SUBNATIONAL
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White Paper on
Refuse Derived Fuel
(RDF)

Notes

This report is based on information from available literature, publicly accessible databases, information from expert discussions and the personal assessment of the authors based on many years of experience in the industry.

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White Paper on

Refuse Derived Fuel (RDF)

created for
Subnational Climate Fund

by Carbon Turnaround
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Executive Summary

Integrated waste management in Developing Economies stands in its infancy and is both a key challenge and opportunity to achieving the United Nations (UN) Sustainable Development Goals (SDGs), and the UN Paris Agreement. Landfilling and dumping in such regions is practiced extensively and is reaching its limits due to environmental concerns and rejection by civil society. Thus, alternative solutions that are affordable and effective are desperately being sought by local and national governments. Integrated waste management covers the value-chain from waste generation, collection, transportation, treatment and final disposal, utilising a multitude of treatment solutions selected and designed based on local conditions. These solutions typically include sorting, and the treatment of different fractions of sorted waste for material recycling, material recovery or energy recovery.

The use of the non-recyclable fractions of Municipal Solid Waste (MSW) to produce an alternative fuel, commonly known as Refuse Derived Fuel (RDF), is considered as a key pillar of an integrated waste management system. The production of RDF in an integrated waste management system follows the Waste Management Hierarchy: (in order of preference) prevention, reuse, recycling, recovery, and disposal. Such use of combustible non-recyclable waste as fuel in cement plants as well as a co-combustion fuel in power plants or other industrial boilers is a well-established practice in Europe and other developed economies. There are many best-practice experiences and lessons learned from these countries which can facilitate and improve the adoption of RDF use in developing economies where such practices are in their infancy.

This White Paper was commissioned by the Subnational Climate Fund (SCF) within this context and aims to serve as a guideline for decision-makers on the sustainable implementation and operation of waste management projects that involve the production of RDF. A 'sustainable' RDF project should safeguard high environmental standards in producing and using RDF – as well as mitigate economic risks. These standards and criteria are therefore relevant to the developer, owner and operator of an RDF production plant and the installations recovering the energy from the RDF.

The following **basic** sustainability criteria ***within* the control or influence** of the developer/owner and operator of an RDF production plant have been identified:

- Pre-treatment of raw waste streams to prepare a fuel according to the need of the energy recovery facility utilizing the RDF

- Capability of the pre-treatment to sort out recyclables and thereby follow the principles of the waste hierarchy
- Constant quality control of the produced RDF for safeguarding output product quality and ensuring market value
- Close cooperation with public (municipality) and / or private and informal (waste collector) actors to integrate the project in the local context and to secure support from all stakeholders involved
- Long term waste supply needs to be secured to guarantee the economic sustainability of the project
- Agreement with RDF off-takers and storage facilities for the product to reduce the economic risks of external factors in marketing the RDF
- Waste hierarchy thoroughly considered to avoid lock-in effects which could prevent an integrated waste management system
- Robust plant design of the RDF processing facility
- Safety risks must be considered for waste collection, logistics, processing, storage, handling, and use of RDF
- RDF plant manufacturer has a proven track record in the design, engineering, and construction of similar projects
- Use of Best Available Techniques for RDF production

In addition, the following **basic** sustainability criteria ***outside* the direct control or influence** of the developer/owner and operator of an RDF production plant have been identified. These aspects should be secured by **contractual arrangements** between the **RDF producer and the RDF off-taker**:

- Emission control and emission monitoring must be in place at the RDF-recovery facility
- Monitoring of product quality or quality of solid residues must be in place at the RDF-recovery facility
- Use of Best Available Techniques for RDF utilization

Furthermore, the following set of **supplementary** sustainability criteria have been defined as **additional factors** that can facilitate sustainable implementation and operation of an RDF production facility:

- Proven climate mitigation effect by reducing GHG emissions
- Traceability of waste input during the pre- and co-processing from reception up to final usage should be possible
- Ensuring that RDF processing and utilization is part of the regional waste management plan

It is important to bear in mind that RDF projects are *always* context specific, and each has to be evaluated individually for its sustainability attributes. The energy market situation, waste sector situation, environmental situation and social situation can vary significantly between countries and regions. Therefore, the **diversity of project contexts** must be considered for any project assessment and for defining an appropriate set of rules to comply with to be considered as a sustainable activity.

The objective of this White Paper is to illustrate the variety of criteria which must be considered to implement successful and sustainable RDF waste management projects and thereby provide guidance to project developers, investors and other stakeholders involved in this industry. By considering these recommendations, such projects can play a key role in the development of an advanced and integrated waste management sector in countries where such practices are not yet established.

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1. Background, Context and Objectives

1.1 Background

Municipal Solid Waste (MSW) in most developing economies is managed by collection and disposal at landfills or dumpsites. In some cases, there is even a lack of collection, whereby waste is littered on the streets, burnt openly, and dissipated into the environment close and afar. The local environmental and health hazards from these practices are significant, as is the effect of the resulting marine litter to oceanic ecosystems. In addition, the decomposition of organic waste on landfills and dumpsites, which often makes up more than half of MSW in these regions, releases methane, a much more potent greenhouse gas than carbon dioxide, especially in the short term. Thus, transforming waste management in these regions into sustainable practices would yield multiple benefits, and accelerating it now is imperative for reaching climate mitigation targets. In fact, it is a low-hanging fruit to reduce methane emissions, as the waste sector emits about 20% of the total methane emissions globally [1].

To transform the management of MSW, a holistic approach addressing the entire system is necessary: this ranges from awareness-raising, engagement and integration of stakeholders, capacity building, source separation, collection and treatment facilities through to final disposal. However, to reduce methane emissions quickly, the first step that can be acted upon is to separate the organic fraction from the MSW and prevent it from being disposed of into a landfill or dumpsite. Thus, while planning and implementing policy changes, awareness-raising, and source separation, a few simple waste treatment facilities can be put into place to separate the organic fraction from the mixed waste. This diverts it from landfill or dumpsites and at the same time also recovers and recycles other valuable resources.

In this respect, a simple waste treatment plant typically starts with a basic sorting plant which may aim at separating the organic fraction, the recyclable materials such as paper, metal and recyclable plastics, and the residual waste, or stream, that cannot be recycled. Instead of sending the residual stream of such a sorting plant to a landfill or dumpsite, this stream can be processed to produce Refuse Derived Fuel. RDF has been mostly used in cement production, but in some cases also in other production processes such as for steel, brick, and energy production.

RDF utilisation is common in developed countries and regions to recover energy from waste following the waste hierarchy [2], in compliance with legally defined emission limits. RDF technology is therefore readily available, relatively advanced and its use is regulated. However, there are concerns about the use of it in developing economies and regions as the legal framework for an environmentally sound utilisation of RDF may not yet exist. Although on the other hand, landfilling and dumping of these materials within the current context of developing economic regions needs a significant amount of land and an appropriate landfill technology even in the best-case scenario. In the worst-case scenario, open burning or dispersion of such materials into the environment and the ocean can lead to micro-plastic pollution due to the disintegration of plastics.

Any waste combustion process releases harmful emissions which must be controlled by air pollution control equipment; oftentimes existing facilities that may not be equipped appropriately are used for energy recovery from RDF (i.e. a fuel derived from waste). In these cases, modifications of the existing facility and quality assurance of both the RDF-input and the combustion emissions are paramount to guarantee a sustainable implementation. This is commonly done and well controlled and monitored in developed economies. Given the lack of governance or capacity, or both, in many developing economies, some concerns prevail that a potential lack of control and monitoring of emissions from combusting RDF may lead to environmental and health risks.

Based on the boundary conditions and the institutional set-up of an RDF producing waste management facility, the sale of RDF may contribute positively to the economic feasibility of a waste management facility. This will either be directly through revenues from sale of the RDF, or indirectly through reduced overall cost for managing the waste. Almost all facilities with a sorting plant will propose to produce RDF if an off-take agreement with a buyer can likely be reached. Many municipalities in developing economies lack the financial resources to build waste treatment facilities, thus needing financing from investors and debt providers. For investors and debt providers - both domestic or international - financial sustainability of the proposed project is one of the key considerations for an investment, or loan decision. The production and sale of RDF can therefore sometimes be a make-or-break element in the business model, because the residual non-recyclable waste fraction can reach more than 30% of a sorting plant's output by weight.

1.2 Context

The international climate mitigation effort places emphasis on rapid methane emissions reduction as a strategy to keep global warming below 1.5 degrees and to reach short-term emission reduction targets by 2030, e.g., the Global Methane Pledge [3]. Diverting organic waste from landfills and dumpsites is therefore a low-hanging fruit and as a result a multitude of waste treatment facilities are being proposed and under development, all seeking financing. On the other hand, investing in waste management in developing economies is on the rise in the mandate or strategy of Development Finance Institutions (DFIs) and Impact Investment funds. In other words, the demand and supply are both increasing – a good time for realising more sustainable waste management infrastructure. In almost all the projects proposed which do not focus on waste to energy from unsorted waste, a sorting plant with RDF production is the first and integral component of a treatment facility.

When the business model makes sense, and the targeted impacts can be substantiated, DFIs and impact investors are willing to finance the project. Environmental and social risks can be evaluated against international standards such as the IFC Performance Standards or the Gold Standard and mitigation methods must be considered. However, there is no clear guidance in those international standards on the environmental and social safeguarding measures specifically related to waste projects involving the production of RDF. This creates uncertainty for DFIs and impact funds, which makes it difficult to make investment decisions or management decisions after investment on how to safeguard the environment and society, running such projects. To support the establishment of new standards and guidelines surrounding the topic of RDF, it is necessary to have a comprehensive understanding of RDF.

Being one of the actors in the ecosystem of development financing and impact investment, the SCF thus commissioned this White Paper for the community to better inform their decisions in financing projects in the waste management sector. The SCF is a blended finance impact fund created to pursue attractive risk-adjusted returns for private investors while generating measurable and certified environmental and social impacts. The SCF is focused exclusively on pursuing investments in mid-size climate infrastructure and nature-based solutions in various developing economies across Latin America and the Caribbean, Africa, the Mediterranean, and Asia.

1.3 Objectives

This White Paper aims to provide technical understanding, value chain insight, and guidelines on safeguarding measures to undertake in waste management projects involving RDF. The SCF as sponsors of this paper, and Norfund as a partner, represent the impact investment community who want to deliver more environmentally and socially sustainable waste management infrastructure in developing economies and at scale and at speed.

This paper has been developed with a developing economies' context in mind and uses experiences and developments from developed economies to provide a complete picture of RDF-utilization. As a sustainability assessment of RDF utilization requires a systems approach, this paper focuses not only on RDF utilization, but also touches upon upstream processes such as waste collection and RDF processing, as well as downstream aspects such as emission control from the RDF utilization.

This paper should enable those who are responsible for the assessment of project proposals to identify whether basic sustainability criteria are addressed in a responsible way and therefore basic sustainability criteria are met by a specific proposed project. Furthermore, it will set out supplementary sustainability criteria to be put in place to minimise potential negative environmental impacts of projects involving the production and utilization of RDF.

As a sustainability assessment always requires expert knowledge and the consideration of the specific boundary conditions (e.g. legal framework, economic boundary conditions, industry sector, etc.) of a project, this paper can only elaborate on basic guidelines to be followed and met to ensure a sustainable implementation of a project. A project-specific Environmental and Social Impact Assessment and Plan must also be conducted; the concepts from this paper may be used to inform - but are not intended to replace - that assessment.

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2. Definitions & Scope

Energy can be recovered from waste in many ways, such as the direct use of waste as a fuel in unprocessed or processed form, or from the combustible gas that results from controlled anaerobic degradation in a digestion unit - or even from a landfill. All methods may be referred to as Energy-from-Waste (EfW) or Waste-to-Energy (WtE) in the literature as well as on the market.

The scope of this White Paper discusses solely the use of Municipal Solid Waste (MSW) to produce RDF to be used as a fuel for thermal processes. Direct mass-burn facilities, scenarios involving the direct incineration of MSW, gasification, pyrolysis, the use of landfill or biogas, as well as the energy recovery from other types of waste are not within the scope of this paper.

There are two main types of RDF utilization that are differentiated for sustainability assessment within this paper:

1. Use of RDF as a fuel in a production facility such as a cement factory, a lime work, or a brick factory (case 1)
2. Use of RDF as a fuel in a power plant or industrial utility boiler that provides energy in the form of steam or electricity (case 2)

There are also other potential options to make use of RDF such as for example recovery in transportation fuels, however, these are outside the scope of this paper.

In case 1, while no solid residues remain from the fuel utilization itself, the product quality of the product produced, e.g., cement, may be at risk. In case 2, like mass-burn facilities, solid residues such as fine ash as well as bottom ash remain from the energy recovery process and therefore need to be taken care of.

Energy recovery from RDF most often allows for the use of existing facilities with comparatively only minor investment needs when compared to newly installed facilities for thermal treatment of waste. Requirements regarding upstream processing as well as process and emission control are different for the previously mentioned two cases of RDF utilization and therefore these aspects will be discussed in the following sections.

For the two cases mentioned previously, in general, two categories of fuel may be used: “primary fuels”, and “secondary fuels” (also named “alternative fuels” (AF) or “substitute fuels” (EBS or SBS in German)). Whereas the term “primary fuel” refers to fossil fuel, the term “secondary”, “alternative” or “substitute fuel” refers to Waste Derived or Refuse Derived Fuel (WDF or RDF, see definitions in the following section). This secondary fuel (RDF is the term generally used throughout this paper, implying a degree of processing prior to its use as a fuel) is used to substitute the primary fuel to a various extent and may even be used as the only fuel.

This section provides an overview of the different types of WDF. For this purpose, definitions are given based on international standards, the system boundaries are set, and the respective off-taker facilities are highlighted.

2.1 Energy recovery from waste: context and types of fuels

The recovery of energy from waste must always be seen in the context of an integrated waste management hierarchy. The so-called waste hierarchy defines the priorities of potential interventions in waste management and defines five hierarchical levels: waste prevention, reuse, recycling, recovery, and disposal. It must be understood that these levels cannot be conceived as one excluding the other, but they coexist in a sustainable integrated waste management. For example, recycling of plastics will always demand processing of the waste stream from where the plastic is to be recovered, even if collected separately upstream. To achieve a marketable recyclable product, this processing will always result in the separation of a non-recyclable fraction that may preferentially be used for energy recovery purposes (e.g., Refuse Derived Fuel). What is considered as recyclable or non-recyclable may differ from case to case as the economical boundary conditions are an important enabler, or an obstacle in a specific setting. In addition, these conditions change over time – also as a consequence of societal development - therefore the quantity and quality of the remaining non-recyclable fraction might change over time.

Figure 1 illustrates a more detailed hierarchy and breaks down the different options for the most desired recovery / treatment of waste fractions.

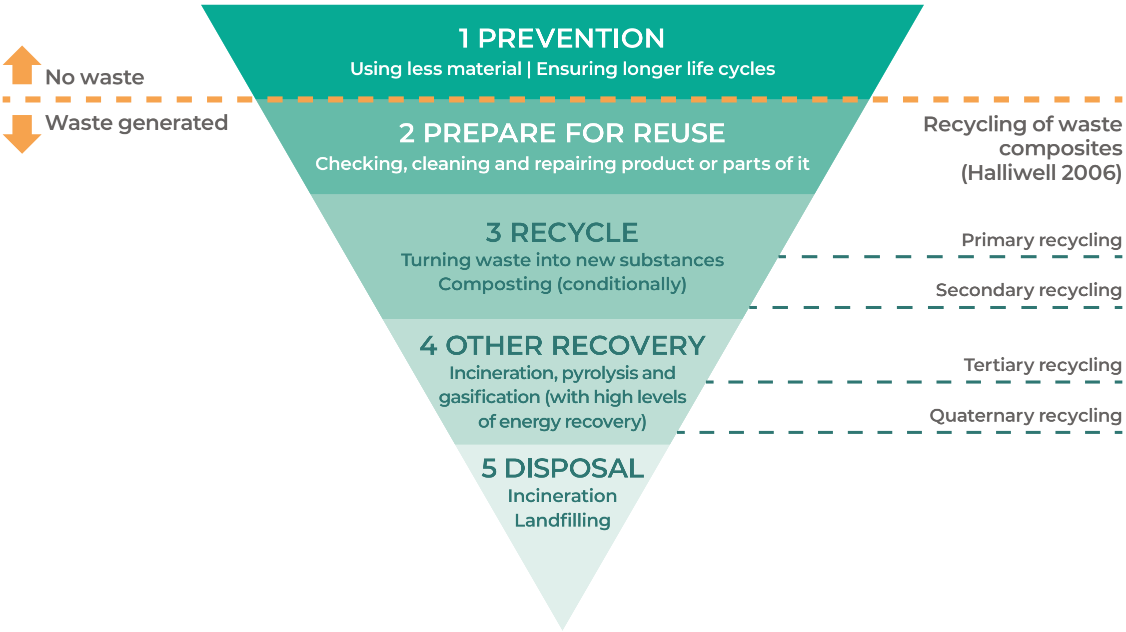


Figure 1: The Waste Management Hierarchy, recovery of energy from RDF is level 4 [4]

The terms used throughout this paper regarding Waste Derived Fuel are distinguished according to their definitions in literature. Although terms are sometimes named differently in various countries, they often have an identical or similar meaning. For better understanding, a common definition of the terms will be used here, with the various acronyms and extended names also given as examples.

Figure 2 shows a schematic delineation of different waste fuel types as well as the level of pre-processing needed in the respective cases and the legal status of the resulting waste-fuel.

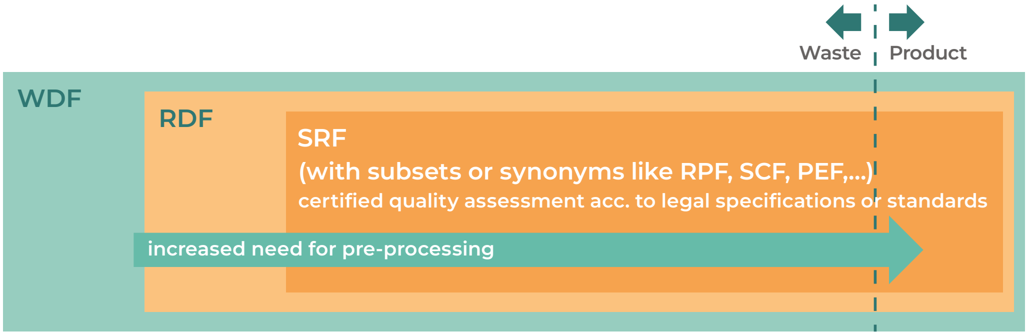


Figure 2: Schematic distinction between different Waste Derived Fuel acronyms based on the definitions as follows and their respective legal status (author's own representation)

Throughout this paper, the fuel derived from waste will be considered as waste in legal terms even though legislation in some countries allows end-of-waste status for high quality waste derived fuels. For example, the Austrian Waste Incineration Directive regulates the end-of-waste status for Solid Recovered Fuel (SRF). Accordingly, substitute fuel products lose their waste status in legal terms for the intended use when they are declared as such based on the submission of a valid assessment certificate to the respective ministry [5].

2.1.1 Waste Derived Fuel (WDF)

According to the UK Waste and Resources Action Programme (WRAP), the term "*waste-derived fuels*" refers to " ... *a heterogeneous group of non-hazardous wastes that do not cease to be* ... [waste] ... *when used to generate energy without having any greater negative impact on the environment than disposal in landfill* ... " [6].

The term Waste Derived Fuel (WDF) in this paper will therefore be used as a superordinate term without any implication regarding the upstream processing requirements, the fuel quality, the energy recovery facility targeted or legal status of the waste to be used as a fuel.

2.1.2 Refuse Derived Fuel (RDF)

According to ISO/TR 21916:2021 " ... *all the secondary fuels are assumed to fall under the generic and common name of Refuse Derived Fuel (RDF)* ... ". Differing from SRFs (see next section), RDFs do not have to be certified to meet standardised classification and specification requirements as laid down in the ISO/TR 21916:2021 standard [7].

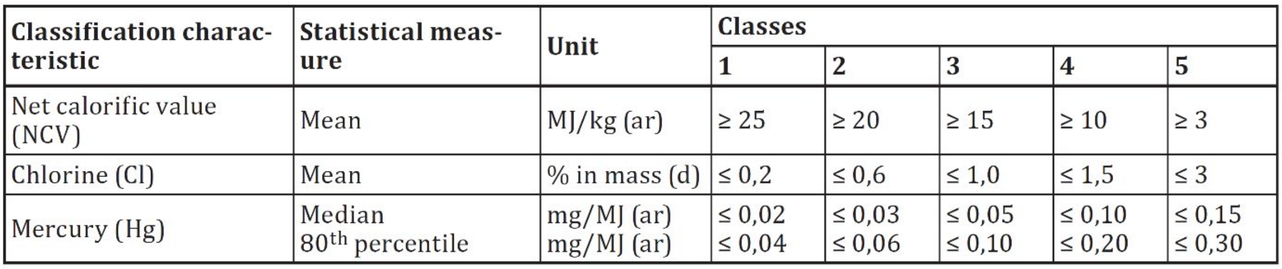
Despite not being certified for its quality parameters, RDF goes through processing to increase the calorific value, which is why the term usually refers to the separated, high calorific fraction of MSW, commercial and industrial wastes [8].

In the context of this paper, RDF will be the predominantly used term. This should emphasize the RDF meeting certain fuel quality criteria as a consequence of processing, while not necessarily requiring the certified compliance with quality specifications as for example laid down in the ISO/TR 21916:2021 standard [7].

2.1.3 Solid Recovered Fuel (SRF)

SRFs is defined as a subset of the family of RDF and, like the main group, produced from non-hazardous waste, whereas SRFs are subject to a quality assurance system. For example, the ISO 21640:2021 standard provides a classification system based on three important characteristics, which are referred to as the main SRF characteristics: one rather energy economically relevant characteristic (net calorific value, NCV), a process related characteristic (chlorine content, Cl) and an environmental characteristic (mercury content, Hg). These key properties are defined by threshold values as shown in Table 1 [9].

Table 1: Classification for Solid Recovered Fuels according to ISO 21640:2021 [9]



Classification characteristic	Statistical measure	Unit	Classes				
			1	2	3	4	5
Net calorific value (NCV)	Mean	MJ/kg (ar)	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Chlorine (Cl)	Mean	% in mass (d)	≤ 0,2	≤ 0,6	≤ 1,0	≤ 1,5	≤ 3
Mercury (Hg)	Median 80th percentile	mg/MJ (ar) mg/MJ (ar)	≤ 0,02 ≤ 0,04	≤ 0,03 ≤ 0,06	≤ 0,05 ≤ 0,10	≤ 0,10 ≤ 0,20	≤ 0,15 ≤ 0,30

d … dry; ar … as received

It must be noted that depending on the firing technology used, the NCV required for self-sustained combustion is in the range of 3 – 5 MJ / kg (ar). Therefore, any lower NCV of RDF (in Table 1 SRF) demands additional energy input provided by auxiliary fuel – most often fossil fuel – in order to achieve complete combustion. This is not considered to be a sustainable practice.

The conformity with one of the SRF classes according to Table 1 is to be documented through an external certification such as provided for example by the *Bundesgütegemeinschaft Sekundärbrennstoffe und Recyclingholz e. V.* [10] in Germany.

It must be clarified that for specific energy recovery from waste projects, many more criteria may need to be met by the waste fuel according to the specific setting and requirements of the off-taker in order to warrant a sustainable implementation.

These criteria can be grouped into the following groups:

- Storage and feeding requirements: such as biological stability, water/moisture content, particle size distribution, energy density, ...
- Process and product (if applicable) related requirements: such as ash content, heavy metal content, chlorine, and alkali metal contents, ...
- Pollutant content: based on air emission control equipment in place and respective requirements other / more information regarding pollutant content might be needed

Sarc (2015) furthermore differentiates between premium quality, medium and low quality SRF based on the criteria Lower Heating Value (LHV) and particle size according to Figure 3 [11].

