is almost entirely vaporized in the kiln or in the preheater and partly adsorbed on the raw gas dust, in the dust collector zone, with an adsorption rate that largely depends on temperature and available surface. Mercury is now assumed to be efficiently removed by the exhaust gas filter equipment adopted in modern kilns. No clinker enrichment in Hg seems to occur[68],[72],[154].

Table C.2 — Mercury content in fossil and conventional fuels utilized in the German cement industry (figure from:[118])

Mercury in fossil and alternative fuels	Range of values	Weighted mean	Arithmetic mean	Median	90th percentile	Analysis	
	Hg mg/kg, ar	Hg mg/kg, ar	Hg mg/kg, ar	Hg mg/kg, ar	Hg mg/kg, ar	Total N°	< DL N°
Hard coal	< 0,020 - 0,413	0,121	0,121	0,082	0,332	39	15
Lignite	< 0,020 - 0,308	0,088	0,088	0,072	0,147	68	5
Petroleum coke	< 0,009 - 0,242	0,093	0,073	0,050	0,103	21	13
Old tyres	< 0,010 - 0,193	0,107	0,056	0,048	0,079	53	3
Used oil	< 0,020 - 0,600	0,147	0,114	0,058	0,208	31	7
Paper & cardboard	< 0,005 - 0,270	0,078	0,064	0,040	0,188	55	17
Plastics	0,009 - 0,830	0,143	0,124	0,100	0,230	420	2
Textile industry waste	0,027 – 0,045	na	0,036	0,036	0,041	5	0
Other IC wastes	0,009 - 2,520	0,142	0,181	0,152	0,309	1585	117
Animal meal	< 0,005 – 0,600	0,040	0,042	0,025	0,073	86	55
MSW fractions	0,049 – 2,337	0,296	0,293	0,250	0,459	423	16
Wood waste	n/a	n/a	0,105	n/a	n/a	2	1
Solvents	< 0,070 - 2,000	0,070	0,129	0,050	0,246	43	32
Sewage sludge	0,070 – 1,358	0,297	0,418	0,386	0,716	154	0
Other alternative fuels	< 0,020 – 1,178	0,286	0,271	0,198	0,531	164	29

KEY

- n/a: value not reported
- Petroleum coke: pet-coke
- IC wastes: industrial and commercial wastes
- MSW fractions: processed fraction of the municipal solid waste

C.2 Coal co-combustion in power plants

The use of wastes as alternative fuels in coal and/or lignite fired power plants has been a common practice, for example, in some north European countries. Many pulp and paper, wood processing, chemical and refining industries have also co-incinerated wastes and residues from internal production processes, for electricity, heat and steam generation (in 2009,[69] 63 power plants were reported in the EU Emissions Trading System, ETS).

In Germany around 40 coal and/or lignite fired plants were reported in operation in the year 2009[69],[120] in the public power sector and in the mining sector. These plants have co-incinerated (up to 25 % of the rated thermal input: Table C.3) around 1,3 Mt of sewage sludge, 0,5 Mt of sludge from the pulp and paper industry, 0,6 Mt of waste-derived fuels from the processing of household and commercial waste, 0.4 Mt of animal tissue waste, contaminated waste wood and other industrial waste materials. At 2016 more than 40 % of the power generated in the country came from coal, 17,2 % of which was from hard coal and 23,1 % from lignite coal. Ten coal-fired power plants with a continuous co-combustion of solid recovered fuels (SRF from mixed municipal waste and commercial wastes) are reported in the country (Table C.4) as well as trials on the use of SRF performed in other power plants (Table C.5)[120].

Table C.3 — Waste co-incineration in some European Large Combustion Plants (LCP) (adapted from[69])

Country	Main fuel	Co-incinerated waste stream	Boiler	Total rated thermal input (MW)	Gross electric power output (MW)	Degree of co-firing (thermal, %)
Austria	coal	SS	WBB	543	246	0,1
France	biomass	PS&PR WW SS	CFBC	85	9	> 25
France	coal	MBM biomass	CFBC	81	12	9,3
Finland	peat wood coal	WDF	CFBC	206	65	8,4
Finland	peat biomass coal	WDF	CFBC	65	n/a	n/a
Germany	lignite	SS	DBB	2 x 2465	2 x 920	1,5
Germany	coal	SS, MBM	WBB	2,100	838	1,0
Germany	coal	SS	DBB	1,370	550	0,1
Germany	lignite	PS WDF PW	DBB	2 x 2,100	2 x 800	1,6 - 1,9
Germany	lignite	WDF	DBB	4 x 762	2,160	2,2 – 3,5
Germany	coal	SS pet-coke	DBB	1,870	824	< 5,0
Germany	coal	WDF	WBB	1,528	658	3,9
Germany	coal	LW GW	WBB	710	247	< 10
Germany	lignite	SS MBM	DBB	1,524	500	< 2,0
Germany	coal	SS	DBB	1,125	474	< 5,0
Germany	coal	MBM WDF	WBB	856	320	2,0
Germany	coal	SS WDF MBM	WBB	887	320	1,0
Germany	coal	WDF	CFBC	80	30	5,0
Germany	coal	WDF wood chips	CFBC	3 x 118	3 x 36	13 - 17
Germany	coal	WDF PS SS	CFBC	89	20	< 20
Germany	lignite	SS WDF WW WB	CFBC	550	107	< 25
Germany	lignite	SS	CFBC	732	201	< 25
Italy	coal	MBM biomass	DBB	418	165	6,0
Italy	coal	MBM biomass	DBB	433	171	6,3
Italy	coal	WDF	DBB	793	320	2,4
Sweden	biomass peat	WDF	CFBC	138	45	8,0
Sweden	coal	RW wood chips	GF	74	16	45,3
Sweden	biomass	WW SWF	Other	74	16	> 25
Sweden	biomass peat	WW AB	CFBC	50	6	> 25
Sweden	biomass	RW	CFBC	146	40	20
United K.	biomass	WDF	DBB	69	11	24

KEY

- *Waste streams*: SS: sewage sludge; PS: paper sludge; PR: paper residues; WW: waste wood; MBM: meat and bone meal; WDF: waste derived fuel; PW: pre-mixed waste; LW: liquid waste from chemical industry; GW: gaseous waste from chemical industry ; WB: waste biomass; RW: rubber waste; AB: animal by-products;
- *Boiler:* DBB: dry-bottom boiler; WBB: wet-bottom boiler; CFBC: circulating fluidized bed boiler; GF: grate boiler.

Table C.4 — Coal fired power plants with continuous co-combustion of SRF in Germany. Situation at March/April 2011 (adapted from[120])

Location	Coal	Firing System	SRF	Start of continuous operation (year)
Jänschwalde	brown coal	DBB	SRF-M	2005
Schwarze Pumpe	brown coal	DBB	SRF-M	2007
Werne/Gersteinwerk	black coal	DBB	SRF-M SRF-P	2004/2005
Berrenrath/Ville	brown coal	CFB	SRF-M	2007
Veltheim/Porta Westfalica	black coal	WBB	SRF-M	2007
Pforzheim	black coal	CFB	SRF-M SRF-P	2009
Flensburg	black coal	CFB	SRF-M	2007/2008
Duisburg	black coal	CFB	SRF-P	2009
Osnabrück	brown, black coal	CFB	SRF-P	1993
Oberkirch	black coal	CFB	SRF-M SRF-P	2004/2006
Werdohl-Elverlingsen [a]	black coal	WBB	SRF-M	2001
Westfalen/Hamm [a]	black coal	WBB	SRF-M SRF-P	2003
Ensdorf [a]	black coal	WBB	SRF-P	2004

KEY

- *Firing system:* DBB, dry pulverized coal firing boiler; CFB, circulating fluidized bed boiler; WBB, wet slag tap boiler.
- *SRF:* SRF-M, solid recovered fuels from mixed municipal waste; SRF-P, solid recovered fuels from production-specific commercial waste.

[a] Power plants with co-combustion inoperative.

Table C.5 — Coal fired power plants in Germany where tests on the use of SRF as an alternative fuel have been carried out successfully or unsuccessfully (test stopped due to the problem mentioned in the table). Situation at March/April 2011 (adapted from[120] and personal information from Thomas Glorius)

Location	Coal	Firing system	SRF	Test period/response/observed problems		
Chemnitz	brown coal	DBB	SRF-M	2007/2010	successful test	
Boxberg	brown coal	DBB	SRF-M	2007/2008		
Weisweiler	brown coal	DBB	SRF-M	2004/2005		
Herdecke	black coal	WBB	SRF-M	2000/2001		
Wedel	black coal	DBB	SRF-M, SRF-P	2001/2002	test stopped due to:	incomplete burnout
Werdohl-Elverlingsen	black coal	WBB	SRF-M	2001		incomplete burnout
Buschhaus	brown coal	DBB	SRF-M	2004		incomplete burnout
Ibbenbüren	black coal	WBB	SRF-P	2000		incomplete burnout (collapse of combustion when trying to feed SRF via bowl mill crusher)
Wählitz	brown coal	CFB	SRF-M	2004/2005		chlorine corrosion
Offenbach	black coal	CFB	SRF-M	2004		high Cl content of SRF-M

KEY

- *Firing system*: DBB, dry pulverized coal firing boiler; CFB, circulating fluidized bed boiler; WBB, wet slag tap boiler.
- *SRF*: SRF-M, solid recovered fuels from mixed municipal waste; SRF-P, solid recovered fuels from production-specific commercial waste.

DBB boilers (dry-bottom ash furnace/dry-bottom boilers)[69] have the highest installed capacity of coal combustion in the world. New plants using this technology with single unit capacities of up to 1,100 MWe are reported in operation for lignite combustion in Europe (coal fired units with even higher capacities for coal combustion occur in the USA and in Japan). That type of boiler operates at temperatures far below the melting point of the ash, to avoid slagging. Up to 20 % of the ash is transferred to the dry-bottom of the boiler and is extracted as bottom ash, the remaining 80–100 % of the ash is transported with the flue gas and then removed downstream. A general schematic for a dry-bottom boiler that also highlights the pathway taken by heavy metals in a such a combustion boiler is given in Figure C.3.

