Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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Refuse Derived Fuels (RDF) and Solid Recovered Fuels (SRF)

A case study of characteristics and opportunities

Master's thesis in Global Manufacturing Management
Supervisor: Jan Ola Strandhagen
June 2023

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Abstract

Refuse Derived Fuels (RDF) and Solid Recovered Fuels (SRF) are two types of solid fuel processed from waste whose purpose is to recover unrecycled waste by producing a substitute to fossil fuels for industries. Orkel is a Norwegian company which produces compactors for the agriculture and the industry in general.

The purpose of this document is to conduct an analysis of the global value chain of SRF/RDF, then to evaluate and assess the role that Orkel's logistics solutions can play. The research is based on a literature study on the RDF/SRF product and market characteristics, followed by an operation analysis of Orkel. Based on these objectives, the research questions are:

- R.Q.1: Which key parameters define the industrial context of Refuse Derived Fuels and Solid Recovered Fuels across markets?
- R.Q.2: Which relationship exist between baling solutions and the RDF/SRF industry developments?

In order to answer these questions, the research consists in exploring 3 fields: literature review on industry developments, a quantitative case study on RDF sector potential developments by region and countries, a case study on the specific relationship between the findings of these chapters and baling technologies.

The study will focus on 6 main findings.

- The composition, highly variable, is determined mainly by waste feedstock nature, country of origin, an end-use intended.
- 5 main end-use sectors have been identified: cement, lime, coal power plants, steel industry, gasification/pyrolysis.
- The main factor influencing the industry developments are regulatory (landfill bans/taxes, gate fees, taxes on combustion), influencing heavily the cost of RDF.
- 39 countries were identified in the RDF literature, and further categorized in 3 groups, according to their advancement on the industry development steps.
- Baling technologies show signs of being relevant in every RDF industry, even more where international trade is important.
- 3 main potential clusters for international RDF trade in the next years have been identified.

Keywords: SRF, Solid Recovered Fuels, RDF, Refuse Derived Fuels, Market characteristics, Product characteristics, Waste recovery, Supply chain, Value chain.

Preface

This project was conducted as a part of the specialization course TPK4430 “Production management and logistics”, within the Production Management group of the department of Mechanical and Industrial Engineering (*Institutt for maskinteknikk og produksjon* or MTP) at NTNU.

First and foremost, I would like to thank my supervisor, Jan Ola Strandhagen. He made me enter in contact with Orkel and contributed greatly to my growing interest in logistics serving circular economy purposes. Throughout these months of research, he provided guidance and support, that paved the road to this thesis.

I would like to thank Miriam Gjønnes Karterud and Gjermund Kambestad, my contacts at Orkel for welcoming me at their company and providing continuous guidelines. They have always been extremely welcoming, and their view on sustainable business inspired my academic and professional development.

Furthermore, I extend my thanks to the fellow students who have assured the role, day after day, of advisors, psychologists, role models, but most importantly, friends. It has been an invaluable chance to share so many, yet so few days with these people, and I know that I will thrive to maintain the friendships that I have built with them during these two years at NTNU.

Last, but not least, I would like to express my deepest thanks to my family, who, despite the distance, showed an unwavering support. Their impact on my academic and personal growth is immeasurable, and I believe they play the greatest role in not only this master thesis, but my professional achievements as a whole. Once again, thanks.

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List of acronyms

List of abbreviations in alphabetic order:

- ADEME: French Agency for Environment and Energy Control (translated from *“Agence De l’Environnement et de la Maîtrise de l’Energie”)*
- ASTM: American Society for Testing and Materials
- B2B: Business-to-Business
- BGS e. V.: German Quality Association for Secondary Fuels and Recycling Wood (translated from “*Die Gütegemeinschaft Sekundärbrennstoffe und Recyclingholz e. V”*)
- CDW: Construction & Demolition Waste
- CEN: European Committee for Standardisation
- CSV: Creating Shared Value
- EEA: European Environment Agency
- ETO: Engineering-To-Order
- GDP: Gross Domestic Product
- GHG: Greenhouse Gas
- IEA: International Energy Agency
- ICIW: Industrial, Commercial & Institutional Waste
- ISO: International Organisation for Standardization
- MBT: Mechanical Biological Treatment
- MT: Mechanical Treatment
- MSW: Municipal Solid Waste
- MTO: Make-To-Order
- MTS: Make-To-Stock
- NCV: Net Calorific Value
- NTNU: Norwegian University of Science and Technology
- USGS: U.S. Geological Survey
- RDF: Refuse Derived Fuel
- SRF: Solid Recovered Fuel
- WTE: Waste-to-Energy

1. Introduction

1.1. Waste-to-Energy, RDF, SRF

The systems of production and consumption as we know them need to be fundamentally transformed, as assessed the European Environment Agency in 2016 (EEA, 2016). This statement originates from the acknowledgment that the World Gross Domestic Product (GDP) has increased 25-fold since 1900, resulting in a tenfold increase in terms of global resource extraction (Krausmann et al., 2009). As we are living in a world with limited resources available, there is a need to limit their use while ensuring development. Considering that communities aim to increase well-being while keeping consumption and production level in development, it is defined by a resource use increasing at a lesser rate than GDP, perhaps even decreasing. The main tool to achieve such result is innovation, driven by a shift in the way of thinking growth (EEA, 2016).

Circular economy is a concept that has emerged in the last decades within this framework. According to the European Commission, it can be defined as "*a model in which products and materials are designed in such a way that they can be reused, remanufactured, recycled or recovered and thus maintained in the economy for as long as possible*" (European Commission, 2020). The "*Reused/Remanufactured/Recycled*" (or "3R") notion, illustrates quite well the circular economy paradigm: each of these processes leads to savings in materials and energy use (European Commission, 2011; Meyer, 2012), with more savings in reuse than in remanufacturing, and more in remanufacturing than in recycling.