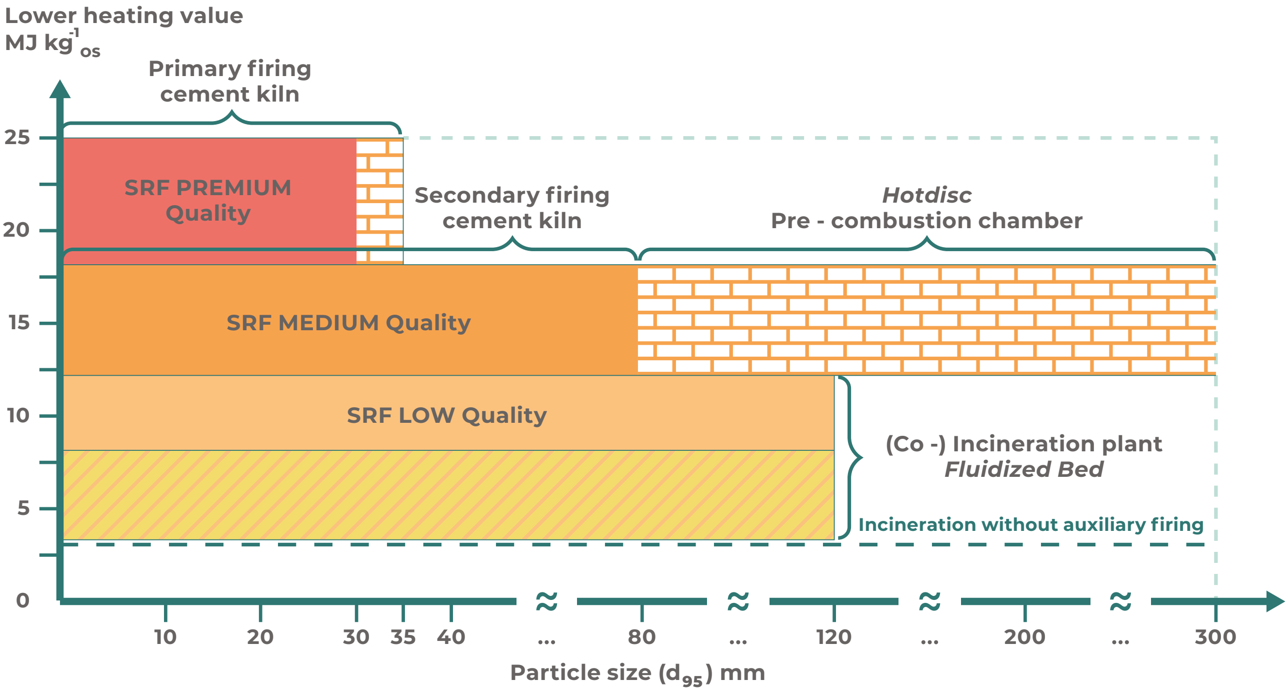


Figure 3: Differentiation between different qualities of SRF according to the parameters Lower Heating Value (LHV) and particle size including the appropriate energy recovery option in each case [11]

Three more detailed SRF qualities are specified as follows:

a) SRF low quality: Particle size <120 mm, LHV <12 MJ/kg usage mainly in fluidized bed incinerators.
b) SRF medium quality: Particle size <80 mm, 12 < LHV <18 MJ/kg, typically used for energy recovery in secondary firing systems in cement kilns or in pre-combustion chambers like Hot-Discs
c) SRF premium quality: Particle size <30 mm, 18 < LHV < 25 MJ/kg, typically used for energy recovery in primary firing systems of cement kilns.

It should also be emphasized that it is reasonable to assess pollutant contents as a benchmark related to the energy content as displayed in Table 1 above in mg/MJ, as this is the only valid benchmark to assess the pollutant content of the secondary fuel compared to the substituted primary fuel, since the energy demand of energy recovery facilities can be taken as fixed. A primary fuel such as brown coal might have a lower pollutant content, however, due to a higher mass-flow needed to provide the energy required, the overall mass of respective pollutants fed to the energy recovery facility might be higher when compared with the case of using a waste fuel.

As explained in section 2.1.2, the term RDF will be predominantly used as quality specifications have to be met by the waste fuel in order to secure a sustainable project, but an external certification of waste fuel characteristics is not yet commonly accessible and affordable all over the world.

It should be emphasized as shown in Figure 2 that RDF might have the same quality as SRF, however as there is no external certified assessment, the waste fuel is still called RDF instead of SRF. To allow for a quality categorization of RDF, the classification according to Table 1 and Figure 3 will be used in the subsequent sections of this paper irrespective of an official certification.

2.1.4 Other terms used

In addition to the terms already mentioned, other terms are used in various countries to name waste derived fuels. In some cases, the descriptions are like those of SRF and/or RDF. Furthermore, more precise definitions based on the type of waste involved or the destined energy recovery operation are also used at national level.

In South Korea, for example, solid waste fuel produced from plastic was referred to as Refuse Plastic Fuel (RPF) until the term was renamed SRF in 2013. In Japan, the acronym RPF (Refuse derived paper and plastics densified fuel) refers to pelletised recovered fuels derived from dry / non-hazardous paper & plastics from industrial production. RPF is regulated by a national standard. In India, non-recyclable fractions of MSW containing plastics and other combustible materials – so-called SCF (Segregated Combustible Fractions) - are used to produce RDF [7].

2.2 System boundaries

To assess RDF utilization projects comprehensively regarding their sustainability, a system approach considering upstream as well as downstream processes must be applied. Figure 4 below shows a generic representation of the central processes of generating RDF and the overall system that needs to be looked at.

Upstream operations, such as the collection and preparation of waste to produce RDF are an important part of the process, as well as down-stream aspects such as product quality or quality of solid residues that need to be treated and disposed of. Therefore, these aspects are an essential part of the assessment - as well as the direct use as a fuel.

A detailed description of the individual processes can be found in Section 4.

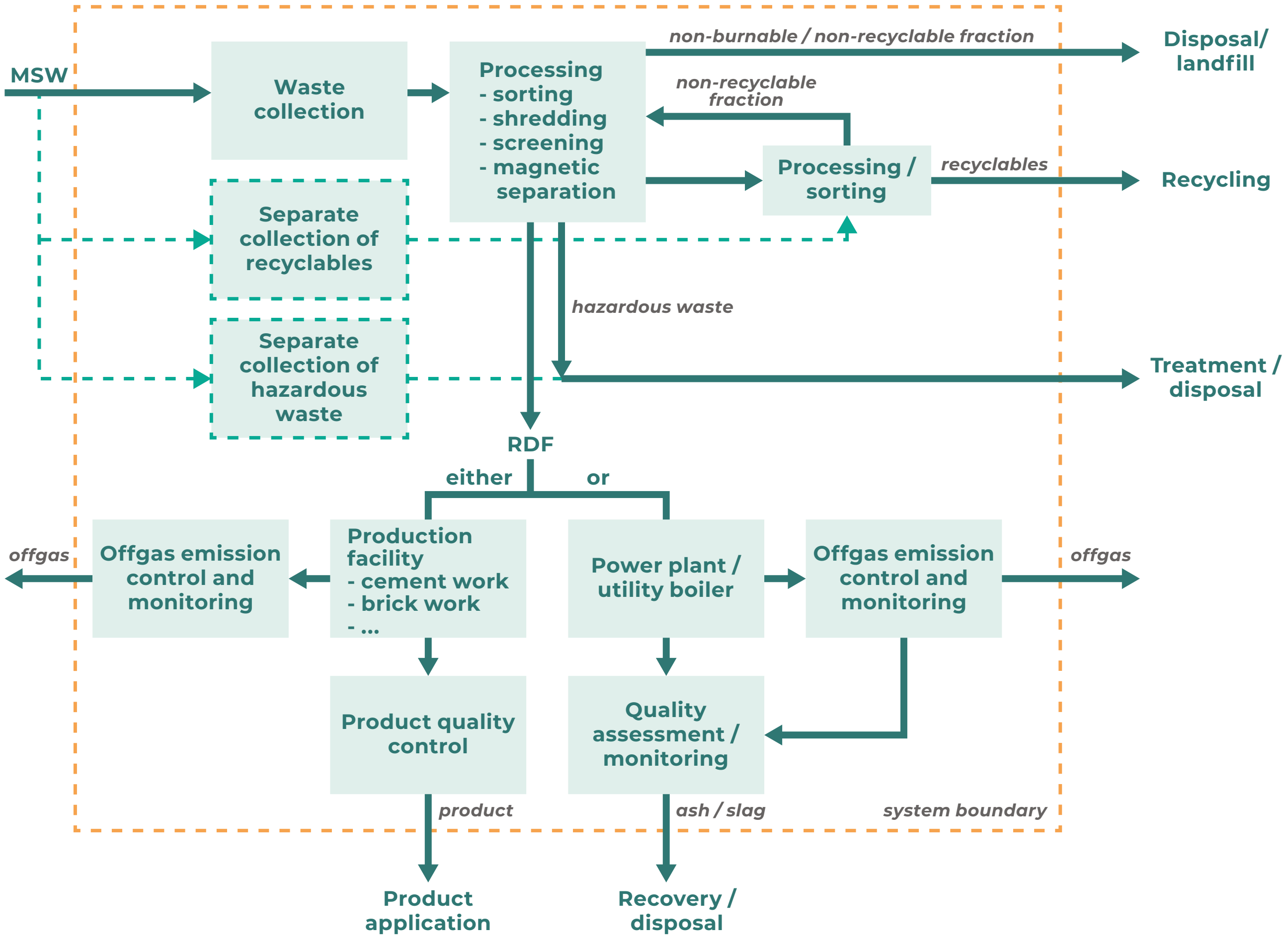


Figure 4: System boundaries of projects involving RDF production & utilization (author´s own representation)

For the specific case of RDF co-processing within the cement industry the following Figure 5 gives a more detailed representation including also logistical aspects such as reception and storage and the respective quality control processes needed.

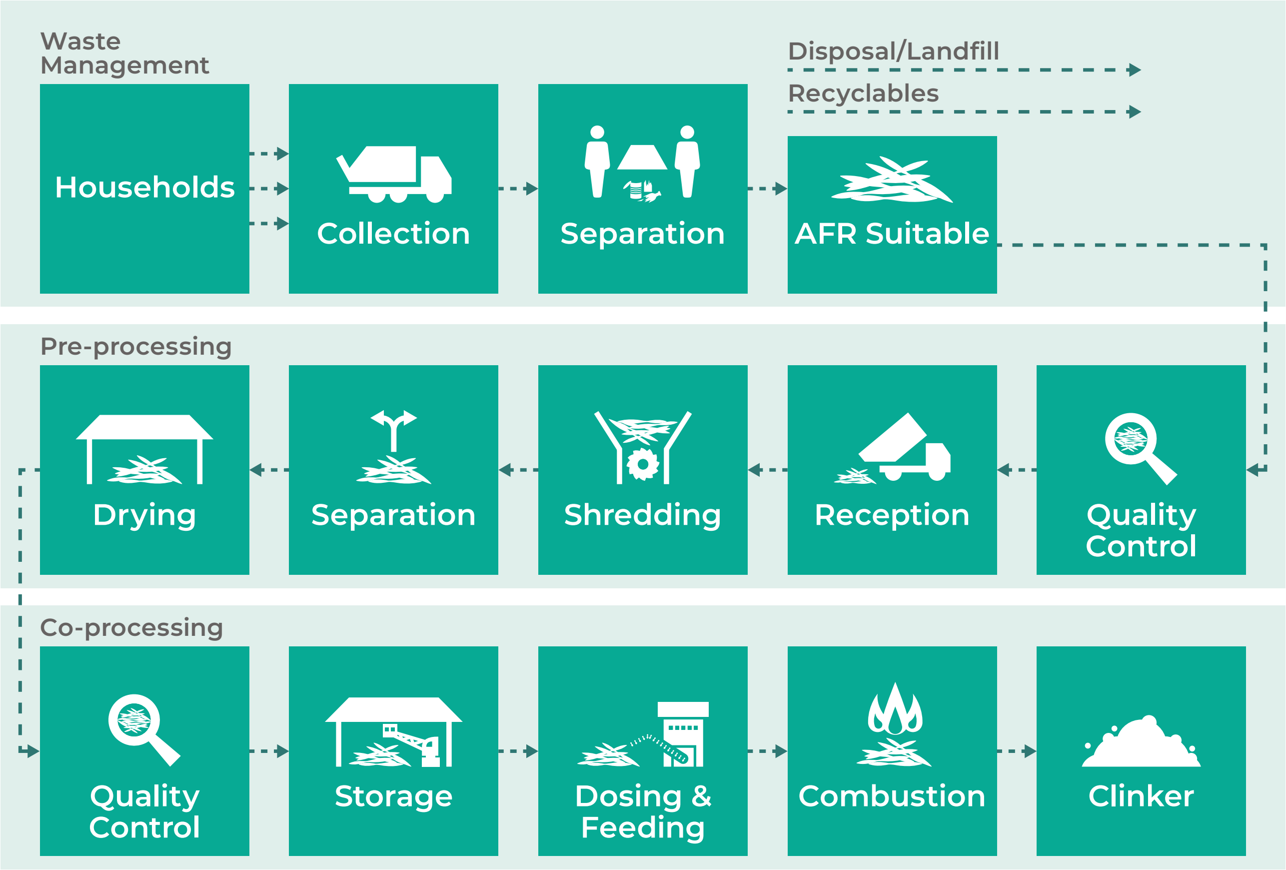


Figure 5: System boundaries of RDF co-processing projects in the cement industry [12] (modified) (AFR ... Alternative Fuel & Raw Materials)

2.3 Waste types

The waste types relevant to produce RDF are:

1. Mixed municipal solid waste
2. Specific waste streams of MSW separately collected (e.g., plastic waste skimmed off from MSW in the collection stage, including recyclable and non-recyclable plastic waste)
3. Non-recyclable waste fractions from the processing of MSW as well as separately collected waste fractions.
4. Residues from landfill mining
5. Commercial and industrial waste
6. Used tyres, used oils
7. Agricultural waste, waste wood

This paper focuses on numbers 1 – 4 which are all fractions stemming from MSW. Figure 6 offers a broader overview of specific types of waste relevant for pre-processing and co-processing for the use of RDF in the cement industry. In addition, Figure 6 shows the typical partners (or customers) for the sourcing of waste to be prepared as a fuel [13].

	Municipal Solid Waste	Industrial Hazardous Waste	Industrial Non-Hazardous Waste	Biomass Residues
Waste Type	- Sorted municipal waste - Dried municipal waste	- Oil & Gas - Chemicals - Pharma - Automotive - Liquid	- Trade rejects - FMCG - Packaging - Tires - Fiscal destruction	- Husks (rice, soya, etc.) - Wood - Seeds - Bagasse
Typical customers	- Municipalities - Waste management companies	- Local and multinational companies	- Local and multinational companies	- Farmers, plantations, millers - Brokers, traders

Figure 6: Waste types relevant for pre- and co-processing in the cement industry [13] (modified)

All of the different types of waste mentioned may require a different level of pre-processing to meet the demand of the off-taker, as well as to guarantee a sustainable implementation of an RDF-project.

2.4 Off-taker-facilities

The industries where the RDF covered in this paper are most used are production facilities of the cement and lime industry, as well as industrial power plants / utility boilers in the pulp & paper industry. Sometimes, but less frequently, RDF is also used by utility companies in their coal-fired power plants as well as in brickworks and steelworks.

As mentioned earlier, different from direct mass burn of MSW, energy recovery from RDF always requires some pre-processing of the waste fuel in order to secure compliance with the minimum requirements of the energy recovery plants of the off-taker. This might be done by the off-taker, the municipality, a third party or a facility implemented as a joint venture between the off-taker and the waste management entity – be it the municipality or a private sector stakeholder (see Section 4.2.1). Private sector joint venture or Public-Private Partnership (PPP) arrangements can secure the waste as a feed to the RDF plant while ensuring economic transparency and compliance with off-taker requirements - and thereby security of demand for the RDF produced.

The various plants that may use RDF are equipped with different emission control equipment due to the nature of the production process and the legislative framework they must comply with – especially if they are existing facilities. Therefore, to incentivize a sustainable and environmentally sound implementation, either specific legal stipulations for the emission control when

RDF is being used need to be complied with, or such environmental standards must be secured by project specific standards that go beyond the legal obligations of the off-taker plant.

In developed economies, off-taker plants using RDF as a fuel must comply with defined limit values regarding the off-gas emissions. In Europe, for example, plants using waste as a fuel must at least meet the requirements of the EU Directive (2000/76/EC) [14] on the Incineration of Waste. In addition to this, the RDF quality (in addition to off-taker specific requirements) might have to meet legally defined minimum requirements regarding pollutant content to guarantee a certain degree of pre-processing. One example for such a legal stipulation would be the Austrian Waste Incineration Ordinance [5].

Section 5 outlines the industrial sectors and the types of technologies that are used to recover energy from RDF and illustrates some types of emission control measures.

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3. Quality criteria

To be able to use RDF for energy recovery purposes certain conditions must be met. Based on the distinction made in Section 2, industrial utility boilers are recovery facilities that have specifically been designed to only use waste (i.e., RDF) as fuel. Whereas production facilities (and sometimes also power plants) are facilities that were designed to be operated with primary fuels. Especially in the latter case, quality criteria for the RDF-input used to displace the primary fuel are very important. These quality-related criteria are [15]:

- defined calorific value and low chlorine content,
- defined particle size and bulk density,
- few impurities,
- low heavy metal content (for co-incineration),
- and the availability of sufficient quantities in the required quality

Therefore, to use RDF properly, it is essential to define and meet quality standards according to the specific need of the off-taker facility. The following is an overview of relevant properties and contents of waste fuels that need to be considered. Subsequently, methods for quality assurance are shown and finally fuel properties of RDF are compared with other (fossil) fuel types. Waste collection and processing influences RDF quality and will be discussed in Section 4 in detail.

3.1 Waste as a fuel: Fuel triangle

Any project recovering energy from waste aims at replacing the energy provided by primary fuels with the energy contained in the waste. Therefore, the waste recovered is considered as a fuel and must be assessed with regard to its fuel related properties.

Figure 7 illustrates the fuel triangle also known as Tanner diagram [17], which shows the relationship between water, ash, and organic/combustible components.

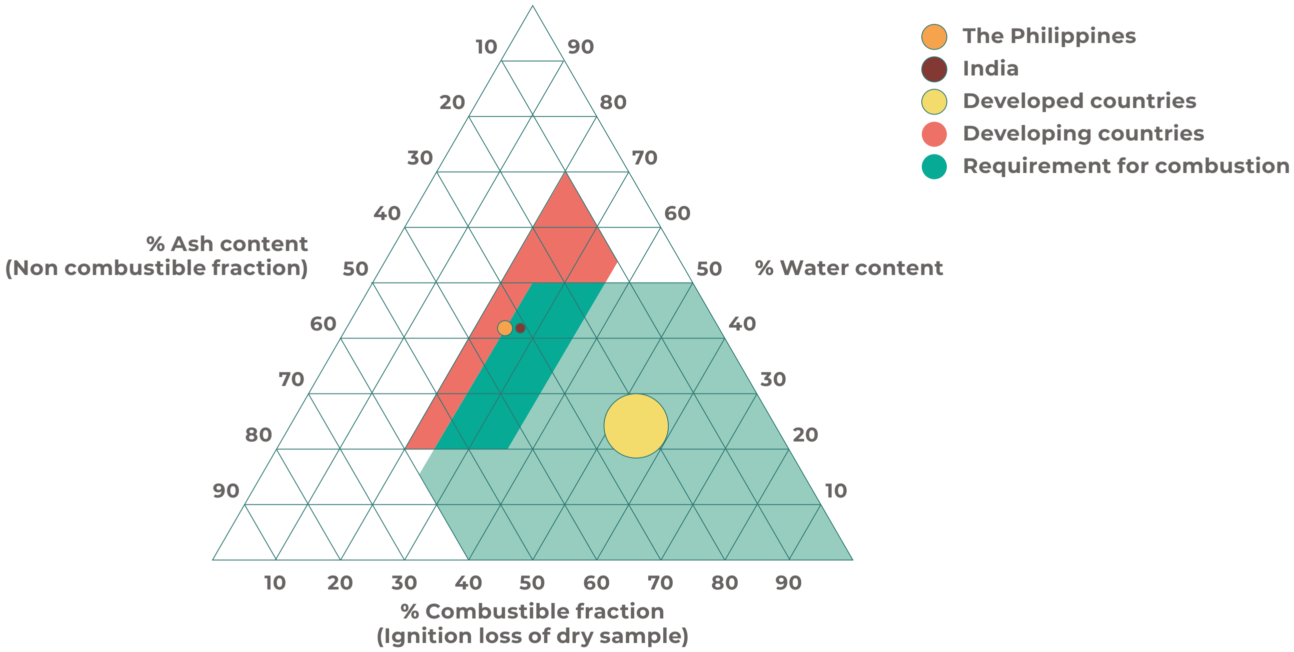


Figure 7: Fuel triangle – ternary diagram to present the fuel quality of MSW (minimum criteria: light green area), other colours display region specific properties) [16] (modified)

Knowledge of any two of the three parameters allows the general fuel characteristics of a waste fuel to be assessed. Each of these parameters has an influence on the net calorific value of RDF, as they are interdependent and therefore determine the amount of energy that can be recovered from the RDF. The respective proportions are plotted in percentages by weight, and complement each other, adding up to 100 %. The right-hand corner represents high caloric fuels, and the green shaded area represents properties required for autonomous burning fuel which must be the absolute minimum goal for any waste management project involving the production and energy recovery from RDF.

The difference in fuel quality between developed economies and developing economies as displayed in Figure 7 is due to the difference in water content in the waste: organic waste is most often not source separated in developing economies , which explains the much higher water content.

3.1.1 Combustible content

The content of combustibles in the RDF is a determining factor regarding the substitution of primary fuels. For some applications – such as the main burner in the cement kiln – a high caloric value is a prerequisite for the use of RDF.

Tanner (1965) describes that the combustion efficiency depends on the waste composition in such a way that it decreases with increasing water and ash content, whereby the influence of the ash content is significantly greater than that of the water content [17].

3.1.2 Water content

Water content, often referred to as moisture content, is used to describe the water present in the waste fuel. The NCV and heating value of the fuel decrease as the moisture content increases. In addition, water content is an important fuel parameter because [6]:

- a higher water content increases the volume of off-gas produced, requiring a larger post-combustion chamber and waste heat boilers as well as flue gas cleaning equipment to allow for the residence time needed.
- high water content reduces the combustion temperature, hindering the combustion of the reaction products resulting potentially in higher emissions and higher fuel quantities required. Auxiliary fuel may also be required to maintain combustion temperature.

3.1.3 Ash content

According to ISO 21656:2021 on “Solid alternative fuels – Determination of ash content”, ash content is the “ … *mass of inorganic residue remaining after combustion of a fuel under specified conditions, typically expressed as a percentage of the dry mass in the fuel* … “ [18].

After complete combustion, a non-combustible inorganic fraction of the waste fuel remains in the form of ash. This mineral fraction includes non-combustible, inorganic minerals contained in the fuel as well as sorption agents potentially added during the combustion process to control gaseous emissions.