WBB boilers (slag tap furnace/wet-bottom boilers)[69] operate at temperatures above the melting point of the ash to ensure a liquid ash with a fluidity adequate to flow down the protected walls. The liquid ash is quenched in a water-filled collector. A large part of the ash is transported to the walls and flows in a liquid form down the walls and through the bottom outlet. Fly ash in this type of combustion system can be recycled to the combustion chamber to produce boiler slag as a residue instead of fly ash. The wet-bottom boiler is mainly used for the combustion of coal (e.g. anthracite), with a number of volatiles that is relatively low. Waste co-incineration is often relatively easy in slag tap furnaces. A general schematic for a wet-bottom boiler that also shows the pathway of heavy metals in such a combustion boiler is given in Figure C.4.

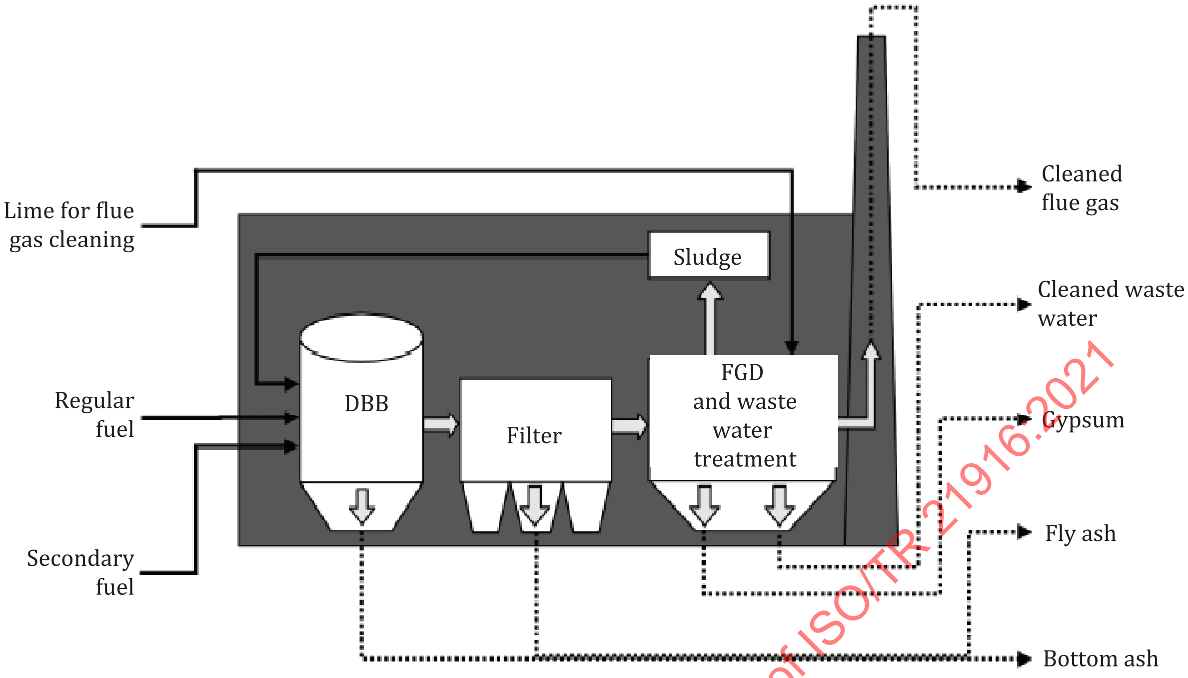
The combustion temperature falls in the range 1,000-1,400 °C (1,000-1,100 °C, in the case of brown coal combustion) for the DBB boilers and in the range 1,400-1,600 °C for WBB boilers (hard coal). In *DBB boilers* and *WBB boilers*, solid fuels are pulverized (or the liquid fuels atomized) before combustion. The fuel-gas mixture is injected into the combustion chamber and burnt with combustion air. Different coal burner configurations exist for coal and lignite boilers[69].

In the case of *fluidized bed combustion*, the fuel is injected into a hot turbulent bed formed of inert material and ash, where primary combustion air is injected from the bottom of the boiler[69]. The bed of particles – including fuel (between 1 % and 3 % of the bed material), ash and sorbents – is fluidized by upward flowing air and flue-gas in a furnace. The temperature in fluidized bed boilers typically falls in the range 750–950 °C. The lower limit comes from the combustion reactivity of the fuels, and the upper limit from the starting point of the fuel ash sintering.

Small units operate with static fluidization; with a growing boiler size and with low reactive fuels, the use of circulating fluidized bed combustion is preferred. Cyclone separation and the recycling of coarse particles to the bed are integral to the system. A few pilot plants that operate at higher pressures, integrating a gas turbine for flue-gas expansion (pressurized fluidized bed combustion, PFBC systems) are reported.[69] Currently two different types of fluidized bed boilers exist: *bubbling fluidized bed combustion (BFB)* and *circulating fluidized bed combustion (CFB)*. Figure C.5 provides a general schematic for both and also an overview of the pathway of heavy metals in such combustion boilers[69],[116].

In *bubbling fluidized bed combustion boilers,* the fuel is fed into the bed which generally consists of sand, fuel ash, dolomite, and limestone. A particle size distribution in the fluidizing bed in the range 0,5–1,5 mm typically occurs, smaller particles being carried out with the fluidizing gas flow, with larger particles going down to the distribution plate (Figure C.5).

Circulating fluidized bed combustion (CFBC) differs from the previous type due to the bed material being recycled along the furnace walls so that the suspension density above the bed decreases with furnace height and the high share of circulating inert material regulates the temperature profile within it. The most common solution utilized in CFBC boilers for solid separation is the cyclone, whose efficiency is experienced as quite an important parameter for the proper functioning of this combustion system (a high efficiency allows the circulation rate to be increased and a constant high heat transfer to be obtained in the boiler). As an example of a CFB operating plant, mention can be made of the Berrenrath co-generation power plant in Germany (CFB combustion system 2 x 235 MWth), where SRF co-combustion takes place[121].



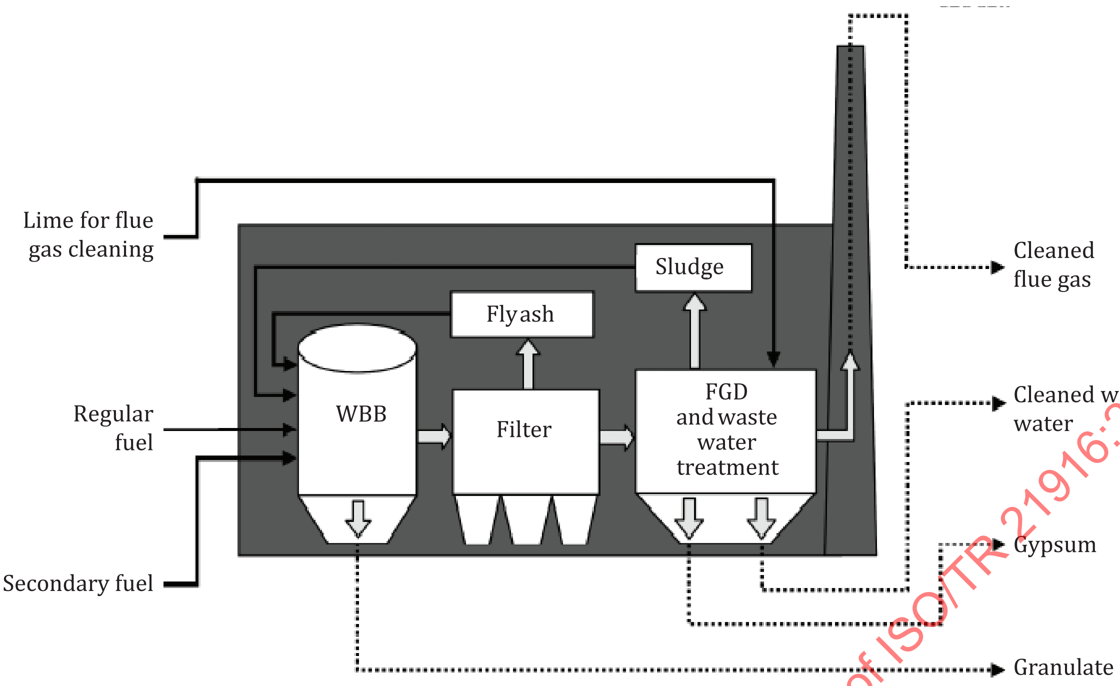
Key

→ input flows with relevant heavy metal loads

⇨ distribution of the heavy metals in the process

⇢ output flows with transfer factors(TF) for relevant heavy metals

Figure C.3 — A schematic view of a dry-bottom boiler (hard coal and lignite) (figure from[116])