A significant aspect of circular economy is how are considered materials. In a usual, linear supply chain, materials flow from extraction through manufacturing, distribution, use and disposal. At this last stage they are considered as waste because they are "*useless, unneeded or excess to requirements*" (Robinson & Davidson, 1999). Waste has for long been considered a negatively connoted materials, but in the few last decades, research has started to consider it as a resource in various fields: food industry (O'Brien, 2012), wood industry (Falk, 1997), plastic industry (Drain et al., 1981) have been addressing challenges and opportunities of waste recovery. Within this philosophy, Dijkema et al. (2000) proposed a new nomenclature for waste: *"an emerged quality of a substance or object"*, i.e., the material being considered as a waste only when it is "emerged", or excluded from the production loop. Therefore, according to this definition, waste can only be considered as a labelling put on a resource under specific conditions.

Waste can be sorted using several methods: by origin, by composition or by handling method (World Bank, 2012). In a logistics' analysis, the classification by origin is useful to operate in first place, in order to qualify the flows of the upstream supply chain. There is no worldwide consensus on classification of waste, because it depends greatly on what is dealt by the municipalities and what is left to the companies to deal with (Gregson & Crang, 2015). However, the world bank is providing definitions that fits most of the research related to the waste-derived fuel literature, particularly the sources cited in the present document (World Bank, 2012). This classification will be used in the rest of this research.

First, waste can be divided into 3 groups: radioactive, hazardous (likely to cause danger to health or environment), and non-hazardous (LaGrega et al., 2001*)*. This study will focus on non-hazardous waste. 4 categories are commonly agreed upon (World Bank, 2012)

- ICIW (*Industrial, Commercial and Institutional Waste*). Industrial waste can be generated from manufacturing, fabrication, power and chemical plants. Commercial waste can be generated from stores, hotels, restaurants, markets, office buildings. Institutional waste can be generated from schools, hospital (non-medical share), prisons, government buildings, airports. These three types of waste are often gathered into the ICIW category.
- CDW (*Construction and Demolition Waste*) can be generated by new construction sites, road repair, renovation sites, demolition of buildings.
- MSW (*Municipal Solid Waste*) is the waste that is handled by municipalities, and usually encompasses residential (dwellings) and municipal waste (street cleaning, landscaping). Although ICIW is often grouped into it, keeping it separated for the rest of the research will help to keep the analysis as detailed as possible. Most of the research focuses on this type of waste, therefore the thesis is mainly focused on it.
- Agricultural waste can be generated by crops, orchards, vineyards, dairies, feedlots, farms. It is the fraction of the agro-industrial waste that cannot be sent to ICIW. They are usually dumped, landfilled or incinerated on dedicated locations, so they are excluded from regular waste handling processes (Sadh et al., 2018).

The various waste types introduced to this point are schematized in **Figure 1**.

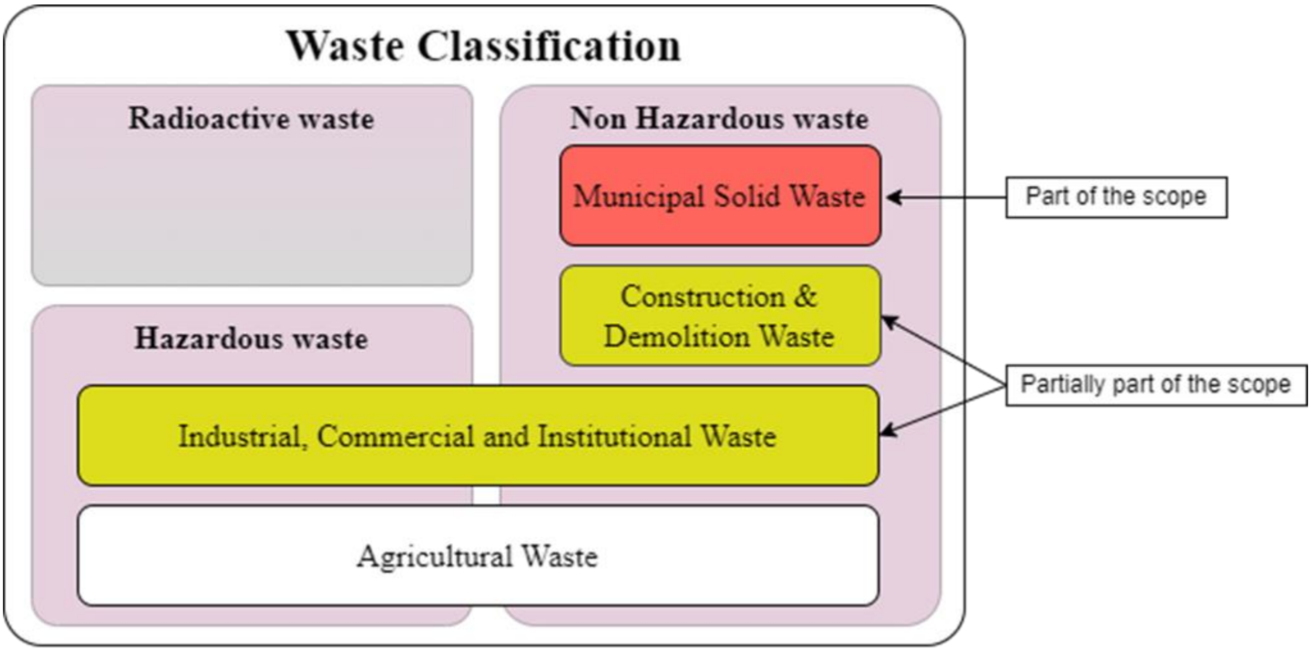


Figure 1: Waste classification

In developed countries, there are usually four types of waste treatment: recycling, composting, incinerating, landfilling. Recycling and composting are considered the most sustainable solutions, while incineration and landfilling's impact depend greatly on the techniques used (whether energy recovery is part of the process of incineration, and whether the landfill gases are burned to reduce the GHG emissions). However, countries with middle and low income ranges still have a significant part of their waste that is sent to open dumps or even not collected (World Bank, 2012). This thesis focuses on waste incineration (**Figure 2**).