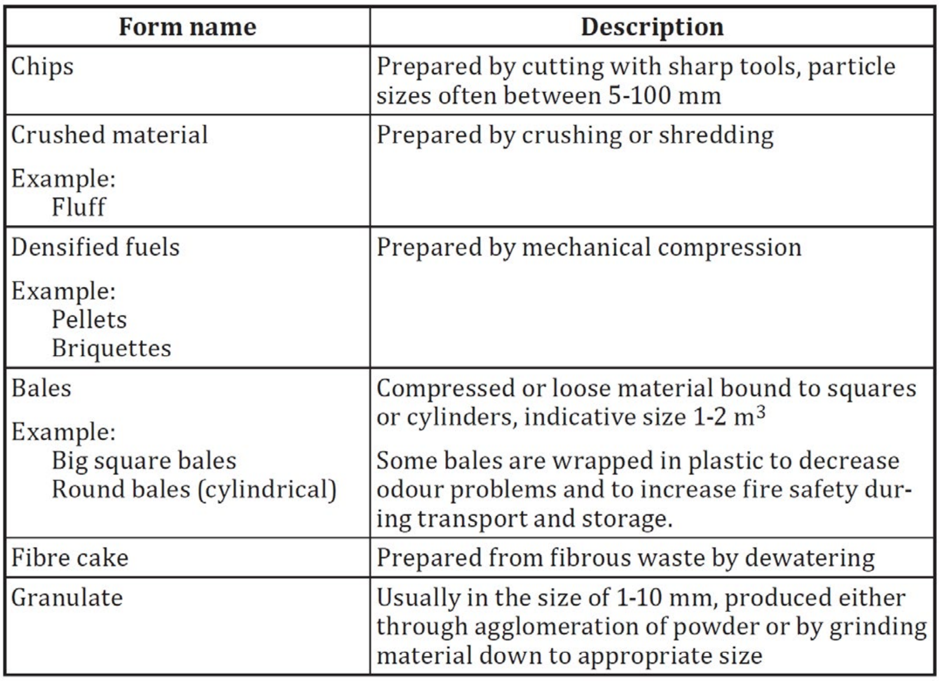
Based on the different scenarios of energy recovery from waste according to Figure 4, the ash content and the ash properties are of relevance as the ash becomes part of the product and thereby needs to meet certain criteria, or the ash might have to be recovered or disposed of downstream according to legal requirements.

3.2 Size / form

Certain physical properties, e.g. grain size or burning behaviour, are required for feeding the RDF to a process. Thus, aspects such as size and shape as well as energy density must also be considered when feeding the waste fuel to a process.

Table 2 shows some examples of the most commonly traded forms of RDF according to ISO 21640:2021 [9]. It is not only the size of the fractions that matters, the shape and nature of the material also plays a role. In Figure 8 different RDF qualities and forms are shown visually.

Table 2: Examples of major traded forms of RDF [9]



Form name	Description
Chips	Prepared by cutting with sharp tools, particle sizes often between 5-100 mm
Crushed material Example: Fluff	Prepared by crushing or shredding
Densified fuels Example: Pellets Briquettes	Prepared by mechanical compression
Bales Example: Big square bales Round bales (cylindrical)	Compressed or loose material bound to squares or cylinders, indicative size 1-2 m^3 Some bales are wrapped in plastic to decrease odour problems and to increase fire safety during transport and storage.
Fibre cake	Prepared from fibrous waste by dewatering
Granulate	Usually in the size of 1-10 mm, produced either through agglomeration of powder or by grinding material down to appropriate size

Figure 8: Various RDF qualities, 1) medium quality SRF acc. to Sarc [11], 2) premium quality SRF acc. to Sarc [11], 3) pelletized RDF [19, 20]

3.3 Biogenic content

Biogenic content means the fraction of biomass in the respective waste fuel. This fuel characteristic comes into play especially when the climate relevance of a WtE project is assessed, as the carbon dioxide stemming from the biogenic part of the fuel is considered to be climate neutral. Compared to the substituted fossil fuel this means a reduction in fossil carbon dioxide emissions.

The determination of the biomass fraction as a percentage of the carbon content is necessary to calculate the emission of biogenic or fossil carbon dioxide per tonne of RDF [21]. There are various methods for determining the biomass content of waste and therefore the biogenic carbon dioxide emissions. According to literature the most important ones include [21, 22]:

- Manual Sorting
- Selective Dissolution Method
- 14C-Method
- Adapted Balance Method

If biogenic content is defined as a quality parameter of RDF, it is important that the content of biogenic carbon can be determined by sampling the RDF before it is used as a fuel. Any of the above-mentioned methods can do so [22].

Manual Sorting

Sorting of the RDF by material fraction allows the biogenic carbon content based on mass fractions as well as the biogenic carbon content per material to be assessed. As the particle size of RDF is rather small, the effort for sorting is very high which makes this method impracticable in practice.

Selective Dissolution Method

This method uses concentrated sulfuric acid mixed with hydrogen peroxide for the treatment of the biomass. The biomass which is contained in the waste fuel will dissolve and oxidize whereas the remaining inert material will remain unchanged. By weighing the sample before and after this treatment with the sulfuric acid the difference in weight is determined. The weight of the biomass content is corrected for the content of carbonates by quantifying the ash content before and after the dissolution treatment (CEN/TS 15440 2006). Figure 9 shows the general procedure for the selective dissolution method [21].

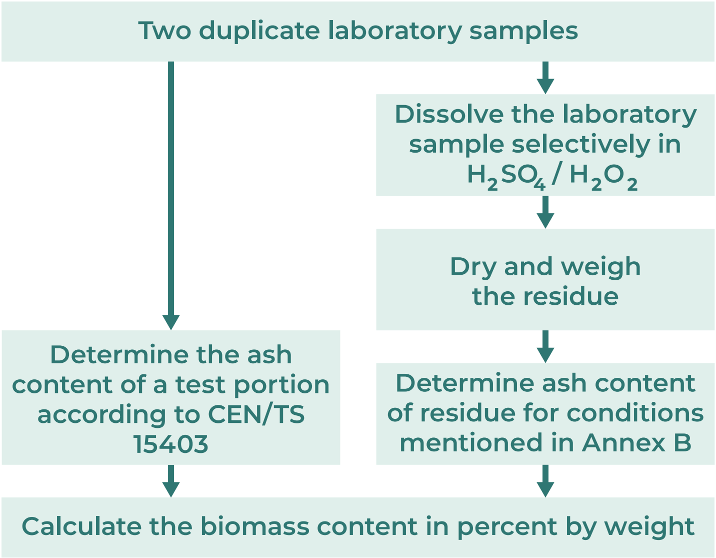


Figure 9: General procedure for the selective dissolution of the biomass content [21]

^{14}C-Method

The ^{14}C – dating method by Libby is an established method and used worldwide for the determination of carbon-based materials since its invention in 1969 [23]. The same principle is used for the determination of the biogenic content of waste streams, as well as the biogenic carbon in the flue gas.

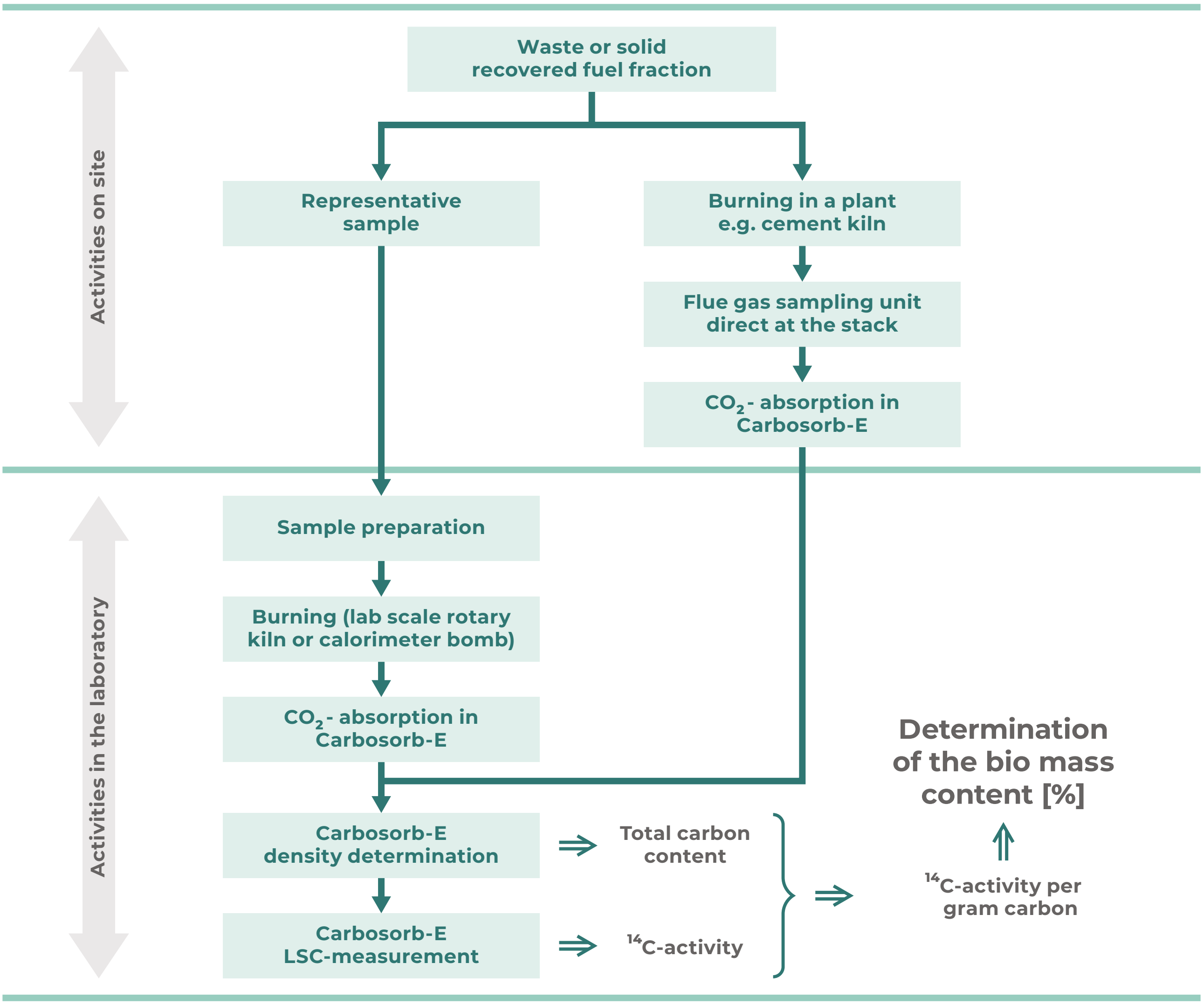


Figure 10: ^{14}C -determination of the biomass content in % [21] (modified)

After around 18 half-life periods (~ 100 000 years) the ^{14}C-content in biogenic material declines to 0.0004%, so small that it cannot be measured anymore. In fossil materials, such as coal or oil, because of its age, the ^{14}C content cannot be measured anymore, whereas in recent renewable materials, such as wood, the ^{14}C content still can be detected. This method therefore measures the biomass content in relation to the ^{14}C activity. The ^{14}C -method is an output-oriented method that determines the biomass content by examining the flue gas of the burnt waste or substitute fuel. There are two main methods (see Figure 10) [21].

Adapted Balance Method [22]

This method relies on the elemental composition of the RDF (assuming it is water- and ash-free). These data can be obtained by ultimate analysis of the RDF. Ultimate analysis is an analysis commonly done for primary fuels as well. In addition, data for the water and ash-free elemental composition of the biogenic and fossil material components of the RDF are needed. These data can be obtained either from literature or through sorting and subsequent analyses of the individual material components resulting from sorting.

Table 3 compares the effort in sample preparation, analysis, and calculation as well as the costs of the four discussed methods to determine the biogenic carbon content of RDF. In addition, an estimate for the time needed until results are available as well as the availability of the respective analytical services are assessed. This information was compiled by Schwarzböck et al. [22] in October 2017.

Table 3: Comparison of the four methods in terms of time and effort required, availability and costs (related to the determination of the fossil share of CO_2 emissions of a sample) [22] (modified)

	Manual sorting	Selective dissolution method	Radiocarbon method	Adapted balance method
Sample preparation				
Necessary sample preparation steps	Drying	Drying, grinding, dividing, up to < 1 mm	Drying, grinding, dividing, up to < 0.2 mm or finer	Drying, grinding, graduation, up to < 0.5 mm or finer
Estimated effort	~ 0.5 h	~ 2 h	~3.5 h	~3.5 h
Optional (for first time application)	+~ 18 h (Grinding for C-determination of the sorted fractions)	–	+~ 3.5 h (Grinding of the sorted biogenic fraction)	+~ 18 h (Grinding for determination of CHNSO content of sorted fractions)
Analysis & calculation				
Necessary steps	Sorting	Determination of solvent residue, annealing residue, C-content	Graphitization, AMS analysis	Determination of CHNSO content, annealing residue
Estimated analysis effort	> 60 h[a]	~ 1.7 h	~ 2.5 h	~2 h
Optional (e.g. for first-time application)	+~ 3-6 h (Determination of C-content and sorting precision of sorted fractions)	–	+~ 20 h (Sorting and re-measurement of the pMC reference value)	+~ 25 h (Sorting and determination of CHNSO content of the sorted fractions)
Availability				
	✓✓	✓	(✓)	✓
Necessary laboratory equipment	No special equipment necessary Optional: Determination of C content available in most analytical laboratories	Determination of C-content available in most analytical laboratories; for mass fraction wet chemical laboratory without special equipment necessary	Specialized equipment required ~ 64 laboratories available in Europe (~ 134 worldwide)[c]	Determination of CHNS content available in most analytical laboratories; O content less frequent

	Manual sorting	Selective dissolution method	Radiocarbon method	Adapted balance method
Sample preparation				
Analysis costs				
Estimated per sample (excl. sample preparation)	> 700 €	80 – 150 €	360 – 650 €	80 – 150 €

[a] Estimated for a sorting of 30 kg RDF and a labour input of at least 2 h for the sorting of 1 kg RDF

[b] Manual Sorting: for the determination of the fossil carbon fraction, information on the carbon content of the individual fractions is necessary in addition to the sorting; these can be determined specifically or, if necessary, taken from the literature; Adapted Balance Method: in the case of first-time application, it may be necessary to carry out sorting in order to generate RDF-specific characteristic values (elemental composition of water- and ash-free biogenic and fossil materials). Appropriate databases could significantly reduce this (usually one-time) additional effort.

[c] http://www.radiocarbon.org/Info/lablist.html (updated in October 2017)

3.4 Pollutant content

In co-incineration of waste, in this case RDF, the pollutants contained, especially heavy metals, can lead to environmental pollution and thereby may endanger the life or health of living beings. In principle, regulations concerning the co-incineration of waste aim to avoid these emissions as far as possible. Where no regulation exists, it is necessary to limit the emissions on a voluntary basis.

In any case the gaseous emissions need to be monitored and must meet minimum standards. The compliance with legally set or voluntarily pre-set emission limits must be proven by emission measurements.

If existing facilities – especially production facilities such as a cement plant – are the destinations for the use of RDF, they may not be equipped with emission control systems comparable to those of state-of-the-art mass-burn facilities / MSW incinerators. In such cases it is also important to monitor the quality of the fuel input. This furthermore also allows for a direct comparison of the pollutant content of RDF with that of primary fuels.

The Austrian Waste Incineration Ordinance [5] plays a pioneering role regarding strict limit values and their verification. This regulation is the national implementation of the EU-directive on the incineration of waste [14] and among other things, it defines limit values for:

- waste when incinerated in co-incineration plants
- substitute fuels used in cement production plants
- substitute fuels used in power plants
- substitute fuels used in other co-incineration plants

and sets further specific requirements regarding specific waste fuels such as waste oil and solvents as well as sewage sludge and paper fibre residues. In addition, among others, requirements with regard to sampling planning, sampling, and external monitoring are defined [5].

Table 4 lists the limit values for alternative fuels when used in cement production plants. The limit values apply to the part of cement production plants where cement clinker is burned.

Table 4: Limit values for SRF when used in cement production plants [5]

Parameter	Limit values in mg/MJ	
	Median	80th percentile
Sb, Antimony	7	10
As, Arsenic	2	3
Pb, Lead	20	36
Cd, Cadmium	0.23	0.46
Cr, Chromium	25	37
Co, Cobalt	1.5	2.7
Ni, Nickel	10	18
Hg, Mercury	0.075	0.15

In Table 5 the Austria limit values are compared to those of the German state of Nordrhein-Westfalia as well as French limit values.

Table 5: Comparison of limit values for waste used in cement kilns in Austrian legislation, in guidelines from Nordrhein-Westfalia (Germany) and those in French permits [13]

Substance	Austria		Germany, Nordrhein-Westfalia	France
	AF in cement kilns with preheating and calciner		Waste as heating fuel (1)	Input criteria for substances for suitable waste fuels used in cement plants
	median	80th percentile		
	Limit values in mg/kg dry matter (AT values converted from mg/MJ assuming a calorific average value of 18 GJ/t. FR converted from ppm and %)			
Arsenic	36	54	13	NA
Antimony	126	180	120	NA
Lead	360	648	200 – 400	6,000
Cadmium	4.14 (2)	8.28 (2)	9	NA
Chromium, total	450	666	120 – 150	1,000
Cobalt	27	48.6	12	1,000
Copper	NA	NA	300 – 700 (3)	2,000
Nickel	180	324	100	1,000
Mercury	1.4	2.7	1.2	10
Thallium	NA	NA	2	NA
Zinc	NA	NA	NA	150,000
Tin	NA	NA	70	NA

Substance	**Austria**		**Germany, Nordrhein-Westfalia**	**France**
	AF in cement kilns with preheating and calciner		**Waste as heating fuel (1)**	**Input criteria for substances for suitable waste fuels used in cement plants**
	median	**80th percentile**		
	Limit values in mg/kg dry matter (AT values converted from mg/MJ assuming a calorific average value of 18 GJ/t. FR converted from ppm and %)			
Manganese	NA	NA	100 – 500	1,000
Vanadium	NA	NA	25	NA
PCB/PCB+PCT (4)	NA	NA	NA	50
PCP (Pentachlorophenol)	NA	NA	NA	50
Total chlorine	NA	NA	NA	4
Σ As+Ni+Co+Se +Te+Cr+Pb+Sb +Sn+V	NA	NA	NA	10,000
Sulphur	NA	NA	NA	120,000
Other halogens (bromide+iodide +fluoride)	NA	NA	NA	5,000
Alkalis (Na_2O+K_2O)	NA	NA	NA	150,000
Phosphates (P_2O_5)	NA	NA	NA	150,000

(1) referred to a calorific value of dry matter of at least 20 GJ/t (± 2 GJ/t), respectively for the high caloric fraction from municipal solid waste the calorific value amounts to 16 GJ/t.
(2) For quality assured Afs (key number 91108 according to German Ordinance on the list of waste, BGBL. II Nr. 570/2003, in the current version) a limit of 8.1 mg/kg (median) and 12.6 mg/kg (80th percentile) applies. (Assuming a calorific average value of 18 GJ/t)
(3) Violation of limit due to inhomogeneity valid in individual cases
(4) PCB: polychlorinated biphenyl; PCT: polychlorinated terphenyl

3.5 Comparison of fuel characteristics: primary fuel ⇔ secondary fuel

With regard to the fuel characteristics and a comparison of primary and secondary fuels, one must differentiate between 1) economically relevant, 2) process relevant and 3) pollutant related properties. The relevance of each of these properties might differ between different recovery facilities and external boundary conditions and must therefore be assessed on an individual project basis.

Economically relevant properties

The level of processing needed for a waste to be processed to RDF meet the quality required by the off-taker is probably the most important economic aspect that needs to be considered. The processing itself will be discussed in Section 4.

The main fuel characteristic of economical relevance is the energy contained in the waste represented by the fuel parameter NCV. For any of the energy recovery options the provision of a certain amount of energy to a specific process is the objective.

Therefore, the NCV of the RDF together with the mass-flow of RDF provided determines the share of primary fuel substituted and therefore fuel costs saved.

For industrial utility boilers that use waste as the only fuel, or for power plants using RDF as a secondary fuel, ash content is also a relevant parameter, as the resulting ash needs to be disposed of – and paid for. Quantity – as well as quality – changes of the solid residues might therefore impact costs.

If carbon-dioxide emissions are taxed or if fossil carbon-dioxide emission reduction can be monetized through compulsory or voluntary carbon credit schemes, the biogenic carbon content of RDF might also be an economically relevant parameter from the perspective of the off-taker of RDF.

Process relevant properties

The properties discussed here have an impact on the energy recovery processes and thereby indirectly also on the investment cost (CAPEX) and/or operational cost (OPEX) at the recovery plant that uses RDF instead of primary fuel.

The main parameter to be monitored is the chlorine-content of the waste-fuel. Especially for off-takers from the cement industry, the chlorine content is a crucial parameter, as chlorine causes unwanted deposits (caking) in the rotary kiln, which reduces the capacity of the production facility and demands a total shut down and removal of the deposits, resulting in higher costs and loss of profit.

Many cement production facilities nowadays have a so-called chlorine by-pass in place that prevents caking to a certain extent. However, limiting the chlorine content in the waste-fuel itself is essential from a process perspective. Although the relevance of chlorine also depends on the extent of RDF use (i.e., share of primary fuel substituted) usually in the cement industry the chlorine content is capped at 1 $\%_{\text{mass, DS}}$ which resembles SRF quality category 3 according to Table 1.

Chlorine as well as sulphur are also relevant from the perspective of corrosion of the plant for an industrial utility boiler or a power plant using RDF as a fuel. The sensitivity of such a plant to chlorine and sulphur depends on the materials used for the boiler, heat-exchangers as well as the off-gas cleaning equipment. Corrosive off-gas components may cause severe problems as pipes can corrode quickly, reducing the service life and increasing the maintenance cost. In addition, the quantity of adsorbents such as dolomite, sorbalite and hearth furnace coke required to ensure compliance with off-gas emission limit threshold values is dependent on the mass of chlorine and sulphur fed to the recovery facility via the waste fuel. Therefore, higher chlorine and sulphur concentrations in the waste fuel (as well as higher shares of secondary fuel substituting primary fuel) increase investment costs due to the necessity to select better steel qualities or cladding to prevent corrosion. Higher chlorine and sulphur concentrations also increase operating costs due to the greater quantities of adsorbent required, which in turn causes more ash that needs to be disposed of – again a cost factor that needs to be considered.

Pollution related properties

From a sustainability point of view, it is important that RDF projects do not impact the emission situation negatively. A secondary fuel such as RDF replaces an amount of primary fuel based on its energy content, so the *pollutant* content related to the *energy* content must be compared for a fair assessment.

The following Table 6 shows a comparison of relevant parameters of primary and secondary fuels.