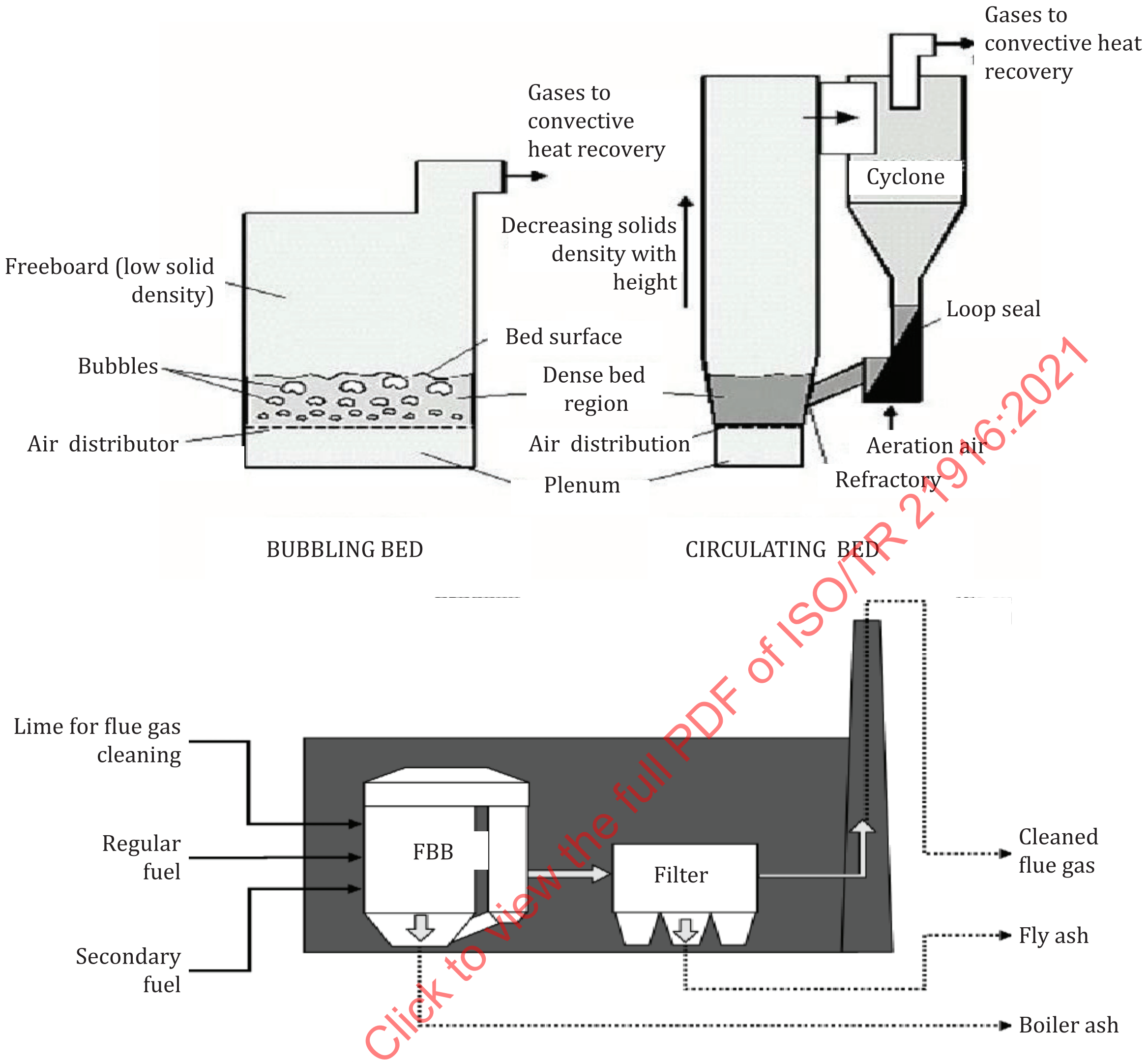
Key

→ input flows with relevant heavy metal loads

⇒ distribution of the heavy metals in the process

⇢ output flows with transfer factors(TF) for relevant heavy metals

Figure C.4 — A schematic view of a wet-bottom boiler (figure from[116])



Key

→ input flows with relevant heavy metal loads

⇨ distribution of the heavy metals in the process

┈► output flows with transfer factors(TF) for relevant heavy metals

Figure C.5 — Top: general schematics for a bubbling fluidized bed boiler and a circulating fluidized bed boiler (top) (figure from[69]) – Bottom: pathway of heavy metals in such combustion boilers (figures from[116])

On the matter of emission to air of pollutants, metals are distributed mainly in the combustion residues, such as fly ashes, and also in the flue gas. Secondary fuels, such as sewage sludge and different types of solid recovered fuels (RDF/SRF, tyres) can show a heavy metal content, (e.g. Hg, Cd, Tl, Sb, Pb, Cr, Cu, Mn), higher than the conventional fossil fuel. Most metals are associated with particulates; highly volatile metals – such as cadmium, mercury, thallium and selenium – can remain in the vapour phase or in the ultrafine fumes, therefore their emission is strongly dependent on the efficiency of the gas cleaning system used. Electrostatic precipitators and fabric filters are widely utilized, that can ensure a particulate removal efficiency of > 99 %, mainly in large combustion plants. As regards the control of air emissions, the flue-gas cleaning processes and technologies applied do not necessarily differ from those utilized for cleaning flue gases from the combustion of other solid, liquid or gaseous fuels. Depending on the properties of the waste and its content of metals and, mainly, of mercury, additional measures may be required. The removal efficiency can be enhanced by using flue gas conditioning with additives added to the flow upstream of the filters, An effective way to reduce the emissions of some metals is the use of wet scrubber FDG systems, as a reduction of the flue gas temperature (to around 50-60 °C) allows more volatile elements to condense from the vapour phase.

C.3 Gasification

Gasification is recognized as an efficient way to maximize the conversion of different feedstocks (low-value fuels) to high heating value fuel gases (syngas)[69],[122],[123],[124]. The process allows carbonaceous fuels to be converted, through partial oxidation, mainly to a fuel gas enriched in carbon oxides, hydrogen, and methane. The fuel gas can be utilized in separate equipment, e.g. combusted in a conventional burner, connected to a boiler and a steam turbine or in a more efficient energy conversion device, such as gas reciprocating engines or gas turbines, or processed to produce a variety of products, as depicted in Figure C.6.

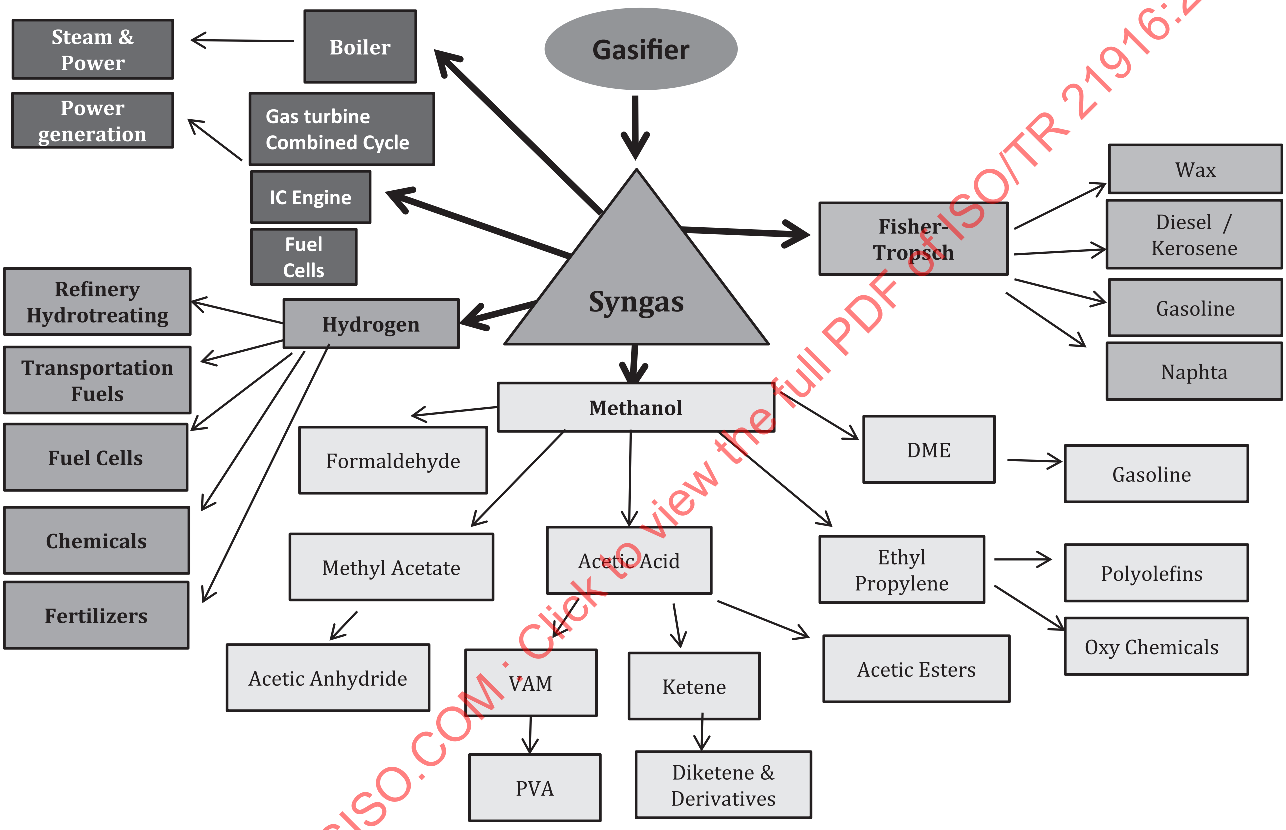


Figure C.6 — Outputs of gasification: pathways

The gasification of solid wastes such as SRF/RDF offers effective/potential benefits over traditional direct combustion, and schematically:

- produces an intermediate product, which is suitable for use in a wide range of applications;
- operating temperatures are typically lower than those of direct combustion [reduced potential for alkali volatilization, fouling, slagging, heavy metal volatilization and (fluidized bed reactors) bed agglomeration];
- allows application for power generation at a smaller scale (typically lower than 120 kt/y);
- allows the use of modular plant;
- except for fly ash and some volatile components, most of the inert, non-combustible materials are collected at the bottom of the reactor, with metals mainly in a non-oxidized form;

— due to the reducing atmosphere, emissions of dioxins and furans are strongly limited so a substantial reduction of NO_X emissions can be obtained; the deficit of air reduces heat losses at the stack and thus increases the energy recovery efficiency.

The gasification is quite a complex process based on different endothermic and exothermic reactions, which runs through a sequence of distinct conversion steps and mechanisms,[122],[126],[155-161] as summarized schematically in Table C.6.

Table C.6 — RDF/SRF gasification: conversion steps (adapted from[126])

	Primary conversion	Secondary conversion
Time (ms)	1-1,000	1,000-10,000
Temperature (°C)	150-700	700-1,200
Phenomena involved	rapid heating and drying pyrolysis comminution of solid particles partial oxidation of primary volatiles and char decomposition of primary tars water-gas reaction ash detachment	hydrogasification water-gas shift CO_2 gasification tar cracking steam reforming Boudouard reaction ash inertization
Main products	Mixed oxygenates, olefins, aromatics, C_xH_y, CH_4, PAHs, H_2, CO, CO_2, H_2O, char and ash	H_2, CO, CO_2, H_2O, ash/slag

Heating and drying of the feedstock occur at temperatures up to about 160 °C. The rate of drying depends upon: temperature; velocity of the gas; external surface area of the feed material as pellets or shredded material; internal diffusivity of moisture and the nature of bonding of moisture to that material; composition: rapid drying is promoted by high levels of low/free–moisture plastics, while vegetable and putrescible material has bound moisture and takes longer to dry. No chemical reactions occur significantly in that step, while physical shrinkage and compression effects can be observed in the waste material, especially when rich in light plastics[162].