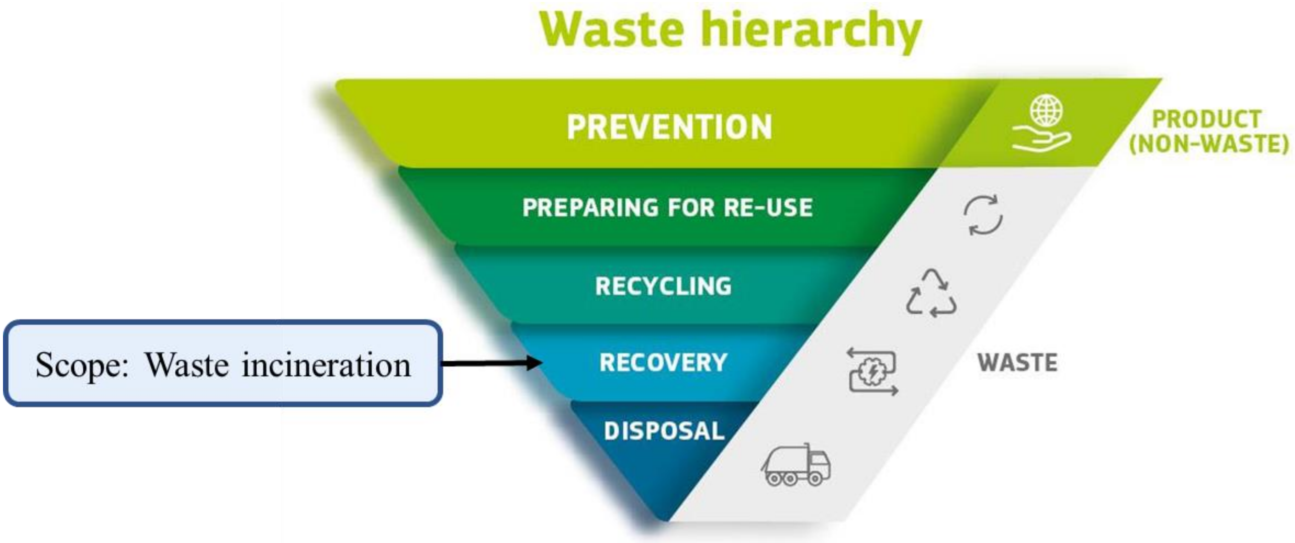


*Figure 2: Waste incineration within waste hierarchy (adapted from (*European Commission, 2020*))*

Refuse Derived Fuel (RDF) is a waste that is used for the purpose of energy generation and satisfies the quality requirement related to its use, particularly a high calorific value, which represents the amount of heat released during combustion (IEA, 2020a; Sarc et al., 2016; Velis et al., 2010). Proof of combusting waste-derived products date back to 1876, when a power plants in England used it to generate steam. It was later adopted in the United States, Germany and Japan, noticeably. However, the waste management issue was addressed in most of the 20th century by dumping, then landfills, for economic reasons (Alter, 1987). In the 1970s, simultaneous US regulations on dumps closing, landfills use reduction, and cleaner incineration technics development were meant to reduce the environmental impact of the industry. This led to emphasis on research for more processed waste in the US: RDF was mentioned for the first time (waste management approach). The oil embargo in 1973-1974 urged Europe and Japan to inquire about these technologies and launch development programs (Alter, 1987). The waste-to-energy business has shown several trends of enthusiasm and crises over history, noticeably because effort and expertise must be given to make engineering alternations and create suitable plants: "*In the beginning of any new technology or industry, too much is taken for granted; an evolving technology cannot be perfect the first time*" (Alter, 1987).

Modern RDF is usually processed from the non-hazardous fractions of MSW, ICIW or CDW (IEA, 2020a; Sarc et al., 2016). It has high calorific value, and contains mostly paper, plastics, textile and wood (Garg et al., 2009). Most recently, RDF has been used continuously in European and Japanese industries since the years 1990s, with a purpose to supply energy to cement kilns, and heating/electricity networks. Comparing to fossil fuels, availability of supply is potentially more secured, while combustion-related emissions are considered lower. However, the high variability of feedstock composition results in a fuel whose quality is complicated to ensure and keep steady overtime (IEA, 2020a; Rada & Andreottola, 2012).

Solid Recovered Fuel (SRF) is a solid fuel, part of the RDF family. It has been processed, homogenized, and improved to a quality that can be traded between producers and users for use in incineration or co-incineration plants for energy recovery (Rada & Andreottola, 2012). The main advantage compared to RDF is its quality insurance. SRF usually describes high quality fuels, that have been more processed than RDF. National and international (ISO TC/300) regulations have been created in the recent years in order to furthermore ensure quality and trust in SRF as a reliable option for end-users.

In the waste management literature, the term "*gate fee*" is often used to refer to the amount of money a waste-dealer actor must pay to deliver waste to another actor downstream of the supply chain. It can be though as a system where "*the producer pays to user"*.

1.2. Orkel, a major actor of waste compacting and baling

Orkel is a Norwegian medium-sized business based in Fannrem, close to Trondheim, which produces industrial compactors for the agriculture and the industry in general. The "*industrial*" segment units have been produced since 2017 and are designed to handle waste (**Figure 3**). Their technology helps to ensure more seamless storing and transportation of goods, noticeably by baling and wrapping (ORKEL AS, 2022).

Figure 3: A "Hi-X", one of Orkel industrial compactor-balers (Orkel AS, 2022)

Orkel has successfully proven the development opportunities of compacting RDF in Great Britain, noticeably for customers willing to export abroad this waste. Since then, through constant increase in sales, and through positive feedback from their customers, there are hints of a potential good strategic fit between their products, and the characteristics of the targeted markets. Furthermore, the growing environmental concern and the difficulty of supply of fossil fuels are expected to boost the development of alternative fuels, hence the growth of the whole market of which Orkel could take part. However, there are as many different challenges to produce, process, and move SRF/RDF as there are countries, states or even municipalities. As SRF has been standardized at an international scale only recently (CEN, 2006), the roles of each actor of the supply chain are still unclear. Furthermore, technical, and bureaucratic readiness levels of using SRF/RDF instead of fossil fuel are still inequal across industries. Therefore, technical, and legal levers would need to be pulled to allow a seamless implementation.