Table 6: Comparison of fuel properties: primary vs. secondary fuel [24, 25, 26, 27, 28, 29, 30, 31, 32, 33]

	Primary fuels								Secondary resp. alternative fuels					
	Hard coal	**Brown coal**	**Anthracite coal**	**Bituminous coal**	**Lignite coal**	**Crude oil**	**Natural gas**	**Petcoke**	**Animal meal**	**Sewage sludge (dry matter)**	**Municipal waste**	**Commercial waste**	**RDF**	**SRF**
NCV [MJ/kg$_{dm}$]	26 – 31	22	30.23 – 34.89	19.77 – 34.89	9.30 – 19.30	39 – 42.7	46.8 – 53.8	29.5 – 34.0	17 – 18	2.0 – 3.5	15 – 18	20 – 29	14.00	23.20
Carbon (%)	80 – 95	40 – 70	67 – 98	33 – 86	29 – 40	-	0.00	71 – 88	35 – 45	33 – 50	30 – 40	40 – 50	2 – 16.0	13.2
Ash (%)	5 – 15	4	3.8 – 20.0	3.7 – 12.0	4.2 – 18.2	~0	0.00	0.2 – 3.0	10 – 30	30 – 50	3 – 22	2 – 39	8 – 32.0	8.90
Water (%)	5 – 20	30 – 60	5.06	4.44	17.75	-	-	0.21 – 0.28	3 – 20	65 – 75	20	20 – 29	17 – 40	17 – 30.3
S (%)	0.5 – 1.2	0.35	0.7 – 2.2	0.3 – 4.3	0.5 – 6.7	0 – 5.7	0 – 10	2.9 – 7.4	0.3 – 0.8	0.5 – 1.5	0.02 – 1.2	0.02 – 0.8	0.1 – 0.6	0.18
O (%)	2 – 10	15 – 30	0.7 – 2.2	300 – 380(1)	12 – 31.0	0 – 3.8	0 – 1.5	0.8 – 4.3	-	10 – 20	5 – 10	5 – 10	3 – 36.0	36.70
N (%)	1.3 – 2	0.7	0.2 – 1.5	1.0 – 2.0	0.7 – 1.6	-	0 – 1.5	0.9 – 1.7	5 – 12	2 – 6	-	-	0.8 – 2.4	0.70
Cl (%)	0.01 – 1	0.03	300 – 380(1)	100 – 340(1)	100 – 340 (1)	~0	~0	~0	0.5 – 0.7	0.05 – 0.4	0.04 – 1.9	0.02 – 2.2	0.1 – 3.9	0.41
H (%)	3 – 6	4.3	0.4 – 3.4	3.8 – 5.9	2.8 – 6.2	10 – 15	20 – 24	3.1 – 3.7	5 – 8	3 – 4	-	-	1.0 – 5.0	7.70
As (mg/kg)	1 – 50	0.3 – 2.5	-	-	-	-	-	-	0.3	4.5 – 5.0	0.3 – 14	2.6 – 39	-	-
P (g/kg)	0.01 – 0.2		-	-	-	-	-	-	10 – 30	2 – 55	-	-	-	-
Pb (mg/kg)	10 – 270	0.07 – 4	-	-	-	-	-	-	0.4 – 5	70 – 100	0.4 – 7,000	0.5 – 4,400	-	-
Cd (mg/kg)	0.1 – 10	0.01 – 0.35	-	-	-	-	-	-	0.4 – 1.0	1.5 – 4.5	0.08 – 29	0.05 – 162	-	-

	Primary fuels								Secondary resp. alternative fuels					
	Hard coal	Brown coal	Anthracite coal	Bituminous coal	Lignite coal	Crude oil	Natural gas	Petcoke	Animal meal	Sewage sludge (dry matter)	Municipal waste	Commercial waste	RDF	SRF
Cr (mg/kg)	5 – 80	0.08 – 15	-	-	-	-	-	-	3 – 9	50 – 70	3 – 2,900	0.7 – 86	-	-
Cu (mg/kg)	0.5 – 70	1.2 – 4	-	-	-	-	-	-	12 – 30	300 – 350	9 – 6,900	3 – 3,600	-	-
Ni (mg/kg)	15 – 100	3 – 11	-	-	-	-	-	-	3 – 5	30 – 35	1.3 – 2,500	0.4 – 1,600	-	-
Hg (mg/kg)	0.03 – 2	0.05 – 0.9	-	-	-	-	-	-	< 0.2	0.2 – 2	0.07 – 2.0	0.02 – 1.6	-	-
Zn (mg/kg)	10 – 300	4 – 22	-	-	-	-	-	-	100 – 150	1,000 – 1,500	-	-	-	-

(1) Concentration in ppm weight dry basis

4. Preparation of Refuse Derived Fuels

The processes and logistics needed to prepare RDF are dependent on the prior collection, the properties of the waste input, the organization of stakeholders (waste owner, RDF producer, RDF off-taker), the agreed fuel specifications and the location of the RDF production facility.

The processes below comprise the crucial aspects for the sustainable implementation of waste management projects involving the production and utilization of RDF:

- Recovery of recyclables by separate collection and/or sorting
- Removal of hazardous waste components
- Securing the desired fuel quality according to the fuel specifications needed for the specific energy recovery from RDF facility (and feeding point)
- Securing a constant and steady flow of RDF to the energy recovery from RDF facility
- Adequate storage of feedstock and produced RDF to allow for variations in waste arising as a consequence of seasonal variability and variations in off-takers needs and other potential end-to-end disruptions

4.1 Waste collection (sourcing)

The initial starting point is the sourcing of waste. As already explained in Section 2, MSW is the major focus of this paper. Nevertheless, the nature of the waste might vary significantly depending on the waste collection system in place.

Oftentimes there will not be any separate collection of recyclables or hazardous waste from households (see Figure 4), and sometimes an organized waste collection might even be missing. Recyclables on the other hand might be skimmed off by informal sector stakeholders. All of these aspects have an effect on the quality and quantity of waste available for RDF processing and therefore need to be considered and addressed in the overall set-up of a project involving the production of RDF.

In settings where no formalized waste collection is in place, the sourcing of waste for RDF production might concentrate on specific locations for ease of accessibility. This for example could be waste accumulated on the shores or in water ways that can be skimmed off or waste from commercial or industrial activities.

Also, old waste dumpsites might be a relevant source of waste for RDF. In these cases, the sourcing of the waste fuel is independent of the current waste management practice and can reduce negative environmental impacts from the dumpsite (i.e., leachate run-off, groundwater dissipation and greenhouse gas emissions) as well as restoring land that could be used for other purposes once the dumpsite is removed.

Any changes in the collection system of MSW (e.g., separation of wet fraction) will have a direct impact on the quality and quantity of waste to be processed into RDF. As the energy recovery facility requires a constant quality of RDF, the RDF processing as described in the following section is an important component of a waste management project producing RDF.

4.2 Sorting / processing

4.2.1 Institutional set-up

There are different options for the institutional set-up of an RDF production plant. Especially in cases when the RDF is to be used as a fuel in a production facility where specific quality specifications are to be met (see case 1 in Section 2) choosing the right institutional set-up for the RDF production is very important. What is best depends on external boundary conditions as well. Therefore, the outcome of an assessment might change in a specific case over time. This asks for some degree of flexibility in the institutional set-up allowing for evolution according to the external boundary conditions.

Typically, especially if a strong institutionalized waste sector already is in place, MSW is treated in a mechanical treatment plant. This facility is most often owned and operated by the municipality. This first treatment step separates recyclables (and also hazardous components) and splits the high-calorific share of the waste stream which can be used to produce RDF from the low-calorific share that is usually treated through biological processes such as composting before the remaining stabilized residue is landfilled. Changing market conditions (landfill tax, regulatory requirements for composting, gate fees for thermal treatment, etc.) might even mean that the low-calorific share can be energetically recovered. Wherever a strong institutionalized waste sector is lacking, the above-described initial treatment of MSW needs to be implemented as a part of an RDF production plant.

Regarding the institutional set-up, in principle, there are three main scenarios (with two of them coming in two variants) that are displayed in Figure 11. The main difference between these scenarios is the respective responsibilities and accountabilities of the waste sector stakeholder and the RDF off-taker for the sourcing of the waste input, as well as the quality of the RDF produced. If there is no institutionalized waste management in place, the number of options is reduced as the municipality might not be ready to be a partner in a Public-Private-Partnership (PPP).

In Scenario A1 (see Figure 11) the waste sourcing is secured as the public entity is responsible for the waste management and any changes in the waste collection are therefore also immediately clear to the

RDF production plant operator, allowing for respective reaction as needed. In this scenario, the responsibility for and risks associated with meeting the quality criteria of the RDF lie with the public entity owning and operating the RDF production facility. The potential savings for the disposal of the waste lie with the public entity, which is to their advantage. A major disadvantage of this scenario is that there is a great risk of conflict between the RDF production plant operator and the off-taker with regard to the quality of the RDF.

Especially where no strong public waste management sector exists, Scenario A2 might be a feasible option. In this scenario, risks associated with sourcing the input for the RDF production plant exist due to potentially changing boundary conditions and evolution of an institutionalized waste management sector or the implementation of a separate collection system. These upstream changes in the waste management system directly affect the waste input to the RDF production plant. Other than in Scenario A1 the plant-operator of the RDF production plant has no influence on the upstream changes.

In Scenario C, where the off-taker is responsible for securing the quality of the RDF, there is a high security that the RDF-quality will be according to the specifications required. It is highly certain that the RDF will be used and energetically recovered. On the other hand, the waste sourcing might be a challenge as any change such as an evolving waste management sector or implementation of a separate collection system directly effects the waste input to the RDF production plant. Also, in this scenario the plant-operator of the RDF production plant has no influence on the upstream changes.

In Scenario B1, the public sector stakeholder joins forces with the private sector stakeholder in a PPP. Sourcing of waste input as well as energy recovery from RDF is thereby secured. The conflict potential is much reduced due to shared responsibilities and common interest. This scenario combines the strength of Scenario A1 and C and thereby is the desired set-up for a sustainable implementation of an RDF production plant.

This scenario might also be conceivable with a private sector third party replacing the public sector actor as is displayed as Scenario B2 in Figure 11. While securing common interest through the formation of a joint venture, this scenario still entails a risk of sourcing waste for the RDF production plant.

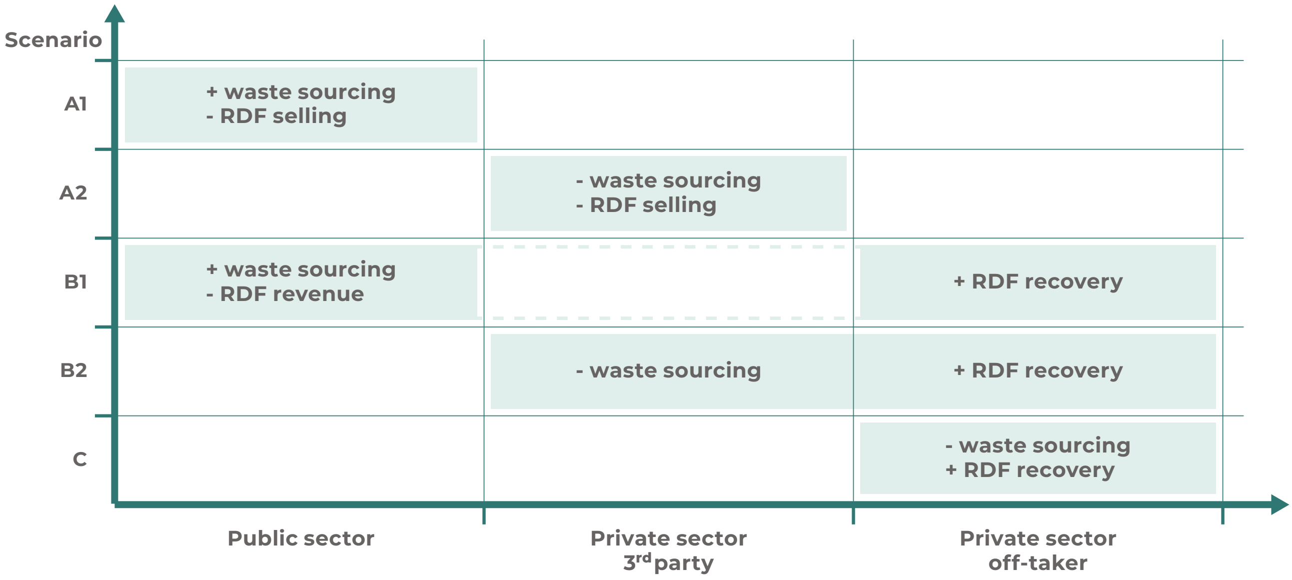


Figure 11: Ownership structure RDF production facility and associated strength and risk (author´s own representation)

The weaknesses of any of the scenarios can be mitigated with respective (long-term) contractual arrangements that also provide room for a shift of the ownership structure or the operational responsibility over time.

4.2.2 Process set-up / plant layout

The sorting / processing stage must achieve the following aspects:

- Separation of recyclables as the priority of recycling is ranked higher than that of energy recovery
- Separation of non-combustible fractions
- Separation of unwanted, hazardous components
- Securing an RDF quality according to the specifications agreed with the off-taker

Different streams of waste, which can be processed to RDF require different pre-processing. This is for example due to variations in water and ash-content, grain sizes and pollutant content as well as different specifications of RDF to be produced. Therefore, the plant concept of an RDF production plant is comprised of different treatment steps to achieve the required quality of the RDF at the end. Table 7 shows the main treatment steps of such a processing plant and explains the influence of each of the treatment steps to achieve the final product.

Table 7: Potential treatment steps for an RDF production plant and their impact on the RDF quality [34]

Pre-treatment options and their effect						
Effect	**Pre-treatment measure**					
	Classifying	Sorting	Shredding	Homogenising	Drying	Pelletising
Heating value increase	great influence especially when screening the fine fraction and sifting the biogenic (heavy) fraction	great influence separation of inert and interfering substances	low influence only indirectly via classification	no influence only when mixing high and low calorific waste fuels	great influence through moisture extraction; irrelevant to the overall process; may make sense if waste heat is used	no influence
Pollutant reduction	low influence only Zn and Pb are removed by sieving the fine fraction	medium influence undesirable substances can be sorted out depending on the process.	no influence	no influence equalisation of pollutant peaks	no influence possibility of optimised separation of the fine fraction by classification	no influence
Fuel optimisation	medium influence equalisation of the fuel band (calorific value, grain size), ejection of low-melting component	great influence possibility of separating different components for other pre-treatment measures	great influence adjustment of the required particle size distribution, improved combustion behaviour	medium influence conversion of heterogeneous structures into homogeneous waste fuel of consistent quality	medium influence improvement of storage behaviour by preventing rotting; facilitation of further mechanical treatment processes (classification)	medium influence improvement of storage behaviour, transport properties and fuel introduction

The main source for RDF-production is MSW waste for which Figure 12 shows a typical set-up of how MSW is processed, to extract the combustible non-recyclable fraction of MSW. Such a plant concept can produce a premium quality fuel according to the classification in Figure 3. This RDF can then be used in a cement kiln. The displayed plant layout also includes inline quality monitoring [35].

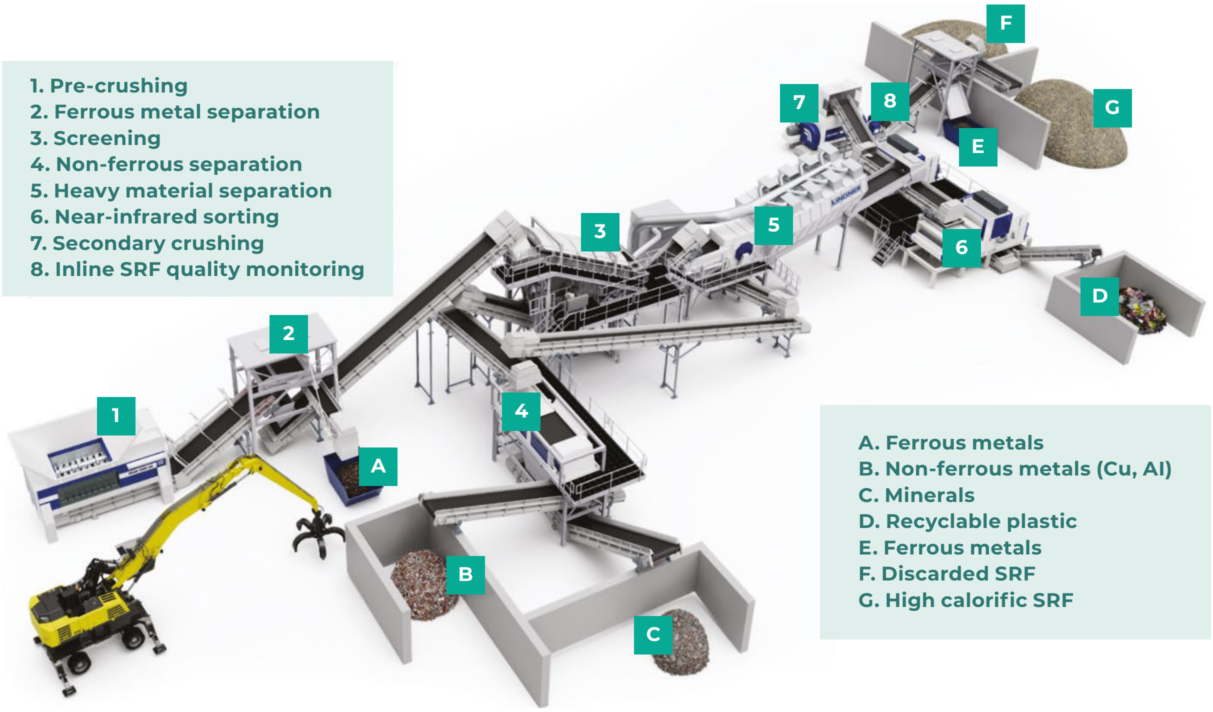


Figure 12: Multi-stage preparation of SRF premium quality [36] (© Lindner, modified)

As the waste streams of the raw waste for RDF production can be diverse in their physical and chemical composition and each usage option has its own requirements, the pre-processing-setup for the RDF can look different from one case to another. In cases when lower qualities of RDF are to be produced, the plant concept will include less process steps.

Not shown in Figure 12 is a potential separation of low calorific components by a third party beforehand. This can easily be done by screening. As described in Section 4.2.1 such an initial treatment step is usually done by the municipality responsible for waste collection and disposal. The low calorific fraction will have to undergo biological treatment to reduce gas formation and methane emission potential before it goes to landfill.

Alternatively, the low calorific part of MSW which has a high share of biogenic components may be interesting for the RDF off-taker as the resulting carbon-dioxide emissions of these biogenic RDF components will not have to be accounted for in a CO_2 emission inventory. However, the high moisture of biogenic components reduces the NCV (as well as the storability etc.,) so the RDF processing plant concept in such cases must also include a treatment stage for drying.

The process layout of an RDF processing plant is adapted according to the type of waste and its characteristics as well as the RDF quality required. The main process steps and their respective sequence are the following:

- MSW waste reception (waste receiving, sampling, manual sorting and bag-opening): Depending on the type of waste, different collection systems are used in order to collect and transport the waste to an RDF production facility. The waste is unloaded, large components as well as recyclables and hazardous waste components are extracted by hand or by means of a gripper. Opening all bags ensures that waste is fed loose to the subsequent treatment steps.
- Primary crushing: In the first crushing step the waste is shredded to less than 100 mm to reach a first homogenization and facilitate handling of the waste.
- Drying process: In case moist / low calorific components remain part of the RDF, drying is required. This is done by using the heat produced by the biological activity of the waste itself (bio-drying, dry-stabilization), hot air (waste heat), sun, or a combination. The organics in the waste are dried (not degraded) to increase storability, reduce volume and increase calorific value.
- Classifying, screening & sorting: During these process steps, recyclable materials and inert materials are removed. This is done by different technological systems like drum screens, wind sifters, optical sensors, etc. That process can be combined at the end with a manual sorting step to remove remaining recyclables. This step also includes magnetic separators to remove metals.
- Secondary crushing: The remaining combustible non-recyclable fraction based on the quality of RDF needed may further be shredded to less than 25 mm. Depending on the technology used this can be done in 1 or 2 shredding steps.
- Pelletisation: if needed, the fluffy RDF fuel is passed through a pellet press which leads to a reduction of volume, homogenization of the fuel and higher energy density. It also facilitates the dosing of the fuel in the energy recovery facility.

Figure 13 shows a more detailed process flow-chart for a pre-processing facility to produce the three different RDF qualities according to Figure 3. This plant concept consists of at least 2 - 3 shredding steps, 2 magnetic separation steps, one eddy current separator for the rejection of non-ferrous metals, and at least two sieving steps. This is considered as a high-end plant concept and would be implemented when high RDF quality is needed, and the RDF substitutes a high share of a primary fuel [37]. As it is likely that in such a case the RDF will also be externally certified the term SRF is used in Figure 13 instead of RDF.

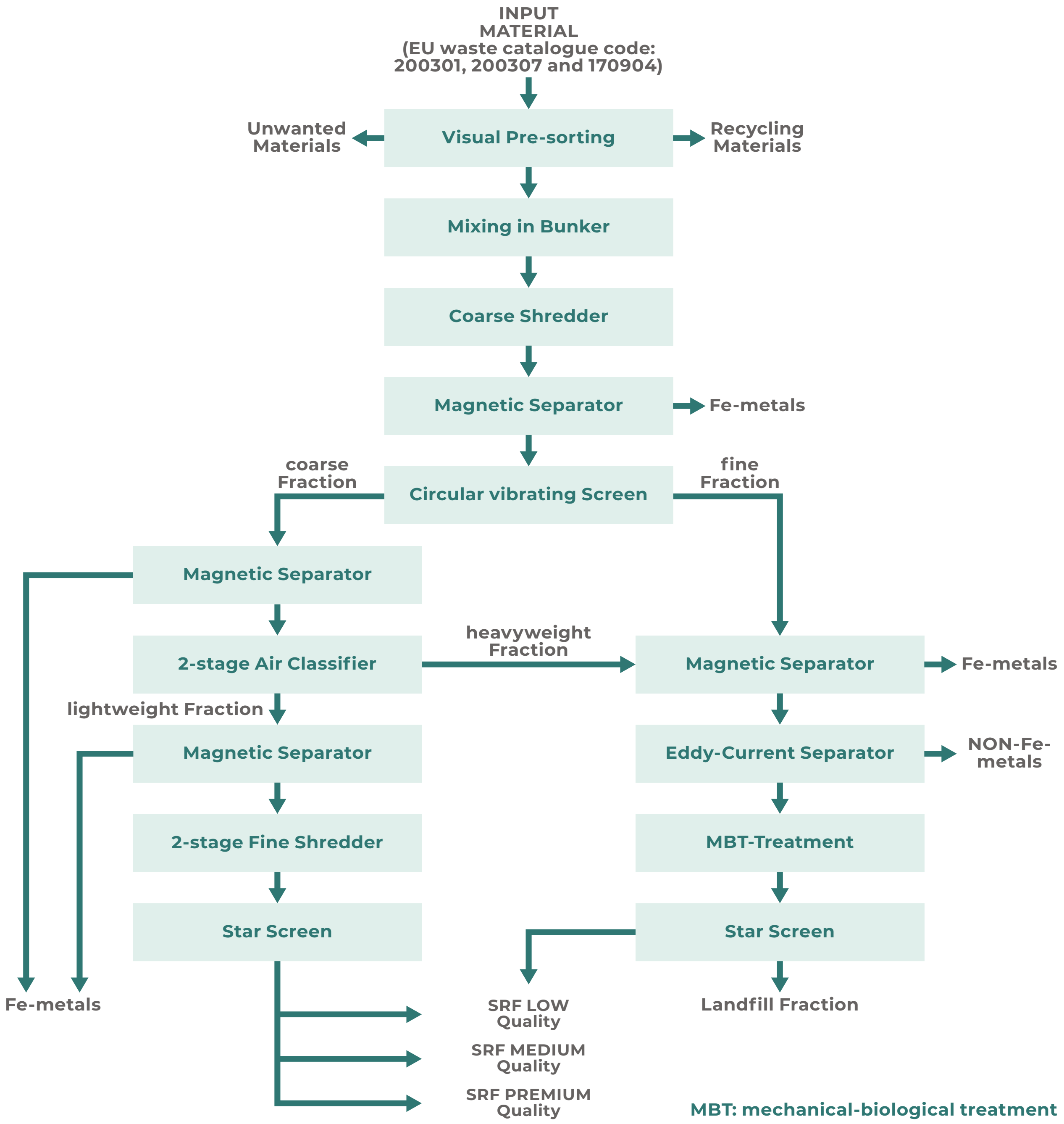


Figure 13: Mechanical waste processing plant for production of various SRF qualities [12] (modified)

The recovery rate of different RDF qualities depends directly on the quality of the raw waste input and on the multi-stage production process which is applied. Lower input quality of the raw waste requires more pre-processing steps like crushing, sieving, magnetic separation, etc. to improve the fuel quality. The waste hierarchy and the circular economy concept also demand the incorporation of new advanced sorting techniques to enhance the recovery rate of recyclables, like Near Infrared Sorting (NIR) techniques for different plastic fractions.

There might be a conflict between recovered quantity of a certain fuel quality and the RDF quality required by the off-taker. The higher the required RDF quality requested by the off-taker, the more intermediate process steps are necessary, which lowers the amount of recovered fuel of a certain quality. Higher fuel quality means higher NCV, smaller particle size and less impurities. This relationship is illustrated in Figure 14 below [12].