De-volatilization (pyrolysis or thermal decomposition) occurs at temperatures up to about 700 °C. This involves thermal cracking reactions, heat and mass transfer and the release of gases (H_2, CO, CO_2, CH_4, H_2O, NH_3), tar (condensable hydrocarbon vapours that are released from the solid matrix) and char (the remaining devolatilized solid waste residue). For MSW and MSW-RDF/SRF, volatiles represent a significant portion of the carbonaceous feedstock.

Chemical species released through de-volatilization (composition, amount and characteristics) mainly depend on the composition and structure of the waste feedstock[163] and on operational factors, e.g. temperature, pressure, composition of inner atmosphere, heating rate, based on the type of gasification reactor. Volatiles and char then undergo a second gasification step becoming the final syngas. A further stage, sometimes referred to as tertiary conversion, may be identified in syngas upgrading at high temperatures due to hydrocarbons cracking.

A possible taxonomy of the available gasification technologies is reported in Table C.7.

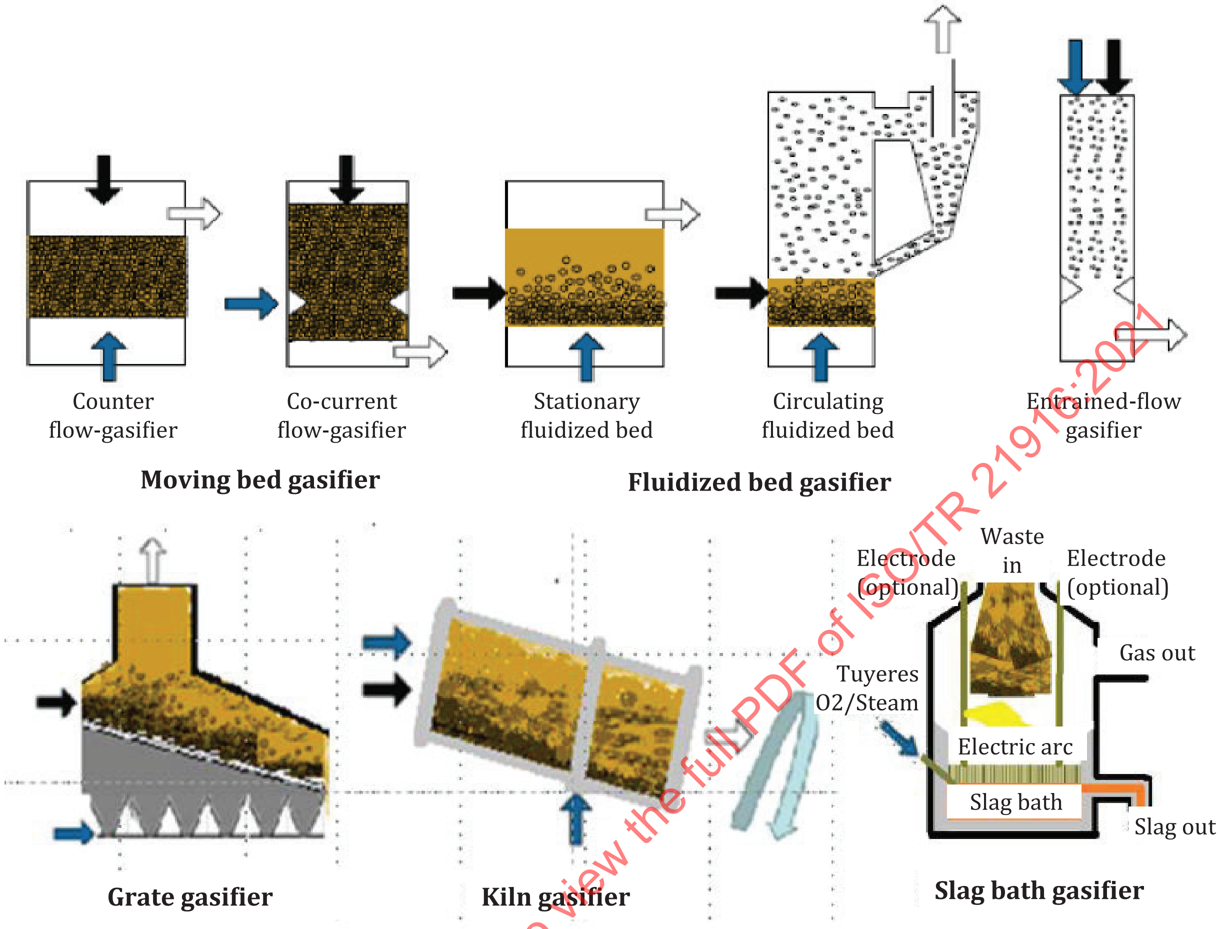
The term *auto-thermal* (or direct) *gasification* identifies a process (some examples in Figure C.7) where the inner partial oxidation of combustible gas, vapours and char with a controlled amount of air, oxygen or oxygen-enriched air, gives the heat that the endothermic reactions need to proceed (energy required for the thermal cracking of tars and hydrocarbons, the gasification of char by steam or carbon dioxide, keeping the operating temperature of the gasifier endothermic reactions fixed). One product gas stream is obtained.

In what is called *allo-thermal gasification,* an external source provides the heat required by the endothermic reactions: this happens by using heated bed materials (some examples in Figure C.8) or in hybrid systems such as the indirect and direct plasma gasifiers.[122],[123] The allo-thermal process generally produces two separate gas streams – a medium calorific product gas stream from the gasification reactor, with a low content of nitrogen, a flue gas stream from the combustion reactor – and facilitates more efficient energy recovery from the input waste stream (complete carbon conversion). A disadvantage is a gas cleaning applied to two gaseous streams.

Table C.7 — A possible taxonomy of waste gasifiers (data from[122])

Criteria	Gasification type	Acronym
Heat supply	Directly heated (auto-thermal) gasifier	
	Indirectly heated (allo-thermal) gasifier	
Pressure	Atmospheric gasifier	A
	Pressurized gasifier	P
Gasification agent	Air gasifier	AG
	Oxygen enriched-air gasifier	EAG
	Oxygen gasifier	OG
	Steam gasifier	SG
	Plasma gasifier	PG
Reactor design	Updraft Fixed bed gasifier	UD
	Downdraft Fixed bed gasifier	DD
	Bubbling fluidized bed gasifier	BFB
	Circulating fluidized bed gasifier	CFB
	Internally circulating fluidized bed gasifier	ICFB
	Entrained flow gasifier	EF
	Rotary kiln gasifier	RK
	Moving grate gasifier	MG
	Plasma gasifier	PG
Temperature	Low temperature gasifier (below 900 °C, typically)	LT
	High temperature gasifier (above 1,200 °C, typically)	HT
Bottom ash status	Dry-bottom ash gasifier	BA
	Vitrified slag gasifier	VS
Energy recovery	Heat gasifier (dirty syngas post-combusted in a recovery boiler with heat/electricity production via steam turbine cycle)	HEG
	Power gasifier (cooled and cleaned syngas burned in an internal combustion engine or in a gas turbine)	PWG

Power gasifier and *heat gasifier* (Figure C.9) are reported as the two main configurations adopted in gasification-based waste-to-energy units, of which the latter (even if less energy efficient) is widely used in the units under operation[122]. A gasification system closely integrated with a combined cycle gas turbine for electricity generation (IGCC-integrated gasification combined cycle) is a solution aimed at producing steam and electric power from a variety of low-grade fuel types with the highest conversion efficiency possible, removing impurities from the syngas before it is combusted. The primary feedstocks in large-scale IGCC plants (100–500 MWth) are often coal, petroleum coke, or heavy oil or other residues from crude oil refinery processes. Pressurized gasification is preferred for IGCC plants. Entrained-flow gasifiers are applied in most of the commercial-sized IGCC projects. Biomass IGCC projects also exist (e.g. the Varanamo IGGC plant in, Sweden) that generally operate on a small scale (10–190 MWth). The formation of tar in syngas is a relevant problem in the case of biomass IGCC; the use of entrained-flow gasifiers could theoretically solve it, a technology more suitable for large industrial-scale gasification facilities, > 100 MWth, thus not feasible for most biomass gasification applications. The available strategies to solve the tar problem are removal (e.g. wet/oil scrubbing systems, partial oxidation and catalytic tar cracking) or in-situ conversion[69].