The goal of Orkel is to implement its unit in the supply chain of RDF/SRF. In order to shape a supply chain, it is useful to characterize markets and products (Mattsson & Jonsson, 2003; Semini et al., 2004; Wänström & Jonsson, 2006). There is therefore an interest in studying the RDF industry on one hand, and Orkel's product on the other hand, as well whether a fit between both notions could exist.

1.3. Thesis motivation: industry study as a tool for the development of an innovative product

Fisher (1997) designed a matrix to characterize products in order to design appropriate supply chains. According to this tool, the machines produced by Orkel belong to the "*innovative*" category, defined by high product variety, high margin and demand difficult to forecast precisely. As opposed to "*functional*" products, such as grocery store items, which face severe competition and low margins, innovative products introduce new designs or new functions, allowing to reach new market segments. However, this comes at cost of demand variability, and often reduced product life cycle – as innovation drives past products obsolescence.

Fisher recommends building market-responsive supply chains for innovative products, using three tools: avoiding, hedging, and reducing against demand uncertainty. In the past few years, Orkel has managed to avoid uncertainty by cutting their lead times. Uncertainty has also been avoided by increasing flexibility: the production process was shifted from Make-To-Stock (*MTS*) to a mix of Assemble-To-Order (*ATO*) and Make-To-Order (*MTO*). Hedging against uncertainty is achieved thanks to nationally located suppliers, with whom information on production schedule and orders is shared (Oldebråten, 2017). Orkel also strives to reduce uncertainty by sharing standardized components for most of the production process, so that the demand for components becomes more predictable. In this framework, Fisher describes another tool to reduce demand uncertainty: *"finding sources of new data that can serve as leading indicators"*. In this concept lies an important driver for this thesis: an innovative product can use information such as market characteristics and trends to achieve a more responsive supply chain.

Innovative product often follows a list of given states throughout their life cycle (De Wit, 2020; Porter, 1980): introduction, growth, maturity and decline. Several indicators show that Orkel's industrial compactors is located between the introduction and growth steps (**Figure 4)**. Indeed, industrial compactors have the characteristics of a newly introduced product (high skilled labour content, few competitors, high margins) while developing aspects of growing product (increased product quality, significant exports). When entering the growth phase, the potential market evolves, as buyer groups get wider (De Wit, 2020). This hypothesis drives another motivation for this thesis, as characterising the market is not only a process-related need, but also a business strategy key-element.

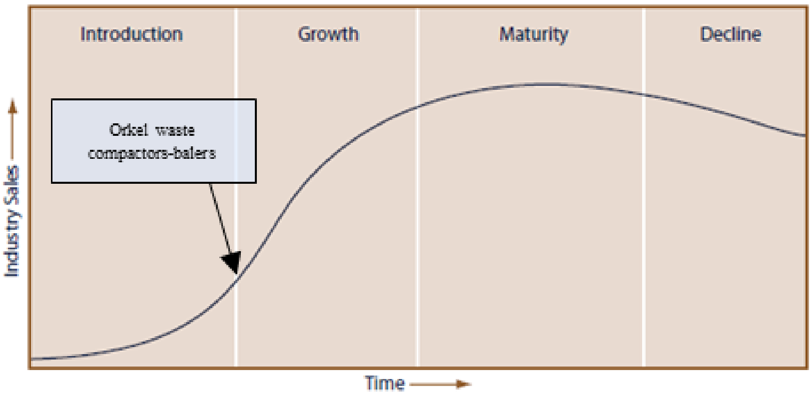


Figure 4: Stages of a product life cycle, de Wit (2017)

1.4. Research objectives

1.4.1. Problem statement

Through its sales and information channels, Orkel perceives that the RDF and SRF show signs of potential growth, which is assumed to impact the evolution of the waste baling market.

Characterizing the RDF/SRF industry is of a great importance for Orkel, as it can help the company shaping its business strategy, influencing many business units such as its manufacturing process. Furthermore, a product in the "growth" phase, in order to succeed, must fit with the market context.

On a more general basis, RDF and SRF lack a consensus on product definition, mainly because of its ambiguous status of simultaneous waste and fuel. In order to support the development of this resource, an analysis of industry current and potential development can be of great help.

1.4.2. Scope

The scope of this research is determined along 3 dimensions: vertical scope, horizontal scope, international scope.

The vertical scope represents the activities performed along the value chain. The vertical scope of this study includes waste collection, transportation to treatment facilities, treatment into RDF/SRF, distribution to end-users, and utilization. A particular emphasis is placed on RDF production, which corresponds to the step where most baling is involved.

The horizontal scope represents business segments involved. Upstream of the value chain, the horizontal scope of this study involves RDF and SRF prepared from non-hazardous waste, MSW mostly, with some study of other feedstocks such as CDW and ICIW. To a lesser extent, agricultural waste is mentioned. Downstream of the value chain, the scope explores end-uses of various kinds:

- Usual end-uses (cement industry, coal power plants, dedicated combustion)
- Potential end-uses (lime industry, steel industry, gasification/pyrolysis).

Because RDF and SRF can be produced from waste, potentially any country can become a producer of this resource. The international scope studies countries that have shown research and/or practical use of RDF/SRF. These are mainly countries of high-income levels (OECD), and middle-income levels (particularly in Asia and in the Middle East).