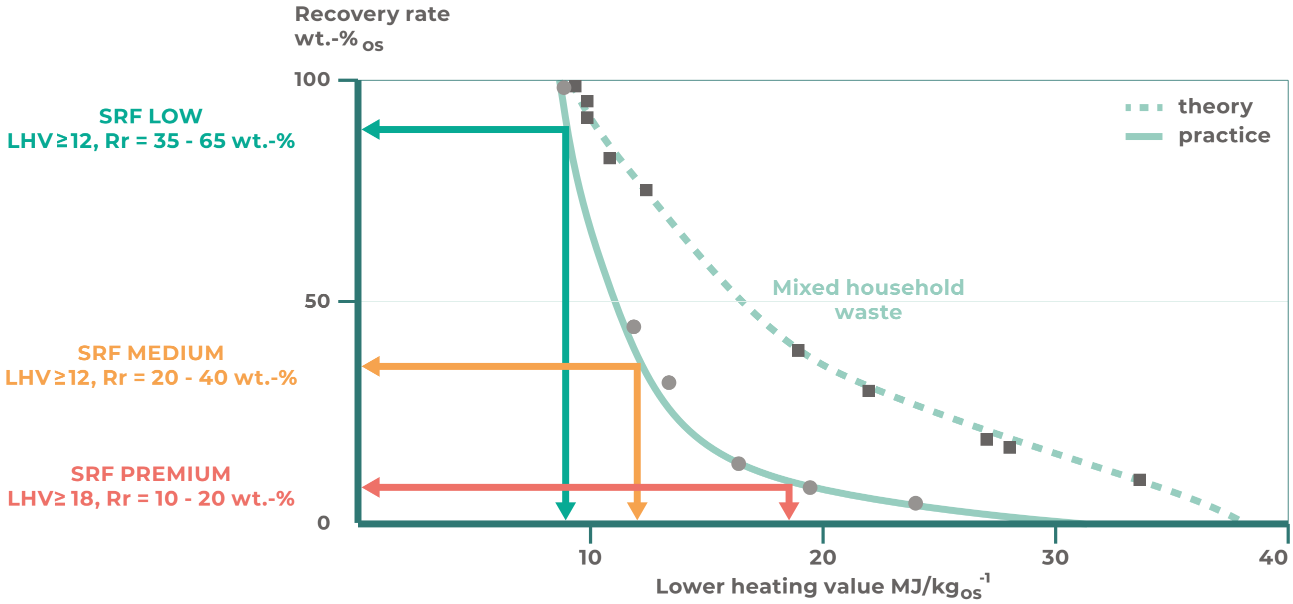


Figure 14: Correlation between lower heating value and recovery rate for mixed household waste [12]

The increasing costs of pre-processing for higher RDF qualities has restricted the commercial use of certain types of waste with high concentrations of impurities and other undesired fractions. This can be overcome by optimizing separation at the source and by developing quality standards to reduce costly technical process steps for waste pre-treatment [38].

4.3 Storage

Safety of the RDF use is key for its further diffusion globally, especially in developing economies. Incidences of fires and dust explosion in the past have drawn significant attention to the proper handling and storage of RDF fuels to reduce such risk. A proper risk management plan for RDF storage should consider the following influence factors:

- Temperature of the RDF storage piles
- Moisture content of the fuel
- Duration of storage of the RDF fuel
- Composition of the RDF fuel
- Total storage volume

RDF is physically and chemically not a stable product and should not be stored over long time periods. Biological and chemical processes during a prolonged storage time can increase the risk of self-ignition or dust explosions [39].

Bacteria can break down the biogenic fraction in the RDF, consuming oxygen and releasing carbon dioxide. In confined spaces this is a safety risk for workers. After the consumption of all accessible oxygen, anaerobic bacteria start to produce hydrogen sulphide, hydrogen, methane, and carbon dioxide. These gases can form an explosive environment which should be controlled as part of a proper risk management plan; e.g., regular ventilation and avoidance of long storage and transport times [40].

RDF processing plants need two separate storage spaces, one for the raw waste feed, the other for the final RDF product. The latter might be split into separate parts if more than one RDF quality is produced.

The raw waste usually is stored in piles and the handling is done with front-end loaders. There should be a storage capacity of at least 2 to 3 days of production capacity of the RDF plant to manage any supply interruption. The piles should be covered by a building to reduce odour nuisance and litter from polluting the surrounding environment as well as to reduce the influence of weather.

The storage of the final RDF product must comply with strict safety standards in order to avoid any risk for employees, neighbours or the environment. One main risk is the self-heating of the RDF fuel, especially when it gets wet. In addition to the fire risk this can also cause hazardous emissions. The ISO Standard ISO 21912:2021 [41] for storage and handling of SRF fuels therefore recommends a storage infrastructure which prevents the fuel from getting wet.

Additionally, the following safety measures should be taken:

- Good ventilation of the storage area at all times
- Installation of an adequate fire extinguishing system

The temperature and moisture content of the fuel should be monitored constantly; the moisture content should be less than 10 % (by weight) [42]. When handling in the storage facility, it should be ensured that the fuel does not become powdered in excess, as fine particles can increase the risk for self-ignition.

Commonly, pelletized RDF fuel is accumulated in big piles. The bigger the pile, the bigger the risk of self-ignition, thus ideally the fuel should be divided into smaller piles. This safety measure can reduce the risk of self-ignition and allows a safer and quicker extinction of a fire by fire-fighters. A minimum distance of 10 to 15 meters between the piles is recommended by the ISO Standard ISO 21912:2021 [41].

If fluffy RDF is the final product, typically this fuel is compacted in bales to reduce the storage volume. Such bales should be stored in a stable formation to avoid collapse. The risk of self-ignition should be controlled in a similar manner to RDF pellet piles.

Another alternative way of storing RDF is in silos. Such installations should not be oversized, thereby reducing the risk of self-ignition. The accumulation of CO is an additional risk, which can be controlled by constant gas monitoring.

Figure 15: Various storage types of RDF, 1) deep bunker acc. to [43], 2) alternative fuel storage at the production and storage hall acc. to [44], 3) bale stack acc. to [45], 4) storage box acc. to [46]

Figure 16 shows the necessary modern fire extinguishing system that can be used in RDF plants for effective firefighting or its prevention. The first picture shows the infrared system that scans the bunker around the clock, while the second picture shows a single turret with ranges of up to 65 m. On the third picture the sliding and protection device can be seen [47].

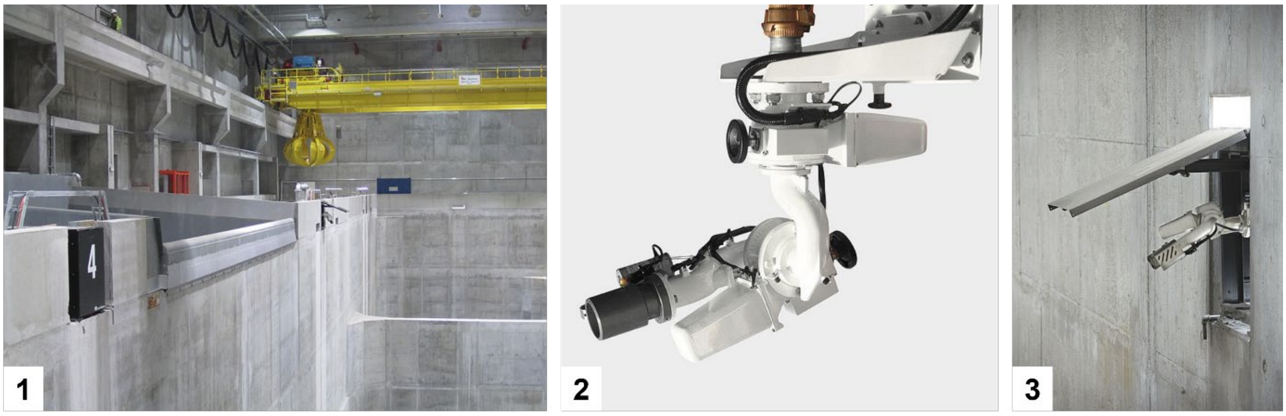


Figure 16: State of the art of modern fire extinguishing for RDF plants [47]

4.4 Transport

The transportation of RDF fuel can be done by road, rail or ship. Depending on the final RDF product - whether fluffy RDF (so-called Fluff), pellets or bales - different factors have to be considered. Fluffy RDF fuel cannot be transported economically over large distances, so it should be produced and used near the recovery facility or even on-site, for example at the cement factory. Transportation in that case can be done by means of a pipe-conveyor, for example.

Bales and pellets allow a transportation over larger distances due to higher compaction. Bales can have an average weight of up to 1 t per bale and are a typical way to export RDFs by train or truck. To reduce logistics costs, reverse haulage options should be considered in order to avoid driving empty trucks on the road.

The transportation of RDF should be done by registered waste carriers and should comply with all valid national regulations regarding waste transport. Transported RDF must be described accurately so that it can be handled in an appropriate manner and avoid any escape of waste to the environment.

There have been reports about problems with RDF transportation and storage. RDF may have a high organic fraction and is therefore biologically not stable. Bad odour and leakages may occur and produce environmental contamination and attract rats and flies. Proper wrapping of bales is a good way to avoid these problems.

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5. Options of the use of waste derived fuels

In principle, there are two general cases of RDF usages that need to be differentiated (see also Section 2). Firstly, the use of RDF as a fuel within a production process without any resulting solid residue stream as the ash of the RDF becomes part of the product produced (case 1). Secondly, the use of RDF in (industrial) utility boilers or power plants that supply electricity and/or steam to an industrial site or the grid (case 2). There are different options, and the implemented solutions might differ significantly, however, the aspects that need to be considered from a sustainability point of view remain the same.

In Section 5.1 the options to use RDF in the cement industry are discussed in detail as an example for a production process using RDF (case 1). In Section, 5.2 RDF use in industrial utility boilers versus power plants is discussed (case 2), Section 5.3 discusses economical aspects of RDF use in different scenarios.

Other potential RDF uses, such as for example transportation fuel have low relevance in the context of developing economies, and are therefore not covered in this paper.

5.1 RDF utilization in production facilities: cement industry

The use of RDF fuels in cement kilns is in some countries a well-established practice with at least a decade long track record. Especially in Europe, for example in Austria, Czech Republic, Germany, and Poland this use is common and the share of RDF fuel to produce the process heat needed in the cement process reaches more than 80 percent already.

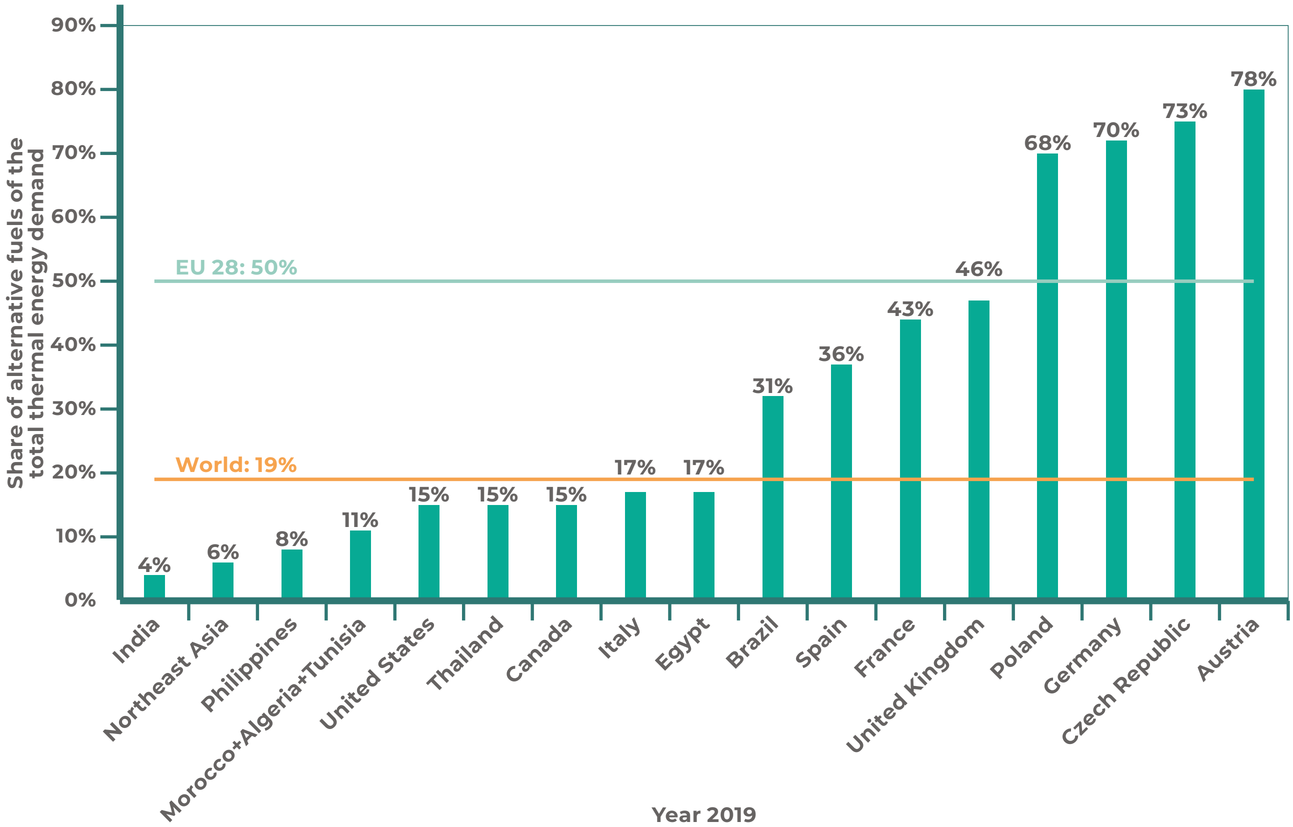

Figure 17: Use of alternative fuels in cement industries [48] (modified)

Figure 17 shows the use of alternative fuels in the cement industry in 2019, contrasting selected countries with their share of alternative fuels based on the total thermal energy demand. While alternative fuels were used in the cement industry worldwide at an average rate of 19%, consumption across the EU was 50%. Austria can be seen as the front-runner with a primary fuel substitution rate of 78% [48].

The pressure to decarbonize industry is especially challenging for the cement industry because of its high energy demand and because of its process related CO_2 emissions. 7 % of global GHG results from cement production. Increasing pressure on the cement industry incentivized intensive research to find ways to decarbonize the production of cement. The use of alternative RDF fuels is one of the most promising approaches. While this is already widely applied in developed economies, there exists still a high potential for the application of RDF fuels to decarbonize the cement industry on a global scale. For this application, different types of alternative fuels are used, which can be completely biogenic, like agricultural wastes, wood, or sawdust, or can be based on RDF products produced from MSW, used tyres, waste oil or sludges from water treatment plants. On a global level, the use of RDF in cement plants is gaining considerable interest and is continuously growing.

Figure 18 gives an overview about the diverse fuels which are used in the cement production process.

Figure 19 shows an illustration of the cement production process steps according to the technology most often used [50].

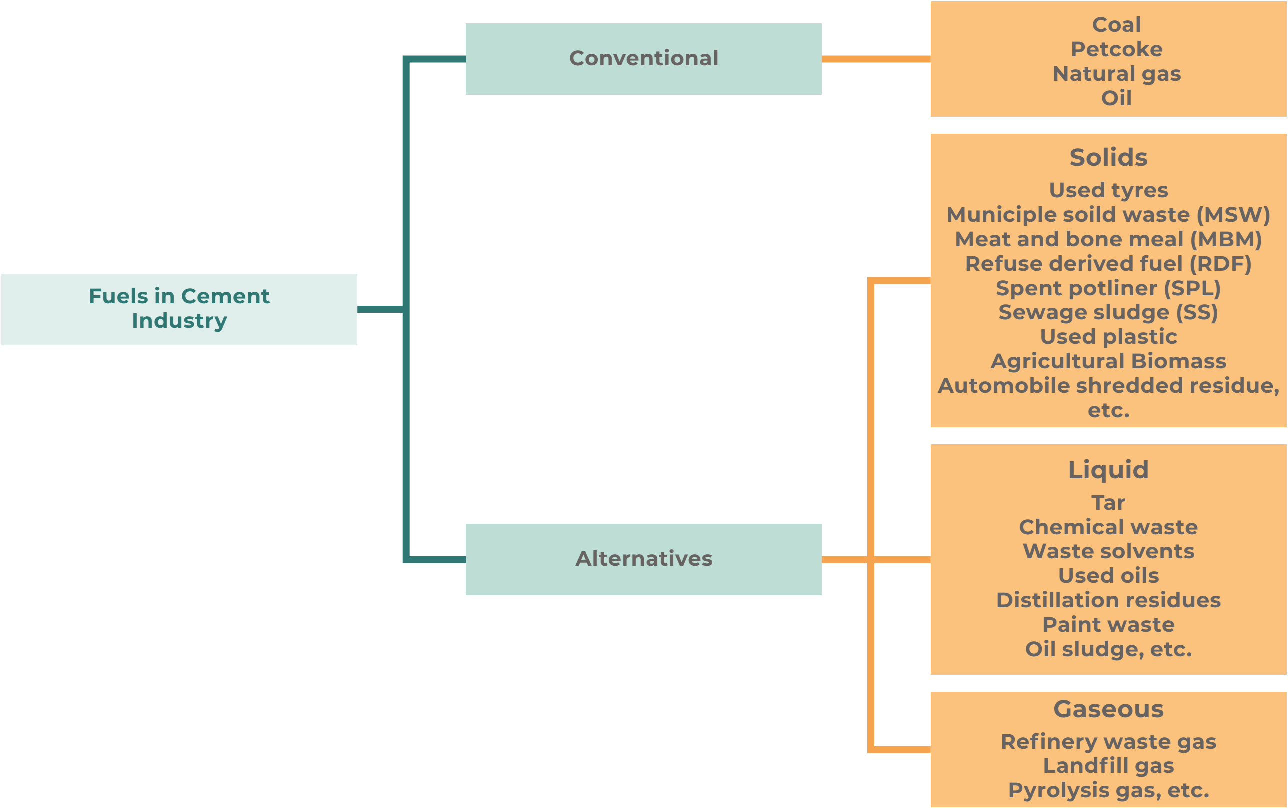

Figure 18: List of fuels (conventional & alternatives) in cement industry [49] (modified)

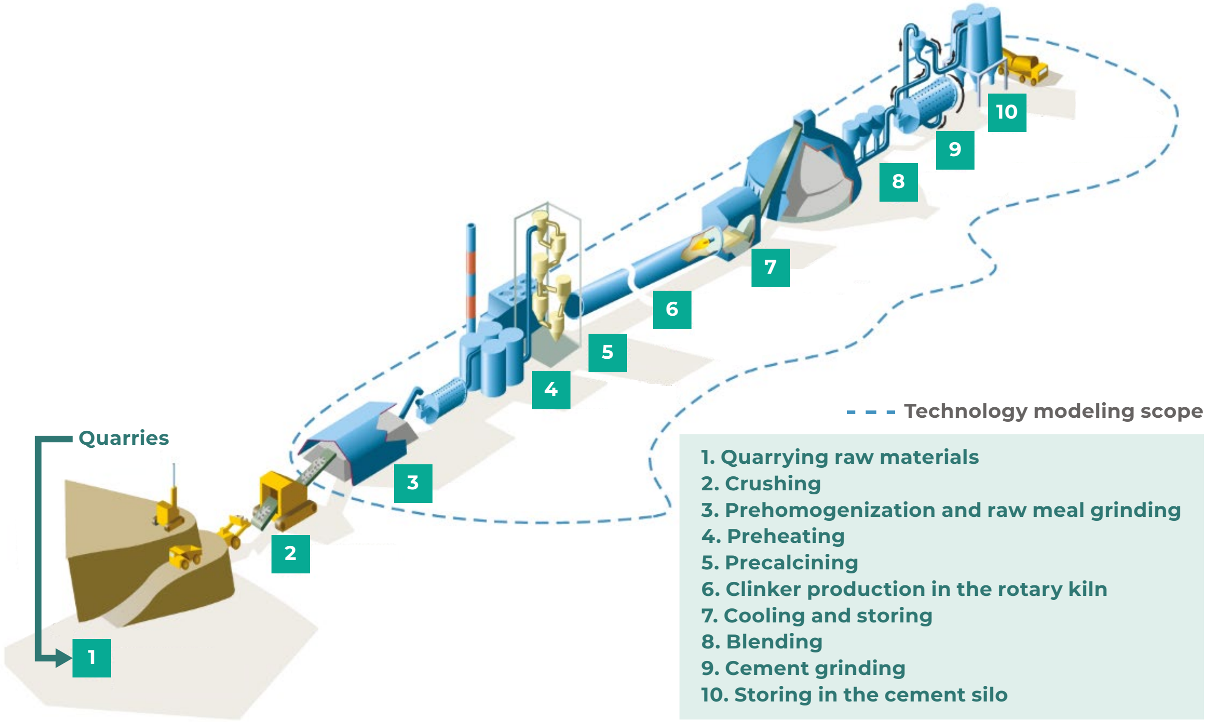

Figure 19: Process lay-out of Cement Production [50]

5.1.1 Advantages of RDF use in the cement industry

There are several reasons for this increased use of RDF in the cement industry:

- Cement plants exist in almost every country worldwide, which make the use of RDF with low additional CAPEX investment possible. No new dedicated WtE plant must be developed and built, and cement plants can be easily adapted to make them fit for RDF utilization.
- Different RDF qualities can be utilized in cement plants at different feeding-points in the production process.
- High pressure on the cement industry to decarbonize their production to contribute to international climate mitigation goals. Cement production emits high amounts of CO_2, on the one hand non avoidable geogenic – process-related - emissions and on the other hand pyrogenic emissions related to the fuel usage that can be influenced according to the fuels used.
- Fuel costs account for almost 1/3 of the production costs of clinker [51]. This in connection with an unpredictable and volatile price development of fossil fuels makes their replacement an interesting alternative.
- Very high combustion temperatures and long residence time can destroy organic pollutants (e.g. persistent organic pollutants (POPs)), which makes this application an ideal solution to get rid of waste containing these types of pollutants [52]
- The mineral content in RDF products (Ca, Al, Fe, Si) is incorporated in the final cement product. Thereby RDF-use also contributes to a reduction of natural resources used up in the cement production process. This also results in the avoidance of fly ash and bottom ashes if RDF is used for cement clinker production.
- The use of RDF in cement plants is a highly efficient WtE process with much higher energy recovery than RDF usage for sole electricity production [52].