Key

➡ fuel

➡ gasification agent

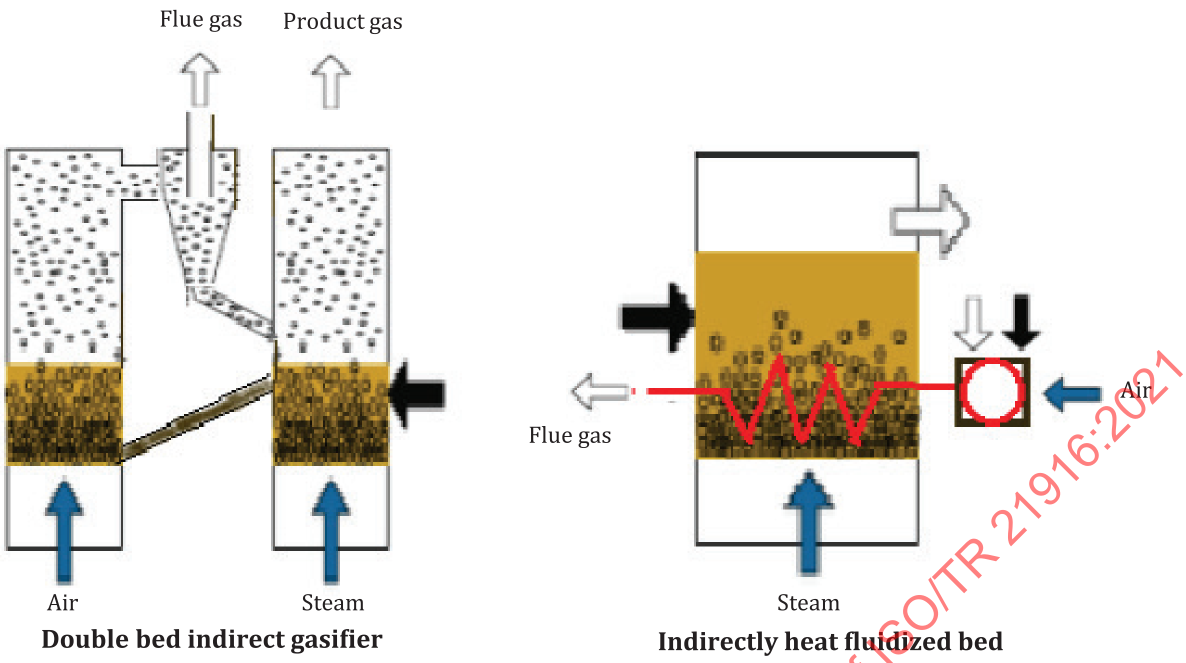
⇨ product gas

▩ fuel in fixed bed

▨ fuel and bed material in fluidized bed

⁘ circulating fuel and bed material

Figure C.7 — Examples of auto-thermal gasification processes in different type of gasifiers (figure from[123])



Double bed indirect gasifier

Indirectly heat fluidized bed

Key

➡	fuel
➡	gasification agent
⇨	product gas
▩	fuel in fixed bed
▨	fuel and bed material in fluidized bed
⁘	circulating fuel and bed material

Figure C.8 — Examples of an allo-thermal gasification process and gasifier (figure from[123])

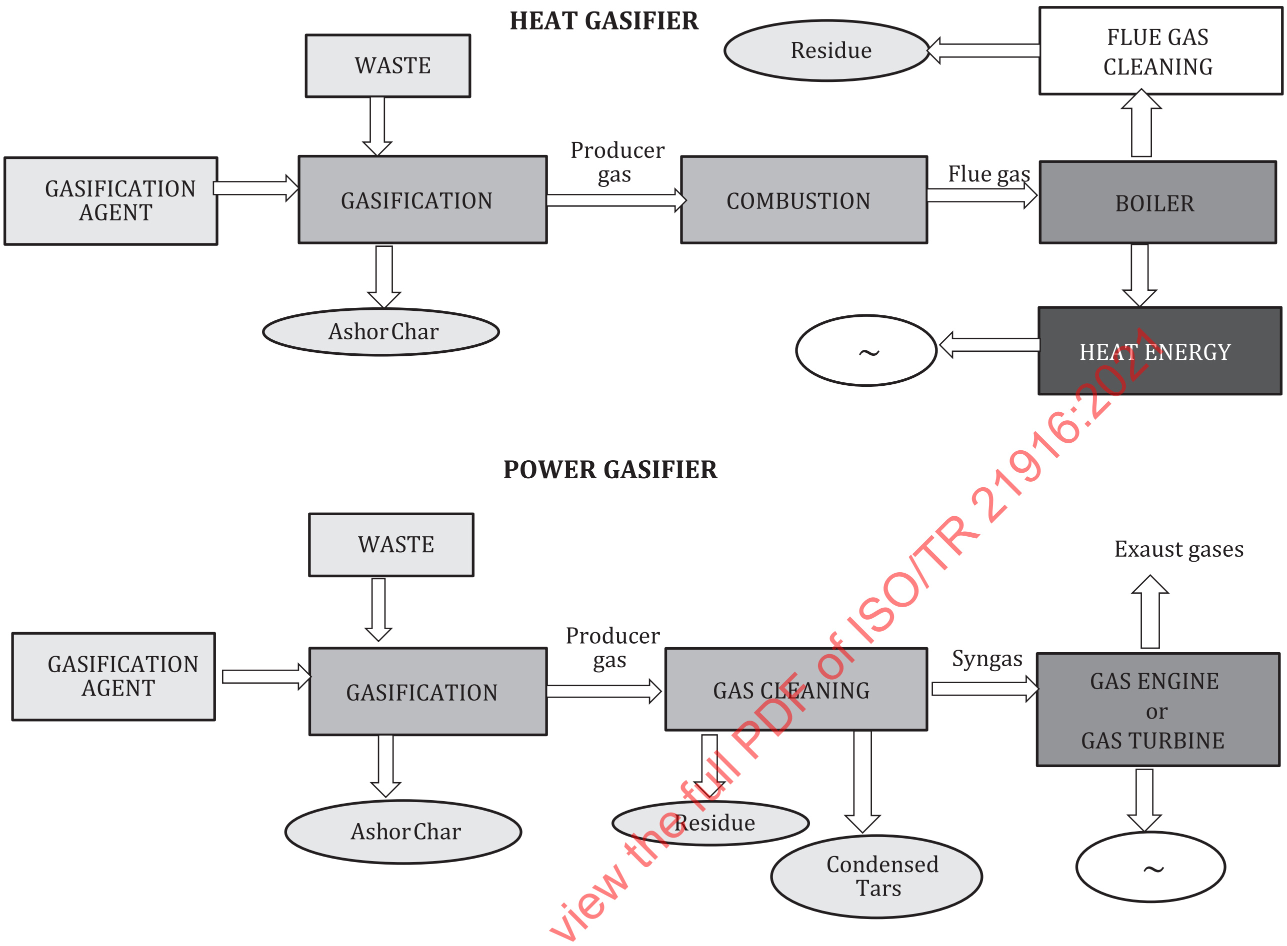


Figure C.9 — Schematic view of the two possible configurations of a gasification-based EfW system (figure from[122])

Different technologies and waste feedstocks have been explored in research studies on experimental and pilot plants. Commercial and demonstration gasification-based EfW plants have been created worldwide, some of which are fed with solid recovered fuels, alone or in mixture with MSW or other biomasses and conventional fuels (coal)[69],[122]–[124].

Examples of existing gasification based EfW plants are provided in Table C.8, most of which have been developed and commercialized for the cogeneration of heat and power from the syngas, on the basis of the above mentioned "heat gasifier" configuration. Only a few plants, particularly in Japan, utilize a "power gasifier" configuration or are operated to produce chemicals (in particular, ammonia). In Japan, where the waste gasification technologies were first widely utilized, it is interesting to note that the main reason for the relatively low maximum capacity of the MSW gasifiers (on average, about 70 kt/y, much smaller than that of Europeans plants) is probably related to policy choices, according to which municipal governments are in principle required to treat wastes inside their own territories[122],[164].

In Table C.9, typical characteristics of the main type of gasification reactors are summarized.

Table C.8 — Some examples of companies with gasification-based EfW plants that offer a commercially proven process. Gasification processes are identified according to the taxonomy reported in the previous Table C.7 adapted from[122])

Company	Gasification process a	Solid waste b	Plant n°	Capacity kt/y
AlterNRG (Canada), Westinghouse Plasma corp., Hitachi Metals (Japan)	A/PG/HT/VS/PWG	MSW/RDF/ASR/TDF	3	8 - 90
Ebara TIFG (Japan)	A/AG/ICFB/LT/BA+VS/HEG	MSW/ASRF/MPW/IW	12	30 - 125
Ebara Co., Ube Industries Ltd (Japan)	P/OG/ICFB/Lt+HG/VS	MPW	3	10 - 60
Energos (Norway/UK)	A/AG/MG/BA/HEG	MSW/RDF	14	10 - 80
Hitachi Zosen (Japan)	A/AG/BFB/LT/BA+VS/HEG	MSW/RDF	9	10 - 100
JFE, Kawasaki Steel and NKK (Japan),	A/EAG/DD/HT/VS/PWG	MSW/RDF/IR/IW/EW	10	30 - 110
JFE (Japan), Thermoselect (Switzerland)	A/DD/HT/VS/PWG	MSW/RDF	7	30 - 200
Kobelco (Japan)	A/AG/BFB/LT/BA+VS/HEG	MSW	13	20 - 170
Mitsui (Japan)	A/AG/RK/HT/VS/HEG	MSW/ASR	9	60 - 150
Nippon Steel Engineering (Japan)	A/EAG/DD/HT/VS/HEG	MSW/IR/IW	37	30 - 230
Plasco Energy Group (Canada)	A/PG/HT/VS/PWG	MSW/RDF	2	5 - 35
Takuma (Japan)	A/AG/RK/HT/VS/HEG	MSW/ASR	2	40 - 100

NOTE

(a) Acronyms as detailed in Table C.7.

(b) MSW: municipal solid waste; RDF: refuse derived fuel; TDF: tyre derived fuel; MPW; mixed plastic waste; IW: industrial waste; IR: incineration residues; EW: excavated wastes; ASR: auto shredded residues.

Table C.9 — Main characteristics of gasification reactors (data from[123])

Characteristics	Moving bed gasifier	Stationary fluidized bed gasifier	Circulating fluidized bed gasifier	Entrained flow gasifier
Capacity range thermal (MW) (operating pressure)	downdraft < 1 updraft < 10 (atmospheric)	10 – 50 (atmospheric) < 200 (< 2 MPa)	20 -150 (atmospheric)	100 – 400 (1-3 MPa)
Particle size, bed material (mm)	none	0,1 – 0,5	0,1 – 0,4	none
Particle size, fuel (mm)	10 - 100	1 - 100	1 - 100	< 1
Operating temperature, (°C)	800	800 (bottom) 200-300 (top)	800 - 950	1,400 – 1,500
Gas superficial velocity, (m/s)	0,1 – 0,5	0,5 – 1,5	4 - 8	15 - 25
Gas mixing	near plug flow	complex	dispersed plug	near plug flow
Solid mixing	very low	high, complex	high, complex	low
Temperature gradient	high	low	low	high
Tar content in gas, (g/Nm^3)	downdraft < 1 updraft >> 10	> 10	> 10	<< 1
Particles in gas (g/Nm^3)	0,1 - 0,2	0,1 - 1	2 - 20	1

In *a fixed bed gasifier,* a deep bed of waste is present in almost all the volume of the reactor.[125] In the *updraft reactor* the waste is fed in at the top of the gasifier, and the oxidant intake is at the bottom;

the waste moves counter-currently to the gases, and passes through different zones (drying, pyrolysis, reduction and oxidation) successively. The fuel is dried in the top of the gasifier, so that waste with a high moisture content can be used.