1.4.3. Research objectives and research questions

The hypothesis that is used as the foundation for this thesis is that the RDF/SRF sector is going to grow in the next few years. An important research objective is to find elements to support or disprove this hypothesis. A further goal is to identify the existence of different trends across regions of countries. Another objective is to determine how beneficial this development could be to Orkel through its compacting-baling solutions. In order to make decisions on where and how to implement their solutions, a strategic analysis can be done, using several different tools. Throughout the literature study, the subject was changed to be oriented towards describing the industrial context of RDF/SRF. Therefore, the main focus of this project is to determine how industry development takes place in this sector, how can Orkel influence this industry, and to what extent would this context dictate a particular type of behaviour.

Based on the main objectives of research, research questions can be formulated. They will define the purpose of the study, and which problematics it seeks to answer to. The research questions of this thesis are:

- **RQ1: Which key parameters define the industrial context of RDF and SRF across markets?**
- **RQ2: Which relationship exist between baling solutions and the RDF/SRF industry developments?**

1.5. Thesis structure

Chapter **3** is a literature review on how RDF and SRF industry develop. In paragraph **3.1**, the study deals with the product characteristics, noticeably on how standards change the status of a product that can have many various natures, by enabling a shared nomenclature based on quality criteria relevant for their end-uses. In paragraph **3.2**, a description of the five actor groups influencing the industry development is given, following Porter's five forces: waste suppliers, RDF producers, RDF buyers, substitutes/complementors, and the threat of new entrants. Paragraph **3.3** highlights the four types of underlying factors that also influence the industry development: economic, political/regulatory, technological, and socio-cultural drivers. Finally, paragraph **3.4** analyses the trends of the industry development, along six specific dimensions.

Chapter **4** consists in a multi-case study of RDF current and potential industry state. Paragraph **4.1** presents the potential RDF production volumes for 7 country groups, mainly gathered by geographical regions (except the OECD). Paragraph **4.2** highlights the current production volumes of all the countries identified in the literature review and assesses the potential for development based on waste volumes, and importance of the end-use industries.

Chapter **5** explores the relationship between baling operations and the RDF industry developments identified in the previous chapters. Paragraph **5.1** describes Orkel's operations from a manufacturing point of view. Paragraph **5.2** identified that baling solutions are tightly linked to the evolution of RDF international trade, after that 5 potential clusters for RDF trade are identified. Paragraph **5.3** shows how, to a lesser extent, the RDF industry expansion can be beneficial to baling even without long transportation.

The extent to which each chapter answers to the research questions is displayed in **Figure 5**

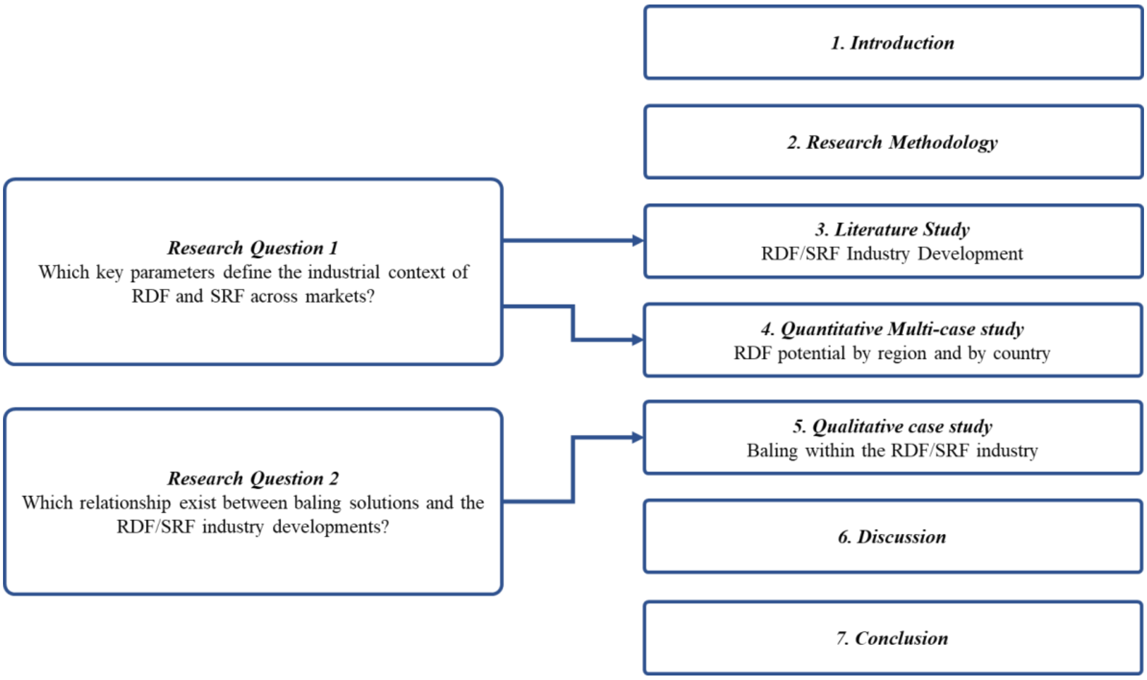


Figure 5: Relationship between the research questions and the thesis structure

2. Research methodology

Throughout the research conducted for this thesis, internet browsers and AI browsers such as ChatGPT and Bing Chat were used in order to extract definitions, understand new subjects and provide examples. These tools helped to structure the research, an get a grasp of notions before exploring the literature.

2.1. Literature study

The literature study conducted for this research was focused on grasping an overall definition of RDF and SRF, throughout diverse perspectives (technical, legislative, economical) and its evolution in the last few years. For the research, online databases – mainly Scopus and Google Scholar – were used. The usual search protocol would deal with article titles, abstracts and keywords. The following queries were identified and used to find relevant research materials related to waste in general, RDF and SRF:

- “Waste management”,
- “Waste” AND “Resource”,
- “Waste” AND “Classification”,
- “RDF” OR “SRF”,
- “Refuse Derive Fuel” OR “Solid Recovery Fuel”,
- “RDF” OR “SRF” AND “Legislation”,
- “RDF” OR “SRF” AND “Classification”,
- “RDF” OR “SRF” AND “Value chain”.