5.1.2 RDF feeding points in cement kilns

In cement plants there are three different feeding points where RDF fuel can be introduced into the process. Each of the feeding-points has its specific requirements regarding fuel quality and physical composition. These three feeding-points are illustrated in Figure 20 [52]. The cement production process requires a different amount of energy at these feeding-points. In case of a high substitution rate this fact becomes very important as it requires different qualities of RDF. The main feeding-points as shown in Figure 20 are:

1. Kiln or main firing (left side of Figure 20)
2. Calciner firing (right side of Figure 20)
3. Kiln inlet- or so-called secondary firing (right side of Figure 20)

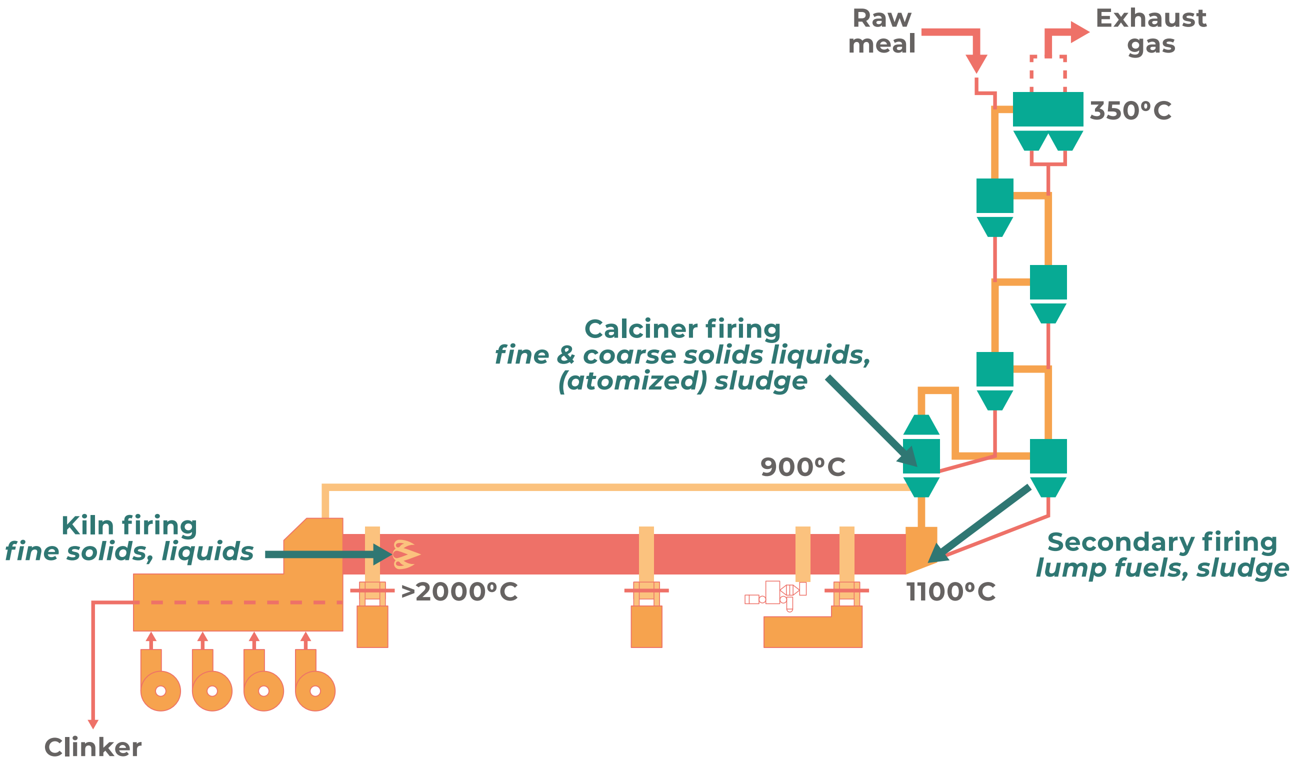

Figure 20: RDF feeding-points of a state-of-the-art cement kiln system (Geocycle) [52] (modified)

In addition to the above mentioned – mainly applied – feeding-points there are also other feeding options that have been developed to optimize and simplify the combustion of alternative fuels in cement kilns. The most promising solutions are Hot-Disc, Pyro-Rotor and also prior RDF gasification which are described in Section 5.1.2.4 in more detail.

5.1.2.1 RDF as an alternative fuel at the main burner

At this feeding-point around 35 - 45% of the total energy demand of the cement production process is required. The fuel specifications are very strict, high quality RDF fuels with high calorific values and a high energy density are required to reach high combustion temperatures of above 2,000 °C. The NCV should be above 18 – 22 MJ/kg to reach this temperature level. The high temperatures and the long gas retention time of 6 - 8 seconds allow a complete burnout and make this part of the cement kiln suitable for the destruction of stable organic compounds like POPs [13].

RDF used at the main burner needs to comply with the specifications of a SRF Premium quality according to the categorization of Figure 3. The RDF needs to be fluffy and have a low ash content (< 10 %) to be able to be pneumatically fed via the main burner and guarantee a complete combustion in the air room above the clinker.

5.1.2.2 RDF as a calciner fuel

At this feeding-point around 55 - 65% of the total kiln system energy demand is required. The fuel needs to be fluidized accordingly to guarantee that the fuel can be burned completely in suspension. The average NCV should be minimum 11-13 MJ/kg [13].

RDF used in the calciner needs to comply with the specifications of a SRF medium quality according to the categorization of Figure 3.

As the quality requirement is not high, this type of feeding point is most likely to be used for RDF utilization in developing economies – provided the cement works off-taker already has a calciner.

The amount of RDF that can be fed at this stage of the cement process also depends on the design of the calciner that needs to secure the respective residence time for the off-gas. Owing to limitations, the RDF substitution rate of primary fuel may reach up to 30% if only the calciner feeding point is available.

5.1.2.3 RDF as an alternative fuel at the secondary firing

This feeding-point is at the elevated end / inlet of the rotary kiln and has low quality requirements for alternative fuels. Even unprepared waste like whole tyres and sludges can be introduced as fuel at this point. Only a small amount, 5 - 10% of the total kiln energy demand - can be fed at this point to the process.

5.1.2.4 Other feeding alternatives

5.1.2.4.1 Hot-Disc

An interesting technology to increase the use of alternative fuels in the cement industry are Hot-Disc systems, which allow the use of low quality and heterogeneous waste fuels. This is an interesting technology for locations where no advanced waste management system is yet in place and the fuel quality is fluctuating significantly over time. In such countries the biogenic content frequently is relatively high, this in turn reduces the NCV due to the high moisture content [53].

Hot-Discs are pre-combustion chambers which are attached near the cyclone heat exchanger of a rotary kiln, which allows a flexible use of alternative fuels of low and fluctuating qualities. The fuel can be prepared with a few processing steps and is combusted in an oxygen-rich environment. The residence time in the combustion chamber can vary depending on the type of alternative fuel and is required to ensure a complete combustion. In addition to RDF fuels, the Hot-Disc allows even the processing of all kinds of lumpy materials, for example complete truck tyres or coarse MSW and sludges and can process any mixture of different alternative fuels. The operation is simple and allows a low cost and efficient use of alternative fuels in cement plants with just a very basic pre-processing of fuels.

Figure 21 shows an illustration of such a Hot-Disc system [54].

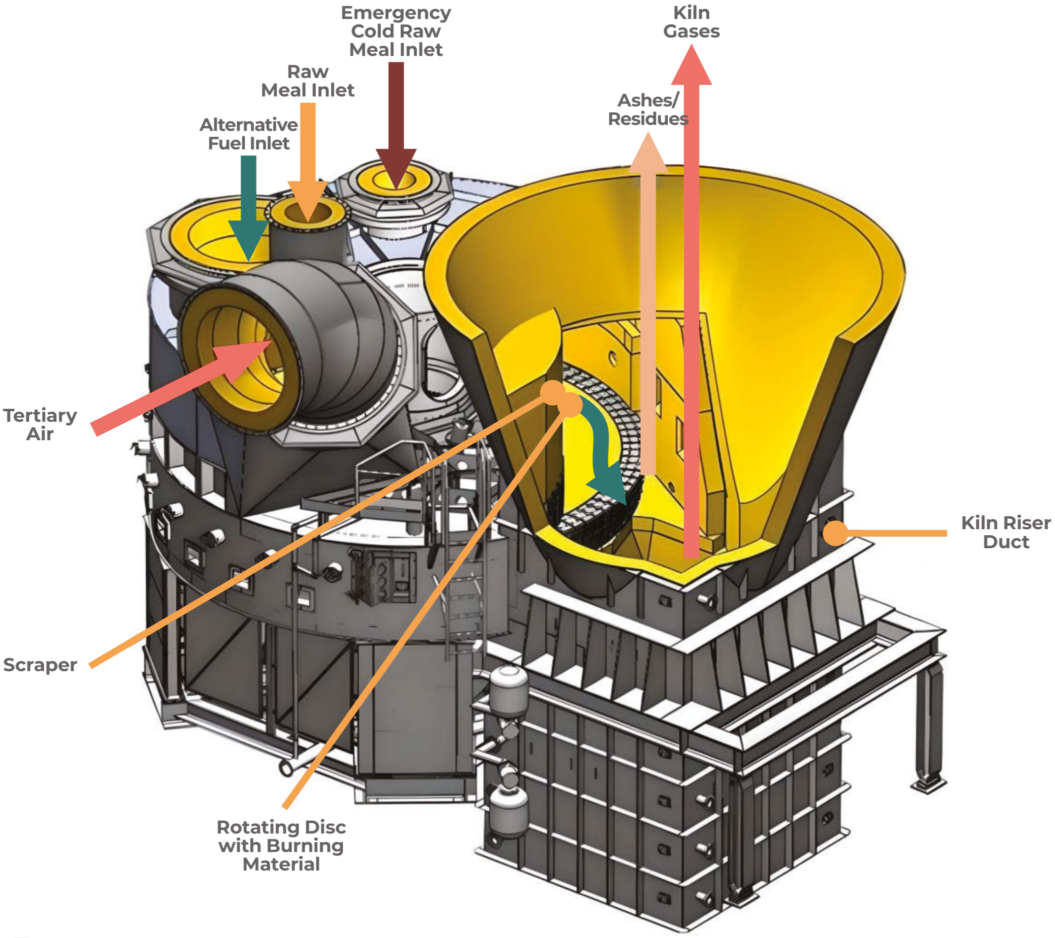

Figure 21: FLSmidth HOTDISC^{TM} technology working principle [54] (modified)

5.1.2.4.2 Pyro-Rotor

Similar to the Hot-Disc technology, the pyro-rotor is a modular add-on technology to existing calciners at cement kilns which allows the use of alternative fuels to reach very high substitution rates. The technology allows the combustion of very challenging and diverse materials and guarantees a comparingly high fuel flexibility without much need of pre-processing of the waste materials. The pyro-rotor allows a complete burn-out of the alternative fuel by a rotary action that results in a constant mixing of the fuel with oxygen-rich hot tertiary air, which optimizes combustion conditions. The rotation speed and therefore the residency time can be varied to control the burn out of the combusted material, depending on the fuel parameters like moisture content or granularity. This allows the combustion of materials like construction waste, tyres, sludges, MSW or contaminated soil. Fuel substitution rates of up to 85 % can be reached in the calciner and this may allow a very important reduction of fuel costs with a clear environmental benefit [55, 56, 57].

Such system was installed for example in Gmunden (Austria) at the Rohrdorfer Cement Group and in South Korea for the company Asia Cement.

Figure 22 shows an illustration of the pyro-rotor attached to the rotary kiln.

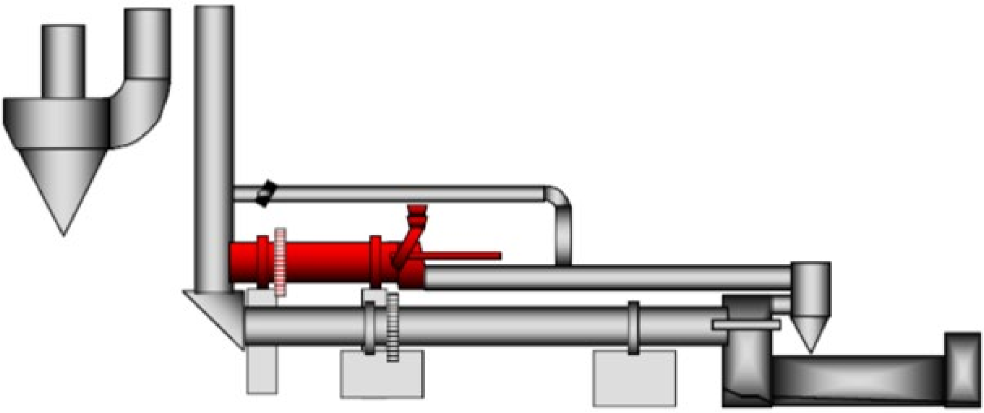

Figure 22: KHD RDF burning technology – PYROROTOR® [58]

5.1.2.4.3 Gasification of RDF in an upstream gasifier

Another interesting technology for the use of alternative fuels in the cement industry is the gasification of RDF fuels and the injection of the gasified fuel into the calciner, where it is combusted together with other fuels. Again, this technology allows the later installation of the gasifier at an existing cement plant. This concept was realized decades ago in the CEMEX cement plant in Rüdersdorf in Germany, where a fluidized circulating bed boiler was installed to gasify MSW and industrial waste. The plant configuration of the clinker production is illustrated in Figure 23.

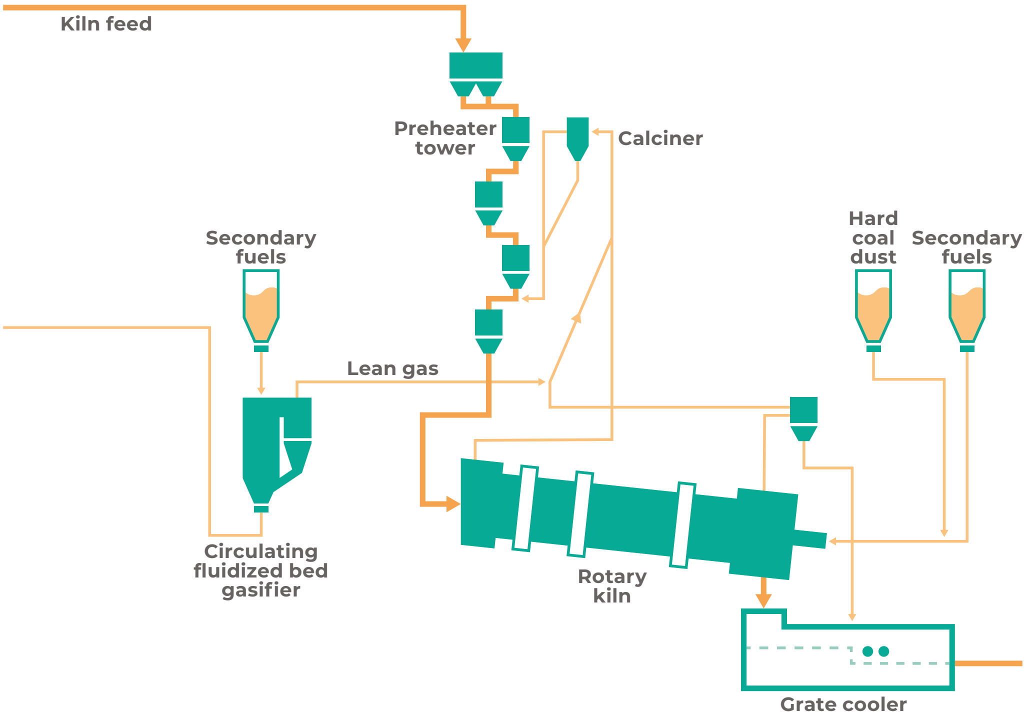

Figure 23: Clinker production with gasifier [59] (modified)

5.2 Co-combustion in industrial utility boilers and power plants

Two main cases are differentiated i.e., the co-combustion of waste-fuels in industrial utility boilers or power plants and RDF power plants that are designed and constructed to use RDF as the main fuel. For power plants, the waste fuel quality required is SRF medium to SRF premium quality. For a fluidized bed based industrial utility boiler SRF low to SRF medium quality may suffice.

The use of alternative fuels in industrial boilers, for example in the pulp and paper industry or in the chemical industry, as well as in power plants for electricity generation has been a common practice for decades. Different types of fuels are used in these co-firing plants, like agricultural residues, sewage sludges, demolition wood, industrial waste, or RDF fuels from MSW.

These fuels can be used in different boiler types but must fulfil the specific quality criteria for each technology. The most common application is the co-combustion with coal in bubbling fluidized bed boilers or in circulating fluidized bed boilers and is an established practice in some countries. Depending on the type of technology used, the share of RDF co-combustion for plants that are not specifically designed for RDF as a main fuel is limited, generally below 10% of the total thermal load of the combustion process. This share can be exceeded in fluidized bed boilers, and nevertheless depends on the compatibility of the RDF with the thermal recovery process of the used technology, which was designed for fossil fuels [7].

The easiest option for co-combustion is mixing of the different fuels before they are introduced in the combustion chamber. In this case, the fuels are mixed for example on the fuel conveyor belt and are ground together before they are burned. Due to different grinding behaviour of fuels, this option is mainly used for dried sludges. For MSW derived RDF fuels this would not be an appropriate option [7].

For fluidized bed combustion, the waste fuel must be shredded and depending on the fuel properties typical grain sizes between 50 – 100 mm are used in order to allow a trouble-free co-combustion. Fuels with relatively high moisture content can be used in fluidized bed boilers, but fuels with low ash melting points are not suitable because they cause technical issues in the furnace. The same is true for RDF with metal impurities, which disturb the combustion process and are difficult to remove from the furnace. That is why certain types of RDF from industrial sources or demolition wood require pre-processing steps to get rid of the metals [7].

Two fuel properties for the use of RDF in coal power plants are of special importance. Firstly, chlorine content of the fuel, which can cause corrosion problems in furnaces and secondly, mercury concentration, which can cause undesired emissions to the atmosphere. To assess the technical and environmental risk of mixing standard fuel and RDF fuels, the resulting overall concentrations of chlorine, heavy metals (such as mercury) and sulphur must be considered. Knowledge and classification of RDF fuel composition is therefore essential to ensure specific fuel qualities are used for the right application [24].

An example of coal plant co-combustion of RDF is illustrated by the Jänschwalde lignite power plant in Brandenburg / Germany. This power plant burns around 400,000 tonnes of RDF fuels derived from MSW waste per year coming from the city of Berlin and other Eastern German cities [60, 61].

For newly developed pulp and paper plants, the combination of RDF production plants and combustion in a CHP plant using local MSW streams together with waste streams from an attached pulp and paper plant are an interesting concept. The excess heat from the CHP plant can be used as process heat for the pulp and paper plant and allows a more efficient WtE utilization than conventional power plants without heat recovery. Such industrial symbiosis concepts are key for a circularity-orientated industrial development [62].

One main difference compared to RDF use in cement kilns is that in industrial kilns and in fluidized bed boilers bed ash and fly ash are a residue of the combustion process. The disposal of these 2 waste fractions must be considered as part of an integral project development.

The most common technology in use in different industries are Circulating Fluidized Bed Boilers which are a very flexible and relatively low-cost solution for the combustion of different and varying types of waste fuels. Pure industrial waste from production processes or mixed with RDF from locally sourced MSW can be combusted to generate electricity and heat for industrial processes in CHP plants. This system concept is illustrated in Figure 24 below [63].

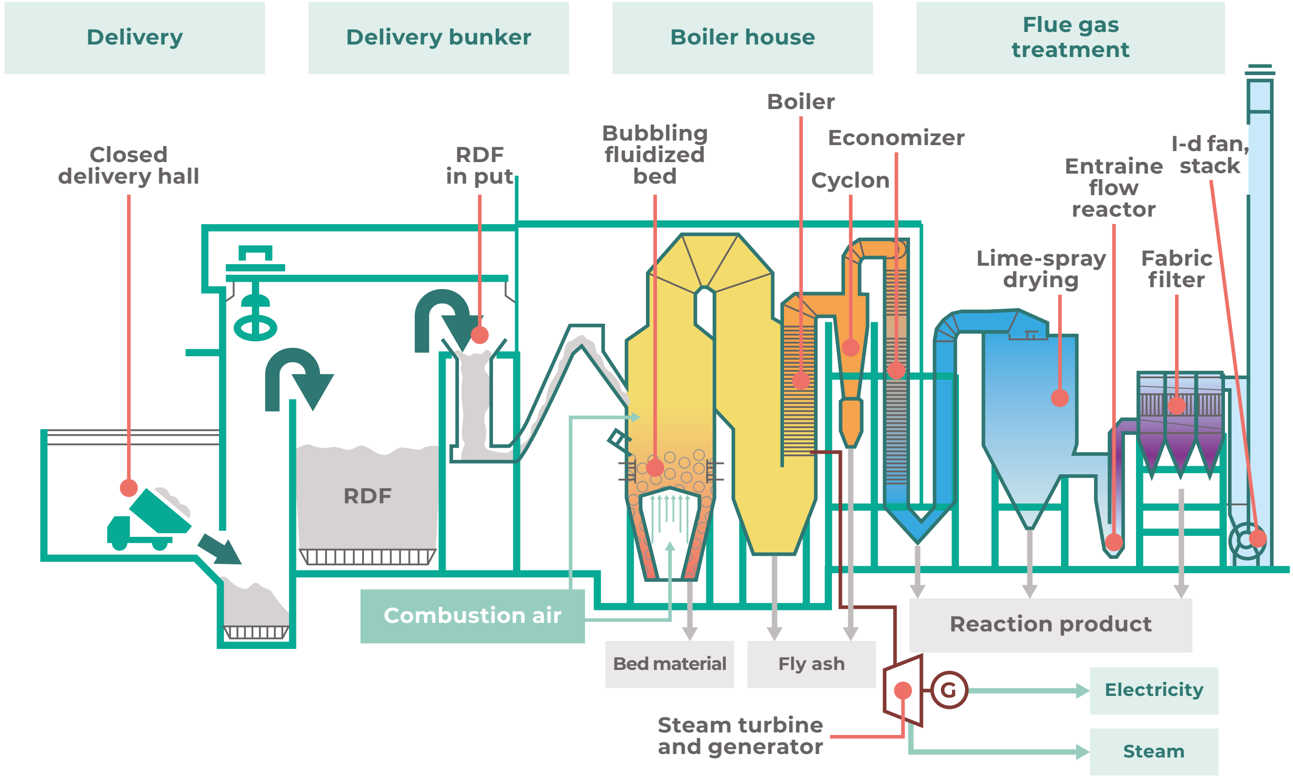

Figure 24: RDF / Waste Utilisation at Infraserv Frankfurt [63] (modified)

Such co-generation energy plants are becoming an interesting alternative for the decarbonization of energy intensive industries. A ground-breaking project was announced at the beginning of 2022 by the company consortium of Veolia and Solvay, two industry leaders from the waste and chemical sector. The industrial energy transition project is called “Dombasle Énergie“, and will replace three coal-fired boilers at Solvay´s soda ash factory with two new furnaces running on RDF. From 2024 onwards, this project will avoid the import of 200,000 tonnes of coal by burning 350,000 tonnes of RDF, supplied by Veolia, each year, and will reduce the carbon footprint of the Solvay plant by 50%. The industrial power plant will have a thermal capacity of 181 MW and a power capacity of 17.5 MW [64, 65].

5.3 Compare the sourcing, pricing and energy efficiency of RDF used in different types of plants

5.3.1 Sourcing and pricing – economic considerations

In addition to investment costs at the plant of the off-taker, one must differentiate between two fundamentally different scenarios:

1) a very low development level of the waste management sector
2) a strongly developed waste management sector already in place.

These scenarios refer to the interdependency of the RDF marketing and the waste sector and strongly influence the commercial aspects of supplying an off-taker with RDF and therefore the economic viability and sustainable operation of an RDF processing plant. As the waste management sector evolves over time, it can be the case that an RDF-producer faces both scenarios over time.

Scenario 1: energy market serves as benchmark

In the first scenario, the benchmark for the RDF supply is solely the energy market – more specifically the energy cost per GJ provided to the process, the energy is needed for. From the perspective of the operator of a cement plant (and also the operator of a power plant or an industrial utility boiler as well) RDF is an energy carrier to provide heat just like the primary fuels natural gas or coal. Whether or not a specific energy carrier is used in a specific power plant, utility boiler or cement plant – besides technical aspects as discussed in Section 5 – depends solely on economic decisions related to the fuel cost. In this scenario the RDF producer identifies itself as a provider of an energy carrier and the off-taker of the RDF identifies itself solely as a buyer of an energy carrier.

This scenario is realistic as long as landfilling or dumping of MSW is legally possible and (including a potential landfill tax) is still less expensive when compared to other waste treatment alternatives such as for example thermal treatment.

The RDF producer will benchmark the cost of RDF-provision to the off-taker directly with the cost of other energy carriers and if no additional benefit – such as for example monetizable credits due to reduced emissions of fossil CO_2 – occurs or if there is no strong contractual obligation or organisational involvement of the off-taker in the RDF production, the off-taker will not use RDF if the energy demand can be met with other less expensive energy carriers.

Excluding logistics, the cost for the provision of an RDF of decent quality that can be used as a calciner fuel in the cement industry are typically around 2.0 US-$/GJ. This assumes that the waste is delivered at 0.0 US-$/t to the RDF processing plant. In case the RDF-processing plant is paid a gate fee to receive the waste, the competitiveness of the RDF might rise. There is some variation depending on the region and alternative fuel, for example Plank reports prime fuel costs of 1.2 – 2.2 €/GJ [66].

The Delivered Duty Paid (DDP) cost for fuels (primary fuels as well as secondary fuels) may be very different from region to region as one must consider the cost for delivery and duty charges. The trends however are always similar across regions as the price of energy follows a world market price. On a regional level, suppliers then orient themselves at indices such as the Newcastle Index for coal in South-East-Asia and PACE Index for petrol-coke in Europe.