In the *downdraft reactor*, the waste is fed in at the top of the gasifier while the oxidant is fed from the top or the sides: then the waste and gases move in the same direction. It is possible to distinguish the same zones as in updraft gasifiers but in a different order. Some of the waste is burnt, falling through the gasifier throat to form a bed of hot char which the gases are passing through. This ensures a fairly high-quality syngas (with a relatively low tar content), which leaves at the base of the gasifier, with ash collected under the grate.

The vertical shaft-furnace developed by a Japanese Company (Nippon Steel) as the "Direct Melting System" is an atmospheric *moving bed downdraft gasifier* (it achieves a high temperature gasification and melting process, with O_2-enriched air injection in the melting section, at 36 % of O_2 concentration), which directly evolved from metallurgical processing technology and can achieve both the energy and material recovery (incombustibles converted into recyclables such as slag and metal) This technology shows a waste flexibility : MSW but also sewage sludge, clinical waste, bottom ash from incineration plants, reclamation waste from landfill, automobile shredder residues, can be processed, without a pre-treatment. The waste feedstock (e.g. MSW) is charged from the top of the furnace together with coke, used as reducing agent, and limestone, used as viscosity regulator, and gradually dried and pre-heated. The combustible waste is thermally decomposed, and the syngas produced transferred from the top of the gasifier to a swirling combustor that transfers the thermal energy generated to a steam turbine system to produce electricity. Power generation from about 400 kWh/t MSW (MSW co-gasified with bottom ash discharged from other MSW incinerators and with combustible and incombustible residues from recycling facilities) to about 670 kWh/t of MSW (MSW as the only feedstock) can be obtained, depending on the feedstock properties (LHV and ash content, which cause a higher sensible heat of melt) and the boiler system.[136] In the combustion and melting zone (1,000 – 1,800 °C) at the bottom of the gasifier, the incombustible waste is melted with the heat generated by coke; slag and metal are then magnetically separated from the molten materials discharged and recycled (e.g. the slag due to its low content of harmful heavy metals can be used as interlocking block aggregate, concrete aggregate, or civil engineering material). Plants of that type have been built in Japan and in South Korea (more than 40 plants), with a capacity ranging from 10,000 to 230,000 Mg per year.

As regards the *Bubbling (BFB) and Circulating (CFB) fluidized bed gasifiers*, in the first case the flow of gaseous oxidant (air, oxygen or oxygen-enriched air) is blown upwards through a distributor plate and permeates a bed of inert material (typically, silica sand or olivine) located at the gasifier bottom, which contains the waste to be treated.[69],[122],[123],[165],[166] The waste is fed over-bed from one or more points along the side walls, flows upwards through the reactor tower, remains suspended in the stream while gasification takes place, and is fast heated and devolatilized. Most of the gasification reactions occur inside the bed and the splashing zone (above the top of the bed).[165],[166] The operating temperature area (window) of a fluidized bed gasifier is determined by the ash melting temperature and by the temperature needed for the gasification reactions.

A *BFB gasifier* operates at temperatures below 900 °C),[122] to avoid ash melting and sintering that can produce a worsening of the fluidization quality or a defluidization of the bed. BFB gasifiers coupled with a melting furnace where the gas is burned at high temperature (>1200 °C) and vitrified slags are produced. What is known as the internally circulating bed (ICFB) is a particular type of BFB gasifier equipped with a specific fluidizing gas distributor (to improve the radial mixing of gas and solids); this technology was developed by Ebara, coupled with a melting furnace that operates at about 1,400 °C[122].

The term *CFB gasifier* identifies a fluidized system where the particle separation and return systems are essential components of the reactor and the regime is defined by the superficial gas velocity and by the flux of solid mass in the system. In a CFB gasifier the waste is fed from the side, rapidly heated and devolatilized and then reacts with air or oxygen-enriched air. The suspension of syngas and particles (inert material and waste char) moves upwards along the riser and enters the cyclone.[69],[122] The temperatures are below 900 °C to avoid ash melting and sintering[122].

CFB/BFB fluidized bed gasifiers may be air-blown, oxygen-blown and/or steam-blown and may be pressurized or operate at atmospheric pressure. Steam and/or oxygen or air are introduced below the fluidized bed, which is suspended by the fluidization gases[69]. CFB/BFB fluidized bed gasifiers accept a wider range of feedstocks, compared to updraft and downdraft fixed-bed gasifiers[69].

Large scale fluidized beds have been built, e.g. the biomass CFB gasifier in operation at atmospheric pressure in Finland (plant located at Vaskiluodon Voima, Vaasa) with a capacity of 140 MW thermal; CFB boilers are available at even higher thermal capacities, that can also be pressurized up to 1-3 MPa to increase single capacity[123]. Allothermal fluidized beds (they use a gasifier-combustor combination, e.g. the Milena, FICFB and the Batelle gasifier design) can have different combinations of fluidization types: two stationary fluidized bed reactors, one stationary fluidized bed gasifier and circulating bed combustor, one circulating fluidized bed gasifier and one stationary bed combustor or two circulating fluidized beds[123]. Air-blown fluidized bed gasification units working at atmospheric pressure and low temperature have been developed to be fed with biomass feedstocks (woods) but can also be utilized with other types of biomass and waste-derived fuels[69]. Pressurized fluidized bed gasification is a technique also used in biomass IGGC systems. The integrated gasification combined cycle (IGCC) is a technique aimed at producing steam and electric power from different low-grade fuel types with the highest conversion efficiency. The primary feedstocks in large-scale IGCC plants are generally coal, petroleum coke, and/or heavy oil. Entrained-flow gasifiers are used in different commercial-sized IGCC projects (mainly those based on petroleum residuals)[69].

Entrained flow gasifiers[69],[122],[123] are commonly operated at high pressure (up to 1-3 MPa with solid fuels, eg. refinery residues and mixed plastic waste, or more with high-energy liquid fuels), in a ash melting mode (ash is removed as slag in the bottom of the gasifier), at high temperatures (e.g. 1,500 °C, or in any case above the ash melting temperature) and with the use of oxygen mixed with steam, to obtain a fast conversion of waste into a high quality syngas. In case of solid fuel (e.g. solid wastes), fine fuel particles (< 1 mm) are obtained (waste pre-treatment) and added to water to produce the slurry, with a solids concentration > 60 %, that is fed to the gasifier; water is utilized as transport medium and temperature moderator, but also s reactant. The fuel preparation in case of solids, and the requirement of using oxygen does not make small installations feasible; only one supplier (Envirotherm) of entrained-flow gasification processes applied to wastes (mainly relatively high energy content liquid wastes) is reported[123].

Rotary kiln gasifiers have been used for example as the first stage of a two-step process (e.g. in the Mitsui Recycling process and the Takoma process) where the waste, fed co-currently with the oxidant (air), is gasified at 450 °C , converted into gas and char with residues of metals, ash;after the recovery of metals (e.g. aluminium, iron), the exit stream is then processed in a a combustion chamber, at 1,300 °C , where ash is also fed in and melted into the recovered slag.

A *mechanical grate furnace,* mainly utilized as a reactor in combustion-based EfW units, has been proposed for waste gasification and several plants in operation are reported to utilize it in Norway, Germany and the United Kingdom to improve the fuel flexibility of the MSW gasifiers[122]. The thermal conversion takes place in two stages: the primary chamber for gasification of the waste (typically at an equivalence ratio of 0,5) and the secondary chamber for high temperature oxidation of the syngas produced in the primary chamber.

Plasma gasification operates as an allo-thermal gasification process. Plasma is produced by ionizing a carrier gas (generally: air, nitrogen, argon, carbon dioxide, steam) in an electric-arc whose earthing can be via a conducting molten bath (direct plasma gasification) within the gasifier reactor (frequently carried out with moving bed and molten bath gasifiers)[122],[123]), or a counter-electrode within the same plasma generator (indirect plasma gasification).

Plasma gasifiers usually works at atmospheric pressure and with temperatures in the range 1,500–5,000 °C[122] and are reported to allow good control of process temperature independently from fluctuations in the feed quality, the feeding rate and the properties of the waste fuel (moisture content, composition particle size)[163]. Plasma gasification units have been built in different countries for the destruction of several types of waste, including hospital wastes, industrial organic chloride and nitrogenous wastes, and municipal (MSW) solid waste[69],[168],[169].

Waste plasma gasification was typically improved as a single-stage process. Applications are reported for RDF gasification[169], as well as (e.g. in Japan) for a thermal waste treatment of melting ash (from incinerators and gasifiers or other sources) or hazardous inorganic wastes and by-products (e.g. asbestos wastes) to vitrified slag[123].

Two-stage gasification processes that combine fluid bed gasification with the plasma technology have been developed (e.g., in the UK and Canada). A schematic view of this process is shown in Figure C.10. The first stage is generally a conventional fluidized bed gasifier (fed with RDF; operation temperature 850 °C) and the second stage a plasma converter; the latter operates on the syngas produced at a temperature of about 1,200 °C, cracks tars and chars (reduction of the tar content in the syngas; increase of the conversion efficiency). The final product is an H_2-rich syngas (ash and inorganics remain in the vitrified slag) that is fed into a gas engine, after a cooling and cleaning. An output of around 1 MWh/tonne RDF, with a net electrical efficiency higher than 23 % is reported[170],[171]. As an example, in the UK[126],[159],[160] a two-stage FBG-plasma process has been experimentally utilized for the gasification of RDF at the Gasplasma pilot plant. In that case the FBG gasifier (designed for steam/oxygen gasification) is coupled to a single carbon electrode plasma converter (PC); the refined syngas produced (LHV = 10–14 MJ/m^3) is then utilized in a gas engine.