The keywords listed above were replaced by synonyms or declination in similar research queries. Additionally, other queries were made with more advanced criteria such as country affiliation, and publication date. The volume of material found was relatively large, but thanks to a number of literature reviews, especially from independent or governmental organisms (EEA, IEA, ISO, United Nations, European Commission), a clear understanding of the main concepts was possible.

A literature review was conducted with the query (“Refuse Derived Fuel” OR “Secondary Recovered Fuel”) and returned the following results. **Figure 6** shows the amount of document found per year from 1970 to 2021, 1970 being the oldest date available on in database. There is an increase in academic work between 1975 and 1988, which can be explained by the environmental regulations in the US and the effect of the oil crisis in 1973, and energy crisis in 1979, especially for European countries and Japan, as explained in the introduction. The current resurgence of academic emphasis started around 2000. This date suggests an impact, once again, of environmental regulations, as well as a novel increase in energy prices and accessibility.

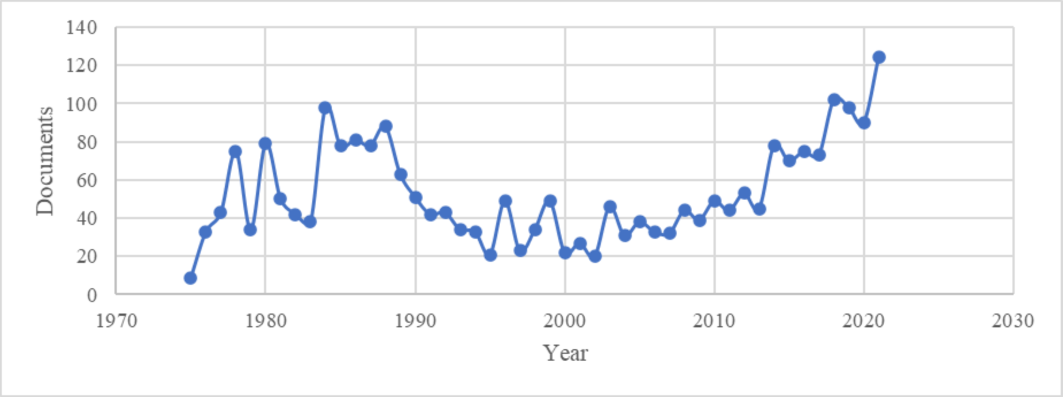


Figure 6: Number of documents per year (1970-2021)

When it comes to regions and countries from which originate the most documents published between 2000 and 2021, two categories seem to emerge (**Figure 7**):

- High-income countries with stricter environmental regulations and/or fossil fuel availability risks: U.S., Germany, Italy, Poland, UK
- Developing countries with densely populated areas and growing energy needs: China, India, Thailand, Indonesia

These two categories will be later confirmed with the case study conducted in chapter **4**

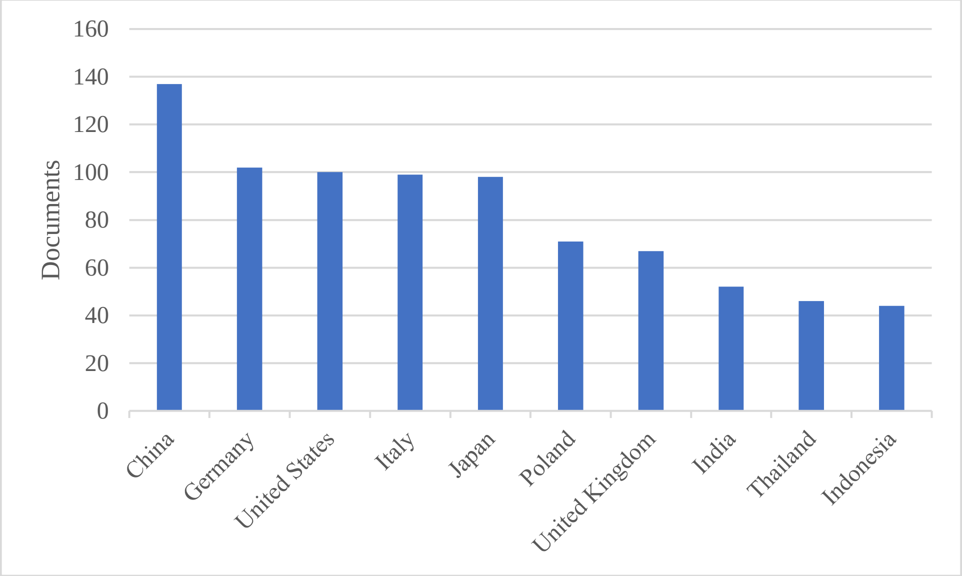


Figure 7: The 10 countries affiliated with the most documents published, 2000-2021

2.2. Quantitative multi-case study

2.2.1. Source for data used

Most of the data used has been gathered from open data sets available online (from the OECD, the USGS, the IEA, etc), especially for waste production, as well as production of end-use products. For current RDF production proofs and production volumes, the main sources were journal articles encountered throughout the literature review.

2.2.2. RDF potential production calculations

Plastic and paper are the main fractions of waste used for manufacturing RDF (paragraph **3.1.3**). Various shares of these fractions are found according to the region, leading to various yields from MSW to RDF:

- High income countries: 50% is observed in Western Europe (De Caevel et al., 2018; Garg et al., 2007). The highest income countries, such as Finland, even achieve 72% (see paragraph **3.1.3**).
- Middle-income countries: 25% is reported in Thailand (Intharathirat & Salam, 2015).
- Low-income countries are out of the scope, because little literature explore RDF in these countries.

Region	**MSW generation, 2025 (MT/Yr, projected)**	**Collection rate, 2012**	**Share of plastic+paper in collected MSW, 2012**
South Asia	207	64%	11%
Sub-Saharian Africa	161	46%	21%
Middle East and North Africa	98	84%	23%
Eastern and Central Asia	130	78%	22%
Latin America and Caribbean	266	78%	30%
East Asia and Pacific	681	73%	23%
OECD	636	98%	43%
World	**2179**	**79%**	**30%**

Table 1: Waste data by region (World Bank, 2012)

Noticeably, observed yields seem to be higher than the share of plastic and paper. This can be explained by the fact that other fractions (foams, rubber, fines) are present in RDFs. In order to assess the potential for RDF production, and based on the share of plastic and paper observed, yields were assumed as so:

- 50% for the OECD,
- 35% for Latin America and the Caribbean,
- 15% for South Asia,
- 30% for the other regions.