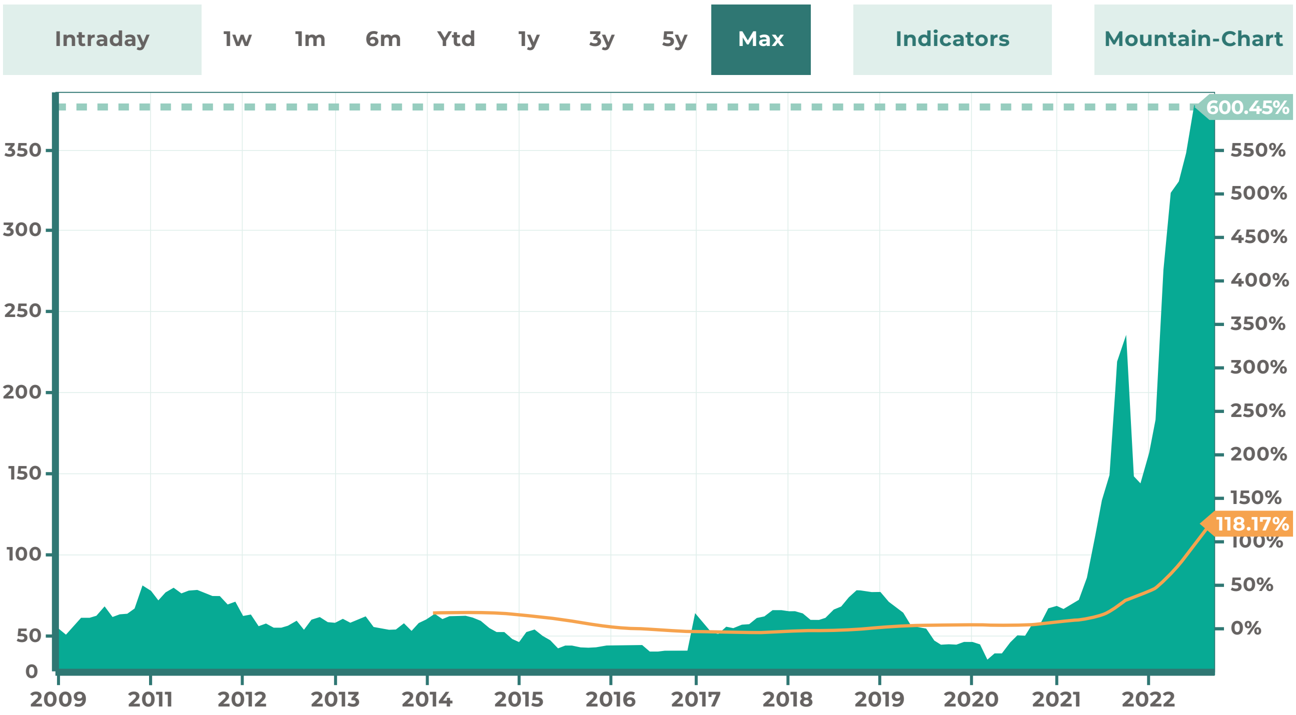

Figure 25: Trend of coal price over the last 13 years [67] (modified)

As of September 2022, prices are much higher than they used to be. The price for coal was typically around 2.5 to 3.5 US-$/GJ, but around 8.0 to 10.0 US-$/GJ in September 2022. However, the prices of energy carriers fluctuate as can be seen in Figure 25. So, it must be said that in this scenario selling RDF is very much dependent on the rather volatile energy market and therefore the economic risk for the RDF producer is high.

Scenario 2: Waste management sector serves as benchmark

In scenario two the situation is completely different. When a strong waste sector has evolved and dumping or landfilling of MSW is not a legally feasible option anymore, the treatment and/or processing of waste becomes the predominant purpose and RDF-processing and energy recovery from RDF is just another alternative treatment option for MSW. In regions / countries with a landfill ban for waste with a high biogenic content such as Germany [68] and Austria [69] - besides recycling of recyclable waste items that are separately collected at source or sorted out from MSW - the only option for managing MSW is thermal treatment. There are several different types of facilities that may be used for thermal treatment each demanding a different level of mechanical processing. In case of thermal treatment in a Municipal Solid Waste Incinerator there is no need for processing, however, if the MSW is to be used as RDF in a power plant or cement plant, there is the need of (extensive) processing according to the quality of RDF to be used.

In such a scenario, the off-taker uses the gate-fee for thermal treatment of MSW in a Municipal Solid Waste Incinerator as a benchmark. The processing costs for RDF including some profit for the processor are deducted from that benchmark and finally this comes down to a gate-fee the off-taker demands for taking over the waste (RDF) and securing the environmentally sound treatment of it according to the legal conditions. In that second scenario, the off-taker identifies itself as an actor in an integrated waste management system taking over the obligation of treating waste, therefore the waste sector and the respective costs of alternative treatment of the waste serve as a benchmark. As the waste management sector is looking for long term solutions, it is likely that in this scenario long term contractual agreements can be concluded and thereby cost risks can be controlled.

Concluding and comparing the two above mentioned scenarios it becomes clear that in scenario 1 the RDF-producer is likely to be able to sell the RDF, however, the sustainable marketing of the RDF is risky due to the dependency on the global energy market. In scenario 2 it is very unlikely that RDF can be sold, however, the disposal cost for the MSW may be reduced at the end.

5.3.2 Energy efficiency and climate relevance of the use of RDF

With regard to the energy efficiency of the energy recovery from RDF, one must consider the following aspects:

- processing needs and related energy demand for RDF-processing
- alternative energy recovery options for MSW
- substitution of primary fuels and
- increased energy demand through logistics

The energy consumption in the processing stage is very much dependent on the actual quality of RDF to be produced. The range of energy consumption here might vary as much as from around 10 kWh (≈ 36 MJ) per tonne waste treated for a very basic mechanical treatment involving a size reduction and screening to about 100 kWh (≈ 360 MJ) per tonne of waste treated to produce SRF premium quality [70]. So, the input of electrical energy in the RDF processing makes up about 1% of the energy content of RDF that is later used for heat provision.

In the case RDF is used solely for electricity production in a Municipal Solid Waste Incinerator the energy efficiency of that process is around 25%. This means that 20 GJ per tonne of RDF – class 2 according to Table 1 (for SRF) - yields around 1.4 kWh (i.e., 5 GJ) of electricity compared to an energy demand of about 0.36 GJ (i.e. 7 %) to process RDF such that quality specifications are met. The energy demand of logistics is not considered in that comparison as it is very much dependent on specific circumstances. As the Greenhouse Gas emission of waste collection and (extensive) logistics are assessed at around 1% of the total Greenhouse Gas emissions of the over-all system [70], the related energy demand is very low as well. Overall, less than 10% of the energy generated by RDF is consumed in RDF collection, transport, and processing.

If RDF is utilised in a Combined Heat and Power (CHP) facility, the energy efficiency is much higher and can be around 80%. If RDF is utilised in a cement kiln, the energy efficiency is even higher, as the RDF directly replaces a primary fuel – meaning a theoretical 100% energy efficiency. Looking a little deeper, it becomes clear that this is not quite right as, for instance, RDF requires more air to be injected into the process when it is used. This in turn means that more energy is needed to maintain the process conditions as they are needed. So, one should account for an efficiency loss of around 10% which means an energy efficiency of RDF in cement production of about 90% [71].

Looking at these numbers it becomes clear that despite the energy demand due to the processing and even when considering the energy demand due to collection and waste logistics, about 10 times as much energy is provided by RDF compared to the energy consumed.

If one furthermore compares the climate impact of the following waste treatment and recovery options

1) RDF processing and RDF recovery at a cement plant
2) RDF industrial utility boiler (combined heat and power, 75% energy efficiency)
3) Municipal Solid Waste Incinerator with sole electricity production (energy efficiency 25%)
4) Landfilling

one needs to make a distinction between direct influences (avoidance of methane emissions in the waste management sector) and indirect influences (substitution of fossil fuels from the energy sector). In addition, it should be emphasized that RDF-production and utilization always involve thermal treatment or landfilling of residues, depending on the stage of evolution of the waste sector in the respective country.

In a study, Ragoßnig et al. (2009) [70] compared the above-mentioned waste management scenarios for commercial and pre-treated waste and found that the scenario that aimed at maximizing waste-to-energy resulted in greenhouse gas emission savings for the specific waste management situation considered, as more emissions are avoided in the energy sector (indirect effect) than are caused by the various waste treatment processes (direct effect).

Comparing dedicated waste-to-energy systems based on cogeneration technology with those systems that generate electricity only, energy efficiency emerges as a crucial factor for climate protection. This is underscored by the importance of choosing appropriate sites for waste-to-energy plants. Compared to a scenario of landfilling of the waste, about 1 - 3 tonnes of CO_2 equivalent can be avoided per tonne of waste treated. These results are calculated for commercial and pre-treated waste, therefore it can be assumed that the climate benefit of rerouting Municipal Solid Waste to RDF processing and RDF recovery might even be higher.

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6. Practical case-studies of RDF utilization

6.1 RDF challenges and use trends in developing economies

The use of RDF in developing economies is still in its infancy due to the lack of proper waste regulations, and difficulties accessing the financing of suitable technological solutions. However, the fast-growing quantity of waste and the environmental burden associated with improper waste management calls for urgent solutions to divert waste from landfilling towards recycling and WtE projects. Several countries have recently adapted their environmental and energy legislation to set the right boundary conditions for RDF production and utilization [72]. However, the social question regarding informal waste pickers must be considered especially because they depend on unsorted MSW to make a living and furthermore MSW which has been sifted through by waste pickers contains much fewer recyclables and a smaller combustible fraction compared to unsorted MSW. This impacts the economic feasibility of RDF projects, which depend on the sale of recyclables and the production of a high share of combustible fraction.

Another driver for increasing interest in RDF fuels in developing economies is the fast-growing energy demand triggered by their economic development. This is especially true in Asian countries, e.g., China, India or Indonesia. Initially the use of RDF fuels was focused on imports from developed economies like Australia, however legal and institutional boundary conditions for domestic production of RDF fuels are implemented increasingly to take advantage of this often not yet recovered energy resource.

This paper has considered outcomes of international research projects, findings from personal discussions and interviews with specialist and expert stakeholders from industry and academia. This aims to provide a complete picture about where the adoption of RDF technology in different world regions stands and identify the key challenges which have to be overcome in order to increase the number of successful projects in developing economies. Besides extensive practical experiences from developed economies, input was received from countries as diverse as Algeria, China, Egypt, India, Indonesia, Iran, Israel, Mexico, and Philippines and is reflected in the conclusions and recommendations of this document.

In the Section 6.2 four successful RDF projects in different regions of the world are described in detail.

RDF projects are always very context specific, and each project has its own boundary conditions which make them successful or may cause its failure. In general, the conclusion can be made that very different drivers for RDF projects exist in developed economies with highly developed waste management systems and countries with a waste sector yet to be developed. In countries without such waste management systems, the energy cost comparison between traditional fossil fuel and the RDF fuel is the key driver, whereas in developed economies, the legal compliance and avoidance of high landfill fees dominate the picture (see Section 5.3.1). The cost situation is extremely volatile and is dependent upon the global energy markets. This makes long-term planning for investors difficult and risky, which is crucial when attracting financing for such projects. Especially in countries with low energy prices because of the availability of domestic fossil fuels, such as in Iran or Mexico, the realization of successful projects is challenging, because energy costs are relatively low. Long term commitments by RDF off-takers are even more important in these locations to guarantee investment security. Emerging carbon pricing and decarbonization commitments by cement producers, like CEMEX in Mexico, are promising signs which are improving investment security [73].

Other important drivers in developing economies are the lack of available land and rising costs for land in regions with a dynamic real estate market. In India and other fast developing countries, the production of RDF from waste from closed or still operating landfills and dumpsites to free valuable land for real estate projects, has become an interesting driver for successful RDF projects. These waste streams differ significantly from fresh MSW waste and bring their own challenges; processing the RDF and finding an off-taker are seen as a way for land remediation in order to clear land from landfills [74].

Figure 26 shows the countries where input and opinions from RDF experts have been obtained in developing this paper and where detailed case studies have been included in Section 6.2.

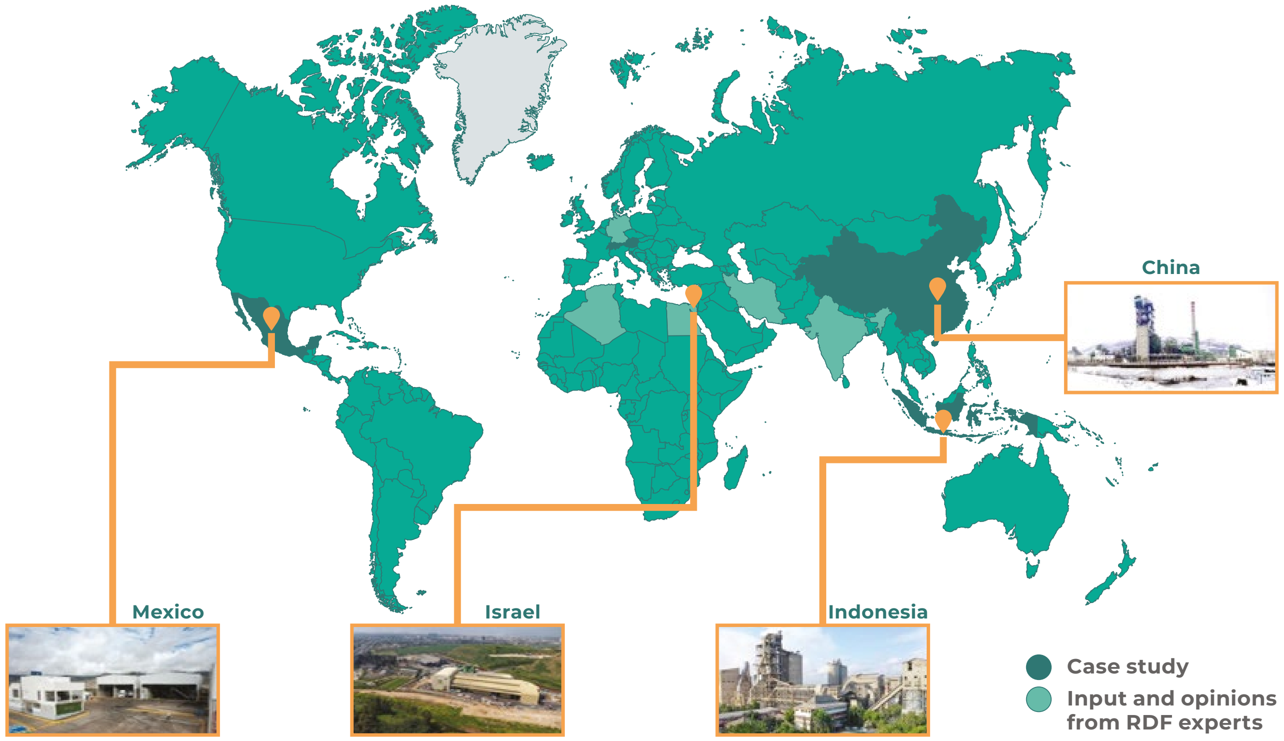

Figure 26: World map of the locations of detailed described case-studies as well as expert inputs (own representation)

6.2 Case studies

6.2.1 Case study Huaxin Cement Co. LTD. in Hubei, China

The information for this case study was provided by Huaxin Cement Co. LTD [75].

Table 8: Overview of the key data of the case study of Huaxin Cement Co. LTD. in Hubei, China [75]

Project Summary	
Project owner	Huaxin Cement Co. LTD
Location	Wuhan/Hubei Province, China
Industry / application	Cement production
Start of RDF use	2018
Type of RDF used	MSW
Capacity RDF use per year	370,000 tonnes per year
Operational model	- MSW collection and transportation by private company managed by the municipality - Pre-processing and co-processing by Huaxin Cement Co. LTD

Since 2018 the Chinese cement manufacturer Huaxin Cement Co. LTD. has been using RDF fuel in its cement plant near the city of Wuhan in the Hubei province. The project successfully uses RDF produced out of MSW from the city of Wuhan to use it as a partial substitute for coal, which is the fuel for most of the cement plants in China. An existing waste legislation is in place in the project area, as well as a pilot CO_2 trading scheme with current carbon prices of 8 €/t (09/2022).

In this project Huaxin Cement Co. LTD. Is responsible for the pre-processing and co-processing of the RDF fuel. The MSW waste collection and transportation is managed by the municipality, but subcontracted to a private company, which delivers the MSW to the RDF production plant with a gate fee of about 17 € per tonne. The final RDF is transported by truck to the cement production plant, which is approximately 80 km from the pre-processing facility. The MSW pre-processing plant has a capacity of 2,000 tonnes per day of fresh MSW and around 730,000 tonnes of MSW per year is processed into 370,000 tonnes of RDF. A continuous quality monitoring system is in place to control the RDF product quality. The principal aim for the RDF production is avoiding MSW landfilling and incineration, no recyclables are recovered at this stage of the project.

The following flow chart shows the MSW pre-processing process for the RDF production (see Figure 27).

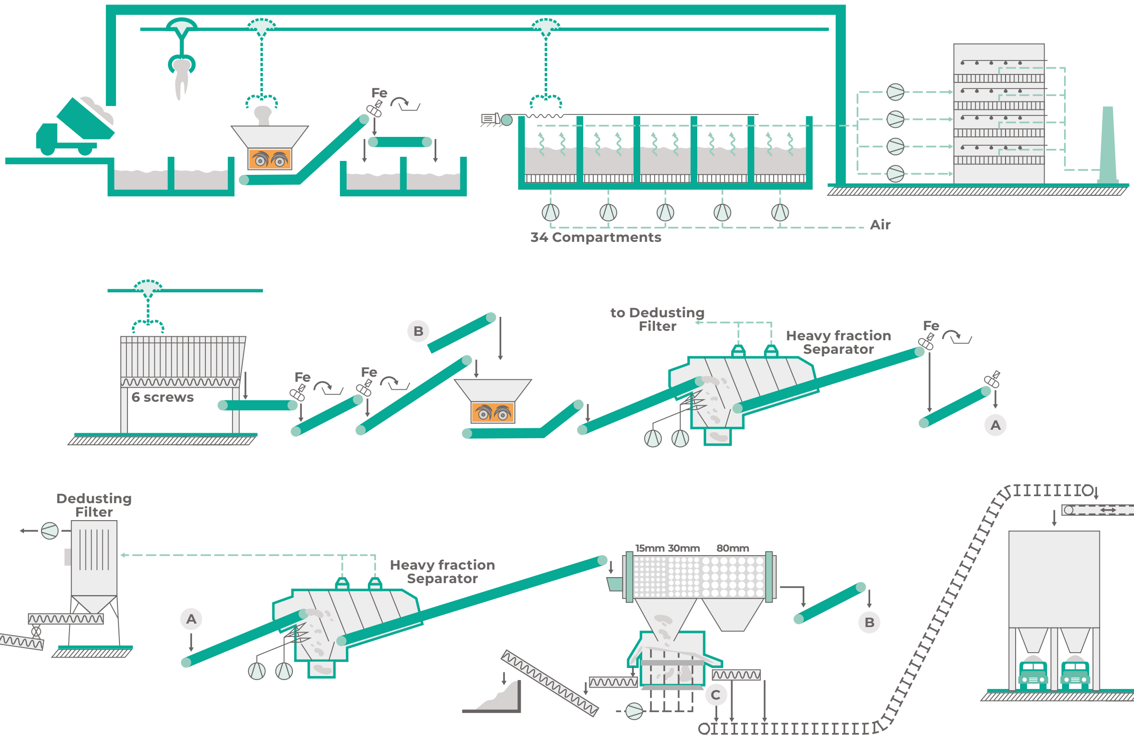

Figure 27: MSW pre-processing process for the RDF-production @ Huaxin Cement Co. LTD [75] (modified)

The cement production facility has a daily capacity of 12,000 tonnes of clinker and is using a preheater and precalciner cement kiln system. The RDF currently replaces 30 % of the coal input in the production process and is introduced at the precalciner feeding point into the cement kiln. The RDF fuel must fulfil the quality standards established in the Chinese RDF Norm GB/T 35170-2017, which includes specifications regarding NCV, ash content, moisture content, chlorine, sulphur, heavy metals and size.

Off gas emission control must comply with the concentrations shown in Table 9.

Table 9: Concentration limits for emission control in mg/Nm³ at Huaxin Cement Co. LTD [75]

Dust	SO_2	NO_x	F	Hg	NH_3
10	50	100	5	0.05	8

Dust, SO_2 and NO_X emissions are measured online and continuously shared with the authority. PCDD/F are yearly measured, whereas the other emissions are quarterly measured.

A chlorine by-pass is in place at the cement kiln to avoid adverse effects to the production facility.

The main driver for this project is reducing the coal consumption for cement manufacturing. The project is planned to expand to reach 60 % of energy substitution in the next three years.

Figure 28 and Figure 29 show the pre-processing and co-processing facilities.

Figure 28: MSW pre-processing plant, Wuhan City, Hubei province [75]

Figure 29: RDF co-processing cement kiln system, Huangshi city, Hubei province [75]

6.2.2 Case study of cement producer PT Solusi Bangun Indonesia Tbk (SBI) in Tritih Lor Village, Central Java, Indonesia

The information for this case study was provided by PT Solusi Bangun Indonesia Tbk (SBI) [76].

Table 10: Overview of the key data of the case study of cement producer PT Solusi Bangun Indonesia Tbk (SBI) in Tritih Lor Village in Java, Indonesia [76]

Project Summary	
Project owner	PT Solusi Bangun Indonesia Tbk (SBI) and Cilacap Regency Government
Location	Central Java, Indonesia
Industry / application	Cement production
Start of RDF use	2020
Type of RDF used	MSW
Capacity RDF use per year	18,564 tonnes per year
Operational model	- MSW collection by municipality - Pre-processing and co-processing by the private company SBI

Indonesian cement producer PT Solusi Bangun Indonesia Tbk. (SBI) – part of SIG, the largest building material company in Southeast Asia – began operating an RDF pre-processing plant in Central Java in July 2020. SBI operates four integrated cement plants, ready-mixed concrete batching plants, an aggregate business, as well as sustainable waste management services in Indonesia.

This project was the first RDF project in Indonesia – and represents a collaboration of several key stakeholders who made this flagship project a reality. The equipment was supported by the government of Denmark through the DANIDA Environment Support Program (ESP3). The Indonesian Ministry of Housing and Public Works provided the required infrastructure for the RDF pre-processing plant. The regional government from the city of Cilacap supplies access to the industrial land and is also responsible for the waste collection and delivery to the project site. The Central Java Provincial Government provided additional supporting facilities, while the cement producer SBI acted as the project initiator, operator and off-taker of the RDF fuel to burn it in its nearby cement plant. The project is also supported by the Indonesian Ministry of Environment and Forestry and the Indonesia National Planning Board. The RDF facility is owned by the Cilacap Regency government.

The waste is unloaded at the RDF pre-processing facility at the storage area, where informal waste pickers get the opportunity to search the waste for recyclables.

The pre-processing plant processes MSW waste using membrane biological drying to produce the RDF product. Currently 44,581 tonnes per year of MSW are processed to 18,564 tonnes of RDF fuel per year, which considerably reduces the landfill gate fees.

After the waste pickers have extracted the recyclable fractions from the storage area, waste is passing through a shredder to crush it to smaller pieces. After this step, the waste is transferred to the drying bay, where a biological drying process reduces the moisture content. Next step is a screening process, where three fractions are extracted. First, inert material unsuitable for combustion; second, the suitable fractions for RDF; and third, oversize material, which is passed back through the shredder and then mixed with the RDF production fraction.

The RDF has to fulfil the following quality specifications:

- Particle size: < 50mm
- Moisture content < 20%
- Ash content: between 10 – 20%
- NCV: 3,000 – 3,500 kcal/kg i.e., 12.5 – 14.6 MJ/kg
- Chlorine-content 0.2 – 0.4 %

The final RDF product is transported by truck to SBI's cement plant where it is introduced at the calciner feeding point for coal substitution, which is the primary fuel in the cement production process at this site. Currently, around 5 % of the total thermal energy demand for the clinker production is replaced by RDF and 2.5 million tonnes of clinker are produced per year at this SBI facility.