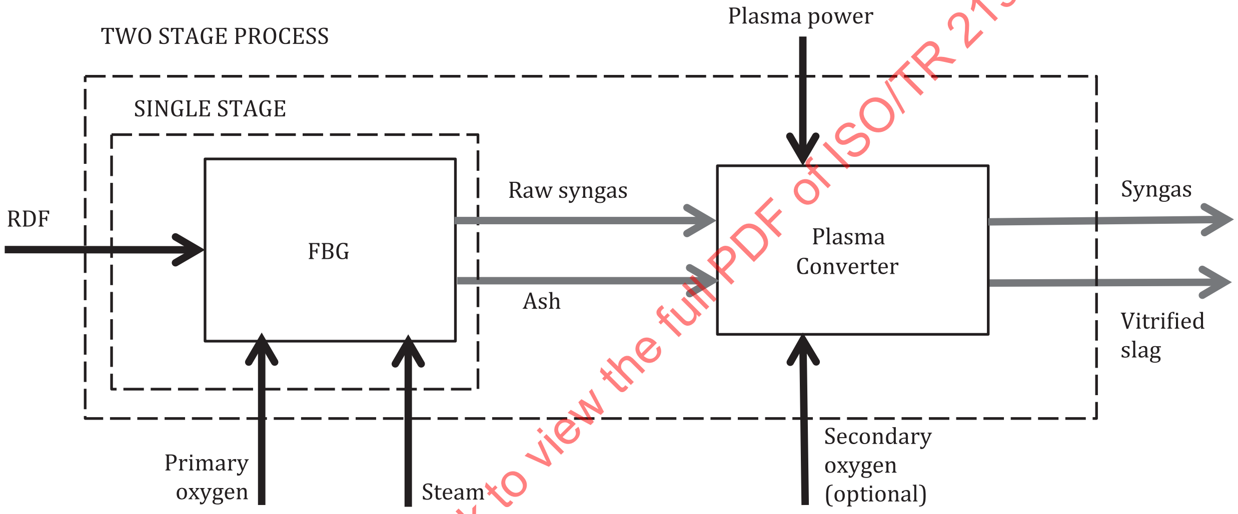


Figure C.10 — Schematic for a two-stage plasma gasification process (figure from[126])

Annex D
(informative)

Typical values for SRF: background data and outcomes of a statistical assessment of measured values

D.1 Background data on typical values for SRF

An assessment of the quality of SRF co-combusted in cement kilns was produced in the past for the purposes of CEN/TR 15508[116]. A statistical analysis of the national series of measured values resulted in the range of typical values for some properties of SRF summarized inTable D.1. Because secondary fuels may be involved in the substitution of raw materials in the cement industry, two SRF categories, SRF with low and high ash content, have been also taken into account in that study, for which the range of values in Table D.2 have been provided for the same parameters.

Table D.1 — End use: CEMENT KILN. Reference values based on a statistical analysis of measured values collected in several European countries (adapted from[116])

Parameter	NCV	Cl	Hg	Cd + Tl
	MJ/kg ar	% in mass ar	mg/MJ ar	mg/MJ ar
Median range	3,2-25,5	0,07-1,7	< 0,02-0,406	< 0,12-< 0,93
80th percentile range	3,4-25,8	0,14-2,00	< 0,02-0,781	< 0,12-0,94

Table D.2 — End use: CEMENT KILN. Reference values for SRF utilized in the cement manufacturing industry with a low or high ash content (boundary 20 %) (adapted from[116])

Parameter		SRF –low ash		SRF –high ash	
		Median range	80th percentile range	Median range	80th percentile range
NCV	MJ/kg ar	11,7 – 25,5	12,8 – 25,8	3,2 – 10,0	3,4 – 12,0
Cl	% in mass ar	0,04 -1,7	0,07 – 2,0	0,07 - 0,77	0,14 – 0,82
Hg	mg/MJ ar	0,004 - 0,042	0,005 – 0,137	< 0,05 – 0,406	0,064 – 0,781
Cd + Tl	mg/MJ ar	0,008 – 0,121	0,008 – 0,264	0,26 - <0,93	0,26 – 0,94

Data reported in Tables D.3 to D.8 are aimed at giving some indicative references on properties of SRFs that have been utilized locally as alternative feedstocks in cement kilns, coal fired power plants and gasification plants.

Table D3 — End use: CEMENT KILN. NCV and heavy metal content measured in coal and SRF utilized as fuel feedstock in the cement industry (adapted from[108])

Property	Unit	Hard coal/ brown coal[a]		Hard coal[b]		Hard coal[c]		SRF[c]	
		Min value	Max value	Min value	Max value	Min value	Max value	Min value	Max value
NCV	MJ/kg d	-	-	28,00	28,00	28,09	28,13	21,46	21,46
Sb	mg/MJ d	0,014	0,071	0,002	0,179	0,036	0,036	0,419	0,685
As	mg/MJ d	0,036	1,786	0,321	1,786	0,018	0,355	0,042	0,410
Pb	mg/MJ d	0,054	9,750	0,393	9,643	0,036	10,66	1,165	7,316
Cd	mg/MJ d	0,004	0,357	0,004	0,357	0,002	0,355	0,008	0,121
Cr	mg/MJ d	0,054	2,893	0,179	2,857	0,018	2,133	0,527	6,524
Co	mg/MJ d	0,036	1,429	0,019	0,929	0,018	0,711	0,028	0,186
Ni	mg/MJ d	0,036	3,571	0,714	2,857	0,018	3,555	0,040	0,979
Hg	mg/MJ d	0,004	0,118	0,001	0,028	0,001	0,156	0,005	0,019
Tl	mg/MJ d	0,004	0,196	0,007	0,143	0,036	0,036	0,001	0,023

[a] Data source: European Commission (2010a) Reference document on best available techniques in the cement, lime and magnesium oxide manufacturing industries. Brussels: European Commission.

[b] Data source: BZL Kommunikation und Projektsteuerung GmbH and DPU-Deutsche Projekt Union GmbH (2000) Abschlußbericht-Anforderungen an Ersatzbrennstoffe aus Abfällen für die Zementindustrie (Final report – requirements on refuse-derived fuels from waste for the cement industry). Oyten and Köln: Im Auftrag von Ministerium für Umwelt und Verkehr des Landes Baden-Württemberg.

[c] Data source: Genon G and Brizio E (2008) Perspectives and limits for cement kilns as a destination for RDF. Waste Management 28, 2375–2385.

Table D.4 — End use: CEMENT KILN. Properties of the pet-coke and the SRF referred to in Italy as CDR utilized as fuel feedstock in an Italian cement kiln (adapted from[114])

Property	Unit	Pet-coke	CDR	Property	Unit	Pet-coke	CDR
		Average	Average			Average	Average
NCV	MJ/kg d	34,86	22,39	Tl	ppm d	0,50	< 0,5
Volatile matter	% in mass d	11,08	12,50	Sb	ppm d	18,15	5,03
S	% in mass ar	4,90	n/a	V	ppm d	1624,5	3,32
Cl	% in mass d	n/a	0,68	Co	ppm d	6,62	3,10
Pb	ppm d	9,30	89,83	PAHs	ppm d	123,12	2,68
Cr	ppm d	12,30	36,32	PCBs	ppm d	0,015	0,23
Cu	ppm d	21,60	131,36	Dioxins/Furans	ppt TEQ	2,20	3,92
Mn	ppm d	48,50	92,80				
Ni	ppm d	66,90	11,35				
As	ppm d	0,60	0,68				
Cd	ppm d	0,50	0,61				
Hg	ppm d	0,30	0,23				

KEY

n/a: value not reported

Table D.5 — End use: CEMENT KILN. Composition and properties of low, medium and premium quality SRFs produced in Austria of which the medium and the premium quality SRF have been utilized as a suitable fuel feedstock in the national cement industry (adapted from[38]).

		SRF		
		Low quality	Medium quality	Premium quality
Components				
Paper, plastics, composites and textiles	% in mass ar	35,6	56,2	52,4
Glass, inert, metals, hazardous wastes		10,6	7,1	1,1
Fine fraction and organic		53,8	36,7	36,5
Property (median value)				
Moisture	% in mass ar	26,5	25,0	15,1
NCV	MJ/kg ar	8,9	15,5	19,3
	MJ/kg d	14,3	21,2	25,0
Ash	% in mass ar	29,6	12,7	12,4
Cl	g/kg d	9,2	10,8	13,8
S	g/kg d	2,9	3,4	3,3
Total C	% in mass d	n/a	46,9	52,8
Fossil CO_2 emission factor	g/MJ d	n/a	34,5	43,2
Property (80th percentile value)				
Moisture	% in mass ar	31,4	29,1	29,3
NCV	MJ/kg ar	10,3	16,8	22,8
	MJ/kg d	15,7	21,4	26,6
Ash	% in mass ar	35,2	15,8	14,8
Cl	g/kg d	12,3	22,2	17,1
S	g/kg d	3,7	4,6	4,5
Total C	wt% d	n/a	48,6	58,3
Fossil CO_2 emission factor	g/MJ d	n/a	41,3	55,7

KEY

- n/a: value not reported

Table D.6 — End use: COAL FIRED POWER PLANT. Properties of SRFs produced in Germany, according to the regulations of RAL-GZ 724 and traded under the trade mark SBS®-1, SBS®-2 and BIOS, utilized as alternative fuels, compared to a common fossil fuel (lignite) (adapted from[1])

Property	Unit	Lignite[a]	SBS^{R}-1	SBS^{R}-2	BIOBS
		Average value (year 2010-2013)			
NCV	MJ/kg ar	10,1	13,2	18,2	11,9
Moisture	% in mass ar	54	24,8	16,4	24,7
Ash	% in mass ar	2,5	9,5	10,1	11,0
Cl	% in mass ar	0,02	0,36	0,74	0,23
Volatile matter	% in mass ar	23,5	53,5	60	52,7
C	% in mass ar	30,5	35,3	39,2	32,5

[a] Lignite from the Rhine region.

[b] Values expressed as 50th percentile.