The short quantitative analysis by country group conducted in paragraph **4.1** will consider these yields. However, the multi-case study of paragraph **4.2** will take for basis a yield of 35%, because of the lack of data available for specific countries, as well as because higher yields are expected in the mid-term perspective, for which this case study's result are intended. This value comes from the IEA (2020a) that assesses it as an average for the main RDF producing countries.

2.3. Qualitative case study

2.3.1. Orkel manufacturing analysis

Most of the data that is contained in the case study analysis originates from Orkel. Among these, primary sources have been gathered from interviews, meetings, email exchanges mainly with the company's R&D manager, Gjermund Kambestad, and Regional Sales / Sustainability manager, Miriam Karterud. The majority of this data is quantitative. Secondary sources encompass web articles published by the case company, Orkel, or published by other organisms and mentioning Orkel.

Orkel's headquarters and production site are located in Fannrem, 50km from Trondheim where I was living while writing this thesis. Therefore, I had the opportunity to visit the facility on two occasions. The first visit was held on December 2022, while I was writing my Specialization Project with Orkel, on RDF and SRF already. I was physically introduced to the company, to discuss the concepts studied, as well as to trigger leads for a potential Master Thesis subject. In March 2023, I visited again the site, where I became more familiar with the equipment and discussed more about the advancement of the thesis with G. Kambestad. I could also exchange communication with two major actors of the UK's RDF business, as they were visiting the site the same day. This visit helped shaping the structure, and purpose of the thesis.

2.3.2. RDF industry and baling

Most of the information involving baling within the RDF industry was found during the literature review conducted for chapter **3.** Consequently, a second literature review was handled, in order to explore further this relationship. The following queries are some examples of the ones used in that perspective:

- "Baling" OR "Agricultural compactor" AND "Sustainability",
- "Baling" OR "Agricultural compactor" AND "RDF" OR "SRF" OR "Waste".

Paragraphs **5.2** and **5.3** gather information that has been found from these two literature reviews.

3. Literature Study: RDF/SRF industry development

Strategy context is the set of circumstances surrounding strategy making. It is characterized by the "where" of strategy (which firms, which environment). Determining the context is a prerequisite to triggering actions, in order to ensure the best decision-making process. Within the strategy context, the direct environment in which firms need to compete is the industry context (De Wit, 2020).

The industry rules arise from the structure of the industry. There is a broad consensus among strategists that these rules evolve overtime, a phenomenon that is named "*industry development*" (De Wit, 2020). **Figure 8** illustrates the relationship between the dimension of this development, and the drivers that can influence trends along these dimensions: product characteristics, actors, and underlying factors. Compared to the theory of De Wit (2020), we added the product characteristics as a driver, because RDF and SRF definitions vary across literature, and shape the very nature of the business (IEA, 2020a).

The product characteristics of RDFs, including SRFs, will be studied in paragraph **3.1.** The actors in play in the industry will be described in paragraph **3.2.** The underlying factors influencing the developments will be identified in paragraph **3.3**. Finally, the changes trends along each dimension of industry development will be assessed in paragraph **3.4**.

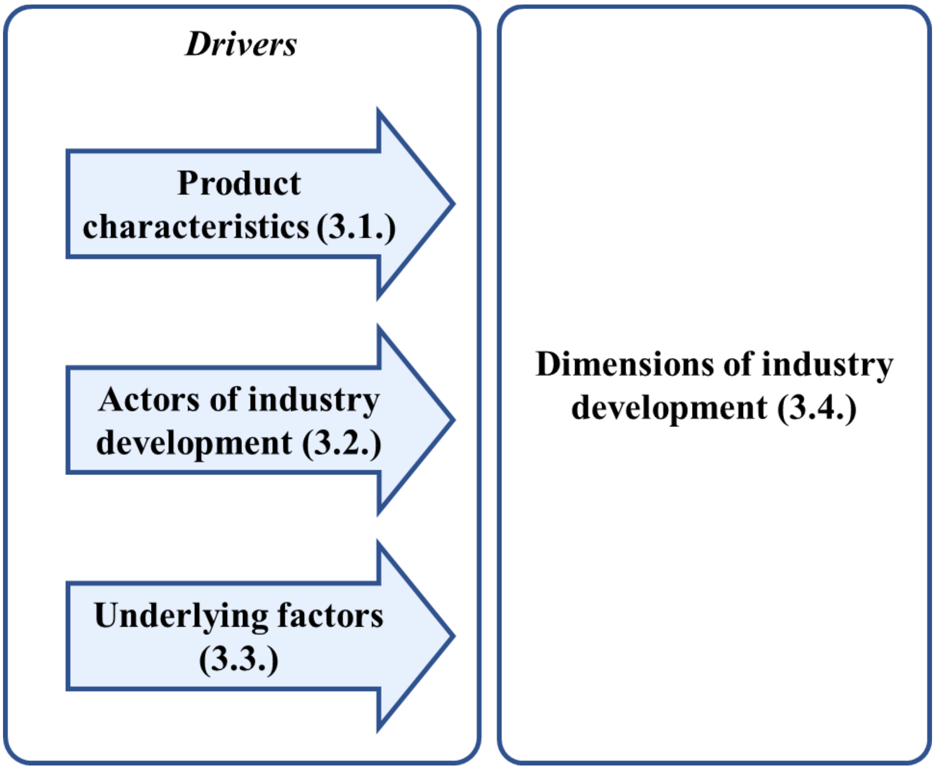


Figure 8: Industry development, adapted from de Wit (2020)

3.1. Product characteristics

In order to discuss the industry developments arising, starting by giving a clear definition of RDF and SRF will help considering the industrial dynamics in play. A literature review was conducted with the query [“*Refuse Derived Fuel” OR “Secondary Recovered Fuel*]. The findings of this review will be discussed in the present part.