SBI maintains compliance with off-gas emission limits as shown in Table 11.

Table 11: Concentration limits for emission control in mg/Nm³ at the SBI cement plant [76]

Dust	SO_2	NO_x	F	Hg	NH_3
70	650	800	n.a	n.a	n.a

n.a. no information available

Figure 30 shows some images from the pre-processing facility. Figure 31 shows the co-processing plant.

Figure 30: MSW to RDF pre-processing facility in Tritih Lor Village in Java [76]

Figure 31: SBI co-processing facility [76]

Initial conclusions about the success factors and challenges of this first RDF project in Indonesia were drawn, noting the key challenge of the heterogeneity of MSW that considerably increases investment needs and operation costs for proper pre-processing. The close cooperation between all involved stakeholders like municipalities, operator, waste-pickers, off-takers, etc. was identified as key to the successful project implementation and operation. Smooth logistics for waste supply and for the final RDF product to the off-taker was identified as key to future successful projects of this type in Indonesia.

6.2.3 Case study RDF plant Tel Aviv, Israel

The information for this case study was provided by Hiriya Recycling Park RDF production [77].

Table 12: Overview of the key data of the case study of RDF plant in Tel Aviv, Israel [77]

Project Summary	
Project owner	Hiriya Recycling Park RDF production
Location	Tel Aviv, Israel
Industry / application	Cement production
Start of RDF use	2016
Type of RDF used	MSW & industrial waste
Capacity RDF use per year	Currently 110,000 tonnes per year. Soon 140,000 tonnes per year
Operational model	Agreement between municipalities, which deliver MSW and C&I waste, Veridis as owner of the RDF production facility and Nesher cement producer as RDF off-taker.

In 2016, the Israeli company Veridis Group (prev. Veolia) began operating one of the largest RDF pre-processing facilities in the world at the Hiriya Recycling Park in the outskirts of Tel Aviv. The project was realized by close cooperation between three entities: the Dan Municipal Sanitation Association, the Nesher Ramla cement factory and Veridis Group (prev. Veolia).

Veridis acts as a kind of subcontractor to the Dan association, which is an association of 15 municipalities in and around Tel Aviv, which delivers all the waste to the Recycling Park, where Veridis operates its pre-processing lines for RDF production. The municipalities deliver more than half a million tonnes waste directly to the site. The project configuration is organized as a kind of BOO Agreement, where Veridis designed, built, owns and operates the plant. This configuration is key to guarantee Veridis with a secured delivery of the waste in the long run. The only obligation from the Dan Municipal Association is to deliver the quantity of waste they need to operate the plant. The investment for the production was done mainly by Veridis, with some contribution for the infrastructure by the Dan Association. Important for the success of this project is also the close alliance with the cement producer Nesher, which guarantees also a secure off-taker for the final RDF product.

Figure 32 shows the Veridis RDF pre-processing facility at the Hiriya Recycling Park.

Figure 32: Veridis pre-processing facility, Hiriya Recycling Park, Israel [77]

540,000 tonnes per year of MSW must be delivered by DAN-region according to the current agreement. No waste separation at sources is implemented up to now in Israel and so all waste is unsorted. A packaging law was implemented in Israel recently, which has diverted some of the waste, but most waste is transported unsorted to the transfer station. From the received waste, around 80 % is MSW - the remaining 20 % is industrial and commercial waste. Originally 3 sorting lines for RDF production where installed, 1 line for dry waste, which is mainly the industrial and commercial waste, and 2 lines for processing the MSW.

At the beginning of the RDF pre-processing line, a shredder shreds the waste to a size of <300 mm because MSW in Israel contains a lot of bulky waste. Originally there were bag openers installed, but because of the bulky content in the MSW the bag openers were eventually replaced by large 2 tonne shredders supplied by Eggersmann, allowing the waste to be processed more efficiently. The second stage of the RDF line is the drum screen (Tromel), where organic waste is extracted. There are holes between 90 mm and 300 mm in the drum. All the organic waste below 90 mm goes to a compost site. All the waste between 90 mm and 300 mm enters the RDF production process. After the drum screen an air separator separates the light and heavy fractions. Only light fractions continue for the RDF processing and pass through a magnetic separator to extract potentially remaining metals to protect the subsequent equipment. The next step is the optical sorting machine, where materials suitable for RDF production are separated and pass through to a final shredder where the material is crushed to about 15 mm to 25 mm ready for its use. The unsuitable fraction goes to landfill.

The following diagram illustrates the RDF pre-processing process at the Hiriya Recycling Park (see Figure 33).

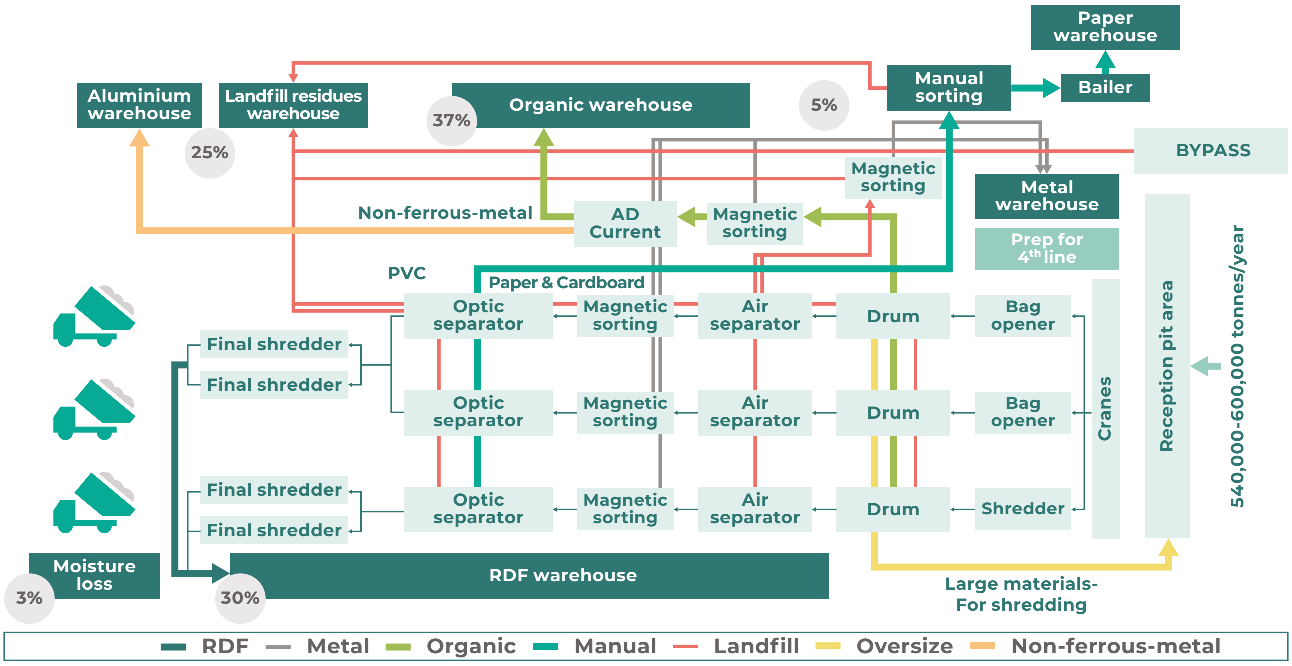

Figure 33: RDF pre-processing process at the Hiriya Recycling Park, Israel [77] (modified)

The RDF pre-processing facility has to comply with the emission limits summarized in Table 13.

Table 13: Emission limits for the RDF pre-processing facility at Hiriya Recycling Park [77]

Substance	emission limit
Particles	10 mg/m^3
Total Organic Carbon TOC	20 mg/m^3
Odours	500 OU/m^3

The cement producer Nesher picks up the RDF from the RDF bunker at the end of the production line. There is a long-term agreement with the cement producer Nesher in place, which requires them to consume at least 110,000 tonnes of this RDF fuel every year. Currently, Nesher receives the RDF fuel for free. The income of the project is generated by avoided landfill fees, which otherwise the municipalities would have to pay for landfilling the complete unprocessed waste.

At the co-processing facility the RDF replaces petcoke, which is used as primary fuel in the cement production process and introduced at the calciner feeding point. The substitution rate is around 2.5 tonnes of RDF are replacing about 1 tonne of petcoke. The average calorific value which is reached by the RDF is around 4,000 kcal/kg i.e., 16.7 MJ/kg. The moisture content is between 24 % and 26 %.

In 2022 a fourth RDF production line was added to the original 3; these 4 production lines will have the capacity to process around 700,000 tonnes of waste per year and produce 140,000 tonnes of RDF.

6.2.4 Case study Veolia RDF plant, Mexico

The information for this case study was provided by Veolia [78].

Table 14: Overview of the key data of the case study of the RDF plant in San Luis Potosi, Mexico [78]

Project Summary	
Project Name	RDF SAN LUIS POTOSÍ
Location	San Luis Potosí, Mexico
Project owner	Veolia
Industry/Application	Cement
Start of RDF use	2022
Type of RDF used	Industrial & commercial waste
Capacity RDF use per year	40,000 tonnes per year
Operational model	Veolia gets paid for the industrial waste treatment and charges the RDF off-taker for the RDF fuel delivery

In Mexico in 2022, Veolia started operations at the San Luis Potosí RDF pre-processing plant to produce fuel from industrial and commercial waste. Veolia has a long-term agreement with the Cement producer Cementos Moctezuma as off-taker of the RDF fuel to reduce GHG emissions at the cement plant. The project is aiming to process up to 40,000 tonnes of toxic and non-toxic wastes to RDF fuel. The typical waste which enters the pre-processing facilities are solvent, oil sludges, contaminated textiles tires among others. The production capacity of the pre-processing facility is incremental and will start with a processing capacity of around 2,100 tonnes per year in 2022, up to the final capacity of 40,000 tonnes in the fifth year of operation. The plant concept is designed to use all the combustible fractions of the waste to produce RDF, the non-combustible fractions are landfilled. Veolia is directly delivering the fuel to the cement plant where it is replacing coal as primary fuel in the cement production process. The main driver for RDF utilization in Mexico is its competitiveness regarding cost per GJ compared to traditional fuels like coal, fuel oil or petcoke.

The quality specifications which must be meet by Veolia for the RDF fuel are: NCV of at least 4,500 kcal/kg (appr. 19 MJ/kg), moisture content of maximum 11 % (weight) and a size specification of 95 % of the fuel < 40 mm. Because the Veolia plant is processing relatively dry industrial waste with high calorific values there is no problem to reach the quality specifications. Special caution is required with the handling and storage of this fuel with a relatively high calorific value. This is done by the installation of a modern fire extinguishing system to reduce incineration risk.

Veolia is using toxic and non-toxic waste which require special treatment. Veolia gets paid from industrial clients for the treatment of this waste by charging them a disposal fee. On the other hand, Veolia is charging Cementos Moctezuma for the delivery of the RDF fuel to its production facility. The main income stream is generated by the disposal fee from the waste generators. The price for the RDF fluctuates considerably with the price of primary fuels for cement plants and in Mexico as it is a large oil producing country, energy prices are in general low.

The distance between pre-processing and co-processing facilities is around 110 km, which is considered the limit for profitable operation of the project.

The planned project consists of two completely identical RDF production lines with a capacity of 7 tonnes per hour each. The first line started in 2022, the second line will be added in year 3 of the operation of the plant.

Figure 34 and Figure 35 show different views of the RDF pre-processing plant in San Luis Potosí, Mexico.

Figure 34: RDF pre-processing plant, exterior view, San Luis Potosí, Mexico [78]

Figure 35: RDF pre-processing plant, 1) interior view, 2) plant in operating conditions, San Luis Potosí, Mexico [78]


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7. Guidelines on environmental safeguards of waste management projects involving production of RDF

Production and utilisation of RDF is a technology that can fall on the spectrum between sustainable and non-sustainable practice. Ultimately, it is the *specific context* of the project and its way of implementation that defines whether RDF production and utilization can contribute to a more sustainable economic system as part of a circular economy. The purpose of this paper is to highlight general environmental and economic criteria that can guide decision-makers in identifying sustainable RDF projects within the context of developing economies. In doing so, it hopes to play a role in the development of an advanced and integrated waste management sector in countries where such practices are not yet established.

In Section 7.1 several 'Basic Sustainability' criteria have been defined which RDF projects should comply with to claim to be sustainable. In addition, 'Supplementary Sustainability' criteria are listed in the subsequent Section 7.2, which should also be considered as much as possible to enhance the sustainability of an RDF project.

7.1 "Basic Sustainability" criteria for sustainable RDF projects

The following criteria should all be fulfilled to indicate that an RDF project complies with high environmental standards and possesses comparably low or manageable economic risks – and can thereby be considered sustainable.

a) <u>Pre-treatment of raw waste streams</u> to prepare a fuel according to the need of the energy recovery facility utilizing the RDF

RDF projects should aim to optimize the energetic potential of the raw waste. This necessitates a tailor-made pre-treatment for any specific case. For an RDF off-taker the RDF is primarily evaluated as a fuel. Waste streams can be very heterogeneous, which asks for pre-treatment steps to produce a uniform quality RDF. There are technologies available for example at cement works that do have lower requirements for fuel related quality specifications of the RDF, however, this involves high investments at the RDF recovery facility, for example for Hot-Disc or Pyro-Rotor installations.

Pollutant related quality specifications of the RDF need to be safeguarded either by ensuring that hazardous waste is collected separately from MSW beforehand or by respective processing steps in an RDF processing plant.

b) Sorting capability for recyclables in order to allow maximization of recycling

To comply with waste management priorities and make use of the resource potential in waste, the RDF production plant must be designed and operated such that recyclables can be recovered to a high degree.

c) Constant quality control of the produced RDF for safeguarding output product quality and ensuring market value

To avoid any technological, operational, or environmental risk, a quality assurance system must be in place to monitor the RDF quality. The RDF producer needs to monitor and document the RDF quality for market reasons and also to document that off-taker quality specifications are met. The definition of such quality specifications is key before setting up an RDF production plant to ensure the appropriate plant design. It is likewise needed to make sure that the waste input mix to the RDF processing facility is of sufficient quality to allow for a high enough yield of RDF of the respective quality.

The potential quality implications of newly identified waste streams need to be identified before the stream is accepted as input into the RDF production process.

d) Emission control and emission monitoring must be in place at the RDF-recovery facility

Emissions must be constantly controlled to make sure that national emission standards, as well as the plant operator’s policy and directives are met. Emission control is also a control mechanism for the reliability of the quality control of the input materials. If there is no sufficient proof of acceptable emissions at the RDF recovery stage, there is a risk that due to inappropriate RDF specifications or bad operation of the recovery plant RDF will cause inacceptable emissions to the atmosphere.

The emission of dust, Total Organic Carbon (TOC), HCl, HF, SO_2, NO_x and heavy metals (Hg, Cd, Tl, Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V) must be checked by a discontinuous measurement frequently, PCDD/F should be measured at least once a year.

At the RDF processing facility, emissions like dust and odour need to be taken care of by respective operational measures.

e) Monitoring of product quality or quality of solid residues must be in place at the RDF-recovery facility

Potential impacts of the RDF on the quality of the product need to be monitored. It must be made sure that the product is not a sink for heavy metals. For that reason, the following should be analysed in the product before and during the utilization of RDF at least once a year: concentrations of Sb, As, Pb, Cd, Cr, Co, Ni, Hg, Tl.

In settings where no product is produced, and solid residues result from the energy recovery from RDF, the qualities of the fly ash, bottom ash or any other solid residue need to be monitored to make sure that these residues can be disposed of according to the regulatory requirements.

Frequent monitoring provides visibility on whether the energy recovery from RDF has an impact on the quality of solid residues.

f) Close cooperation with public (municipality) and / or private and informal (waste collector) actors to integrate the project in the local context and to get support from all stakeholders involved

Waste management projects quite often receive strong rejection from local communities or other stakeholders. It is therefore of utmost importance to involve from a very early stage and with high transparency the public, private and informal stakeholders that are affected by the project to allow an open discussion about the project and to develop a viable overall concept.

This allows the project to be adapted and inserted into the local context, which makes it easier to get support from all involved stakeholders. A formal engagement plan for stakeholder communication should be in place and this should include the informal sector.

g) Long term waste supply needs to be secured to guarantee the economic sustainability of the project

WtE projects are characterized by high investment needs and long financial payback times. For an economically sustainable project, it is therefore essential that long term contracts for waste supply are secured to mitigate financial risks. The risk of changes in legislative framework that could result in alternative diversion and use of waste must be considered and mitigated in these agreements.

h) Agreement with RDF off-takers

The economic success of an RDF production facility very much depends on the marketing of the RDF produced. The economic risk can be mitigated by long-term agreements with off-takers which also should define the quality of the RDF to be delivered. In case the RDF production plant is capable to produce different qualities of RDF, the range of potential off-takers can be expanded and thereby also the economic risk can be mitigated.

Sufficient storage capacities can address variations in RDF demand and are thereby considered as an important measure to reduce the economic risk related to external factors in RDF marketing.

i) Waste hierarchy thoroughly considered to avoid lock-in effects which could prevent an integrated waste management system

Waste management projects involving the production of RDF by no means should obstruct the implementation of an integrated waste management system following the waste hierarchy of prevention, reuse, recycling, energy recovery and final disposal. That is why the use of RDF should always be seen as a complementary part of an integrated waste management system and should not lead to a situation where WtE is preventing the implementation of solutions ranking higher up the waste hierarchy. If recycling solutions are at hand and implemented RDF should be limited to the non-recyclable, otherwise landfilled, waste fraction and not lead to a technological lock-in effect by avoiding the development of adequate waste management systems. This can be secured by obliging the operator of the RDF processing plant as well as the operator of the RDF recovery plant to invest into public awareness raising campaigns that focus waste avoidance, reuse, (separate) waste collection and recycling of waste and thereby to contribute to the evolution of a waste sector according to the priorities set down in the waste hierarchy.

j) Robust plant design of the RDF processing facility

As input waste composition and RDF specifications might change over time, it is of utmost importance that the plant setup for the RDF processing facility is robust and enables the processing of varying waste qualities and allows for later-on adaptations.

k) Safety risks must be considered for waste collection, logistics, processing, storage, handling, and use of RDF

The complete value chain of RDF projects (comprising the different collection systems for specific waste streams, logistics, pre-processing plant, processing of the waste as well the storage and transport to the final off-taker) should consider safety risks and emergency planning and preferably comply with specific international standards like ISO/TR 21916:2021 [7].

l) Use of Best Available Techniques for RDF production and utilization

Contributing to the achievement of the UN SDG´s requires an industrial development with state-of-the-art technology. Therefore, Best Available Techniques (BAT) for the specific use case, as defined in the so-called BAT documents of the Sevilla process should be used, to guarantee an environmental sound and reliable operation of the pre-processing and co-processing facilities.

m) Plant manufacturer has a proven track record in the design, engineering, and construction of similar infrastructure projects

RDF pre- & post-processing in industrial installations are technologically challenging. High investment needs result in high financial risks. To make sure that RDF projects are well planned, designed and implemented, experienced engineering and manufacturing companies should be involved. Inexperienced technological partners increase the chances of project failure or may increase costs considerably.

7.2 “Supplementary Sustainability” criteria for sustainable RDF projects

Additional success factors for RDF Projects may need to be considered to deliver a project with a high sustainability performance. Depending on the project context, different factors may apply.

a) **Proven climate mitigation effect** by reducing GHG emissions

The use of RDF fuels should result in a reduction of GHG emissions compared to the baseline. Due to varying RDF fuel qualities and fuel composition this is not always guaranteed. Less efficient combustion processes could require higher volumes of fuel and depending on the biogenic fraction varying amounts of carbon emissions can be considered as climate neutral. Emissions from waste processing and logistics as well as appropriate disposal measures for residues from RDF processing must also be accounted for. That is why a GHG inventory for a specific project should be elaborated according to international GHG accounting standards like the Intergovernmental Panel on Climate Change (IPCC) or GHG Protocol. Such GHG accounting should include the complete production and use of RDF fuels and consider for example also a comparison with avoided methane emissions from landfilling.

b) **Traceability of waste input** during the pre-and co-processing from reception up to final usage should be possible

In case the RDF produced does not comply with pre-set RDF standards it is important to be able to go back and identify the origin of the waste. To facilitate exclusion of pollutant bearing waste streams or to execute awareness raising measures, it is important to be able to trace back to the waste origin.

c) Make sure that **RDF processing and utilization is part of the regional waste management plan**

Project developers and investors should make sure that the proposed project is considered by local authorities as part of the overall regional waste management plan.

List of Abbreviations

AF	Alternative Fuel
AFR	Alternative Fuel & Raw Materials
AMS	Accelerator mass spectrometry (AMS) is a form of mass spectrometry that accelerates ions to extraordinarily high kinetic energies before mass analysis.
ar	as received
BAT	Best Available Techniques as defined by the European IPPC Bureau within the Institute for Prospective Technological Studies of the European Commissions‘ Joint Research Centre in Seville/Spain. BAT for specific industries which are subject to the IPPC directive resp. its successor directive the Industrial Emissions Directive 2010/75/EU are defined in „Adopted Documents“ to be found at https://eippcb.jrc.ec.europa.eu/reference/
BGS e.V.	Bundesgütegemeinschaft Sekundärbrennstoffe und Recyclingholz e.V. (German Federal Quality Association for Secondary Fuels and Recycled Wood e.V.)
BOO	Build - Own – Operate; a project delivery mechanism in which a government entity sells to a private sector party the right to construct a project according to agreed design specifications and to operate the project for a specified time.
CAPEX	Capital Expenditure
CHNSO	Elemental analysis of C, H, N, S and O
CHP	Combined Heat & Power technology
CRDF	Carbonized Refuse-Derived Fuel
DDP	Delivery Duty Paid
DFI	Development Financing Institution
dm	dry matter
EBS / SBS	Ersatzbrennstoff / Sekundärbrennstoff (German translation for substitute fuel)
EfW	Energy-from-Waste
GHG	Greenhouse Gas
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
IUCN	International Union for the Conservation of Nature
KPI	Key Performance Indicator
LHV	Lower Heating Value
MBM	Meat and Bone Meal
MBT	Mechanical and Biological Treatment
MRF	Material Recovery Facility

MSW	Municipal Solid Waste
MTF	Mechanical Treatment Facility
NCV	Net Calorific Value
NIR	Near Infrared Sorting
OPEX	Operational Expenditure
ORF	Organic Recovery Facility
OU	odour units
PCB	Polychlorinated Biphenyl
PCT	Polychlorinated Terphenyl
PEF	Processed Engineered Fuel
pMC	"Percent Modern Carbon" as calculated against a reference sample of ^{14}C activity from a known standard
POP	Persistent Organic Pollutants
PPP	Public Private Partnership
RDF	Refuse Derived Fuel
RPF	Refuse Plastic Fuel (South Korea); Refuse derived paper and plastics densified fuel (Japan)
SBS	Substitut-Brennstoff (German translation for substitute fuel)
SCF	Subnational Climate Fund
SCF	Segregated combustible fractions (India)
SPL	Spent potliner
SS	Sewage sludge
SRF	Solid Recovered Fuel
TF	Transfer Factor
WRAP	Waste and Resources Action Programme (United Kingdom)
WDF	Waste Derived Fuel
WtE	Waste-to-Energy

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SCF

The Subnational Climate Fund (SCF) is a global blended finance initiative that aims to invest in and scale mid-sized (5 – 75 M $USD) subnational infrastructure projects in the fields of sustainable energy, waste and sanitation, regenerative agriculture and nature-based solutions in developing countries.

The SCF finances projects with a blend of concessional and conventional capital, along with Technical Assistance grants that help mitigate risk and ensure financial and environmental goals are achieved.

For further information about the SCF, visit: www.subnational.finance