Table D.6 *(continued)*

Property	Unit	Lignite[a]	SBS^{R}-1	SBS^{R}-2	BIOBS
		Average value (year 2010-2013)			
H	% in mass ar	2,2	4,5	5,6	4,1
O	% in mass ar	10,3	23,8	26,8	26,2
N	% in mass ar	0,4	1,4	1,0	1,2
S	% in mass ar	0,2	0,2	0,3	0,1
Biogenic C	% of TC	0	74,3	50,0	84,4
Chlorides	mg/kg d	300	2,005	1,655	1,575
Al	mg/kg d	750	5,550	5,685	4,700
K	mg/kg d	215	2,160	1,610	3,190
Na	mg/kg d	1,400	2,665	2,213	1,420
Pb (b)	mg/kg d	1,0	75,0	65,0	45
Zn (b)	mg/kg d	3,5	275	350	210

[a] Lignite from the Rhine region.

[b] Values expressed as 50th percentile.

Table D.7 — End use: COAL FIRED POWER PLANT. Properties of SRF (CDR/CSS, in Italy) produced in an Italian MBT plant and utilized as fuel feedstocks in local power plants (adapted from[140])

Parameter	Unit	CDR/CSS Typical value	Parameter	Unit	CDR/CSS Typical value
NCV[a]	MJ/kg ar	17,9	Pb (volatile)[b]	mg/kg d	96
Moisture[a]	% in mass ar	10,1	Cr[b]	mg/kg d	34,9
Ash[a]	% in mass d	17,6	Cu (soluble)[b]	mg/kg d	53,9
Cl[a]	%in mass d	0,48	Mn[b]	mg/kg d	116
S[a]	% in mass d	0,21	Ni[b]	mg/kg d	15
			As[b]	mg/kg d	2,8
			Cd + Hg[b]	mg/kg d	< 2,6

[a] Average value.

[b] Median value.

Table D.8 — End use: GASIFICATION PLANT. Average values for SRF utilized in European gasification plants (adapted from[143])

Parameter	Unit	SRF# *1*	SRF# *2*	SRF# *3*	SRF# *4*	SRF# *5*	SRF# *6*
Origin		MSW	--	--	Mixed	Mixed	Mixed
Form		fluff	pellet	--	--	fluff	--
Particle size	mm	25	--	--	--	10-15	--
NCV	MJ/kg ar	> 25	15,4	17,0	16,3	17,2	16,0
Moisture	% in mass ar	--	2,5	7,0	15,0	6,5	--
Ash	% in mass d	--	18,5	16,1	21,2	11,8	6,3
Bulk density	kg/m^3	--	--	--	--	600	--
Cl	% in mass d	< 0,6	--	0,65	0,35	0,53	0,26
S	% in mass d	--	0,34	0,43	0,24	0,53	0,08

KEY

- --: value not reported

Table D.8 *(continued)*

Parameter	Unit	SRF# *1*	SRF# *2*	SRF# *3*	SRF# *4*	SRF# *5*	SRF# *6*
Hg	mg/kg ar	< 0,02	--	0,04	--	--	0,02
As	mg/kg d	--	--	1,5	--	--	1,4
Cd	mg/kg d	--	--	2,0	--	--	0,1
Co	mg/kg d	--	--	1,5	--	--	--
Cr	mg/kg d	--	--	70	--	--	21
Cu	mg/kg d			250			20
Ni	mg/kg d	--	--	25	--	--	8,5
Pb	mg/kg d	--	--	350	--	--	4,3
Zn	mg/kg d	--	--	500	--	--	74
Tl	mg/kg d	--	--	--	--	--	< 0,05
Na	mg/kg d	--	--	--	--	--	1,190
K	mg/kg d	--	--	--	--	--	670
Br	mg/kg d	--	--	--	--	--	<3
F	mg/kg d	--	--	--	--	--	43

KEY

- --: value not reported

D.2 Typical values: a statistical assessment of measured values

An assessment of typical values for SRF and other secondary fuels was carried out for the purposes of this document by means of a statistical elaboration of analytical results (measured values) that characterize solid fuels recovered with different origins (country; waste stream) and final destination (end-user EfW plant).

D.2.1 Source of data

A database of measured values was built by means of a literature survey and the contribution of local producers/end users (see D.2.4, Table D.27).

The general characteristics of the database are summarized in Table D.9. A quantitative view of the whole number of measured values falling in the database is provided in Table D.10 (physico-chemical parameters) and in Table D.11 (trace elements). With respect to metals, the database is widely provided with three values per parameter, as the choice was made to include both the “original measured value” (the value as reported in the source document, mainly expressed by mass only as mg/kg d) and the corresponding, calculated value expressed relative to energy (mg/MJ ar; mg/MJ d), so as to allow a better comparison of data.

Table D.9 — Summary description of the database

General	Data sources utilized	Total sources, no.	33
	Waste assay	Total assays, no.	648
	Parameters	NVC, Moisture, Ash, Cl, Hg, As, Cd, Cr, Cu, Pb, Pb volatile, Mn, Ni, Cd+Hg, Cu soluble, Sb, Ba, Be, Se, Te, Tl, Sn, V, Zn, Co, Mo, Sr, B, Al	
Market for the waste fuels	European countries	Austria, Denmark, Finland, France, Germany, Greece, Italy, Netherlands, Poland, Croatia, United Kingdom, Switzerland	
	Extra European countries	Korea, Japan, Thailand	
Origin of the waste fuels	MSW	Total assays, no.	227
	I&CW	Total assays, no.	188
	C&DW	Total assays, no.	2
	Mixed waste streams (MSW+ICW+CDW)	Total assays, no.	111
	Unknown (not declared by the source)	Total no of assays	120
Identification of the waste fuels	SRF	Total no of assays	450
	RPF	Total assays, no.	175
	RDF	Total assays, no.	23
End use of the waste fuels	Coal co-combustion in cement kiln	Total assays, no.	240
	Coal co-combustion in power plant	Total assays, no.	21
	Gasification	Total assays, no.	27
	Incineration	Total assays, no.	137
	Co-incineration (other industrial plant)	Total assays, no.	339
	Unknown (not declared by the source)	Total assays, no.	164

Table D.10 — Summary view of physico-chemical properties covered by data in the whole database and their relationship with parameters it is obligatory to specify in existing standards

Parameter	Unit	Quantity of data	Relationship with existing standards
Net calorific value, NCV	MJ/kg ar	615	Required for: the classification of SRF, according to the standard EN 15359, ISO 21640; the classification of RPF, according to the standard JIS Z 7311
	MJ/kg d	615	
Moisture, M	% in mass ar	644	Required for: the specification of SRF, according to the standards EN 15359, ISO 21640 (Annex A); the classification of RPF according to the Standard JIS Z 7311
Ash content, A	% in mass d	643	Required for: the specification of SRF, according to the standards EN 15359, ISO 21640 (Annex A); the classification of RPF according to the standard JIS Z 7311
Chlorine content, Cl	% in mass ar	575	Required for: the classification of SRF, according to the standard EN 15359, ISO 21640; the classification of RPF, according to the standard JIS Z 7311
	% in mass d	408	
	mg/kg d	37	

Table D.11 — Summary of chemical properties covered by measured values in the database and their relationship with parameters specified in existing standards

Parameter	Quantity of Data expressed as		Parameter	Quantity of Data expressed as	
	mg/kg d	mg/MJ d		mg/kg d	mg/MJ d
Mercury, Hg[a] [b]	399	398	Aluminium, Al	81	78
Antimony, Sb[b]	262	262	Molybdenum, Mn	21	21
Arsenic, As[b]	436	434	Zinc, Zn	96	94
Cadmium, Cd[b]	407	405	Selenium, Se	52	50
Chromium, Cr[b]	451	449	Barium, Ba	51	51
Cobalt, Co[b]	261	261	Beryllium, Be	43	43
Copper, Cu[b]	350	349	Soluble Copper, Cu	61	61
Lead, Pb[b]	348	343	Volatile Lead, Pb	129	129
Manganese, Mn[b]	395	395	Tellurium, Te	33	33
Nickel, Ni[b]	451	451	Strontium, Sr	2	2
Thallium, Tl[b]	215	215	Boron, B	2	2
Vanadium, V[b]	87	87			
Tin, Sn[b]	47	47			

NOTE

(a) Parameters required for the classification of SRF, according to EN 15359, ISO 21640

(b) Parameters required for the specification of SRF, according to Annex A (Normative) of EN 15359, ISO 21640

Almost all of the assays found (97 %) provide a characterization of solid recovered fuels explicitly named “SRF” in the source document (450 assays, of which only 1,7 % were from non-European countries) or, e.g. in the case of the pelletized RPFs (175 assays, all from non-European countries, 95 % from Japan), that can be identified as SRF according to the assumed criteria (see Annex A). Around 3,5 % of the assays found provide a characterization of secondary fuels (produced in Europe: Netherlands, Greece, Switzerland and United Kingdom) that are named RDF in the source document.

As the sources do not provide evidence of the compliance of these refuse-derived fuels with a national/international standard, their identification in terms of SRF according to the assumed criteria (see Annex A) remains in any case uncertain.

Of the total of 23 assays, 9 refer to RDFs with an end user (gasification plants) of specific interest in this document.

Regarding the end use of the waste derived fuels:

- 137 assays refer to SRFs utilized in incineration plants (MSW-SRFs in 63 %, mixed-SRFs in 29 % and ICW-SRFs in 8 % of the examined assays), while SRFs treated in co-incineration plants (other than cement kilns and coal power plants) are characterized in 164 assays, of which 62 % refer to an MSW-SRF and 37 % to a Mixed-SRF;
- properties of SRFs used in gasification plants are characterized in 18 assays: these SRFs are mainly mixed-SRF or an ICW-SRF (38 % of the examined assays, for both the fuel origins), while only 3 assays refer to an MSW-SRF and 1 to a CDW-SRF;
- the majority (76 %) of the 21 assays that refer to an SRF with coal co-combustion in power plants as the final destination (data mainly from Italy) characterizes an MSW-SRF (only 1 assay an ICW-SRF and 4 a mixed-SRF);
- 37 assays have been found that give data on properties of SRF utilized as a fuel substitute in cement kilns, of which 41 % refer to an MSW-SRF and 57 % to a mixed-SRF;