This project focuses on one products family, Refuse Derived Fuels (RDF), with a particular emphasis on a sub-family, Solid Recovery Fuels (SRF). First, an international standards review will be made to assess what parameters defined RDF and SRF throughout recent history (**3.1.1**). Then, the technical description of SRF classes according to the ISO standard will be detailed (**3.1.2**). Finally, a description of the feedstocks mainly used will be achieved (**3.1.3**).

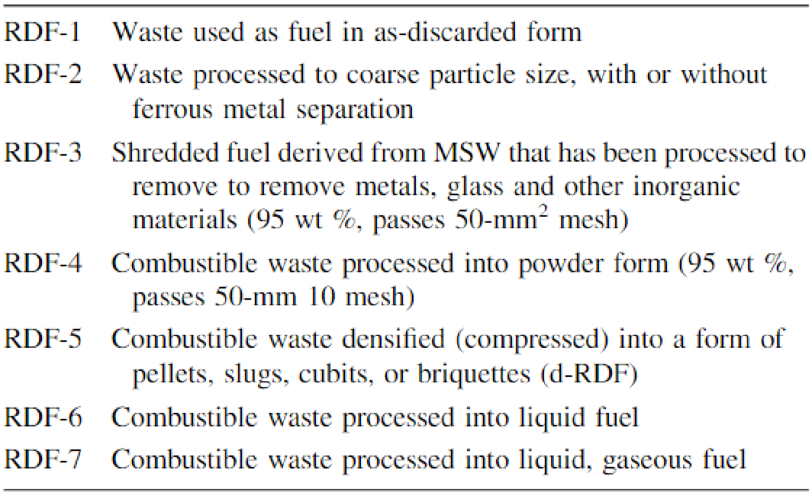
3.1.1. Nomenclature and classification introduced by standards

Refuse Derived Fuels

This part contains abbreviations related to international standards. More information on these abbreviations is available in **Appendix 1.**

The main challenge to the high-scale use of RDF is its variable quality, greatly dependant on the waste input material characteristics, as well as the process (European Commission, 2002; IEA, 2020a). As of today, two main classification systems coexist.

The oldest reported one is a 7-class system mostly based on qualitative criteria (**Table 1**). The classes are ranked by physical form, from raw waste (“*RDF-1*”) to waste processed into gaseous fuel (“*RDF-7*”). This system was published by the “*American Society for Testing and Materials*” [ASTM]. It has seemingly been used in literature, for the first time, by Alter (1987), which mentions an ASTM standard published in 1985. Most of the literature using this system refers to the standard ASTM E856-43 published in 1998 and re-edited in 2004. It is likely that this standard replaced the previous one. This classification is mostly used in non-European literature: U.S. (Chavando et al., 2022), Thailand (Punin et al., 2013), Taiwan (Wan et al., 2008).



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

Table 2: RDF classification, ASTM standard (Alter, 1987)

Although it has existed for several decades, the RDF business has struggled several recessions, particularly because of the variable quality and low level of trust in waste-derived fuels (Alter, 1987; Chavando et al., 2022). To obtain a product with a quality that is sufficient and consistent overtime, industrials identified a need for developing good quality fuels from waste (IEA, 2020a). Accordingly, while RDFs started to be used at a greater scale in Europe between 1990 and 2010, several countries started to develop national standards based on quantitative criteria. For example, the set of Italian standards UNI 9903:1-14 (1998) defines two types of RDFs, based on numerical limits of technical parameters such as: (Ragazzi & Rada, 2012)

- Net Calorific Value (NCV, see definition in **Appendix 2**),
- Moisture & ash content,
- Contaminant content: 10 elements noted, including Chlorine and Mercury.

In addition, other parameters must be measured such as glass content, dimensions, and ash softening (**Appendix 3**).

The nomenclature "*Solid Recovered Fuels*" (SRF) started to be used by academics in the years 2000s, to describe an RDF that is of high quality, and often an RDF that meets quality requirements (classification and specification) defined by national or international standards (IEA, 2020a). The first international *Technical Committe*e (TC) to work on SRF is the group "*CEN/TC 343"*, created in 2001 and working for the European Committee for Standardisation (CEN, 2022). This group published various reports, specifications and standards for SRF, including a first international *Technical Standard* (TS) in 2006: CEN/TS 15359:2006 (CEN, 2006). It defines 125 classes of SRF (5 classes for each of 3 criteria). Nowadays, these standards encompass 30 technical documents, while the most developed RDF standards was constituted of 14. They enable a more specific and explicit description of the product, noticeably with a nomenclature of product that describes directly the performance in each of the 3 classes (see **3.1.2**). However, industry in most countries, including some in European countries, were still not applying these methods to their products, even a few years after their introduction. The main reason is that the specifications they were using were tailored for specific end-users, hence from producer to customer, regardless of a third-part organism (IEA, 2020a).

Great progress was achieved in 2015, when an ISO *Technical Committee* was constituted ISO , ISO/TC 300. An international standardization is expected to help to get a universal perspective on the product. Further on, the International Energy Agency considers that it will help to increase the trust in SRF as a secondary fuel, and eventually develop markets that are not active nowadays (IEA, 2020a). In June 2023, there are 15 published standards within this set, among which the first was published in 2021. The technical committees of CEN and ISO worked together to come up with the most recent ISO standards. Therefore, they replaced former CEN standards as they have been or will be endorsed by CEN, then by national European standard organisations (ISO, 2021a).

Little literature commenting the ISO standards is available. However, a comment can be made that this standard involves a rather small number of parameters, 3, in its nomenclature, and that these parameters seem to be the ones found most often in previous national standards. With regards to new environmental regulations, recent research suggests nomenclature systems that integrate more parameters, such as the French Agency for Environment and Energy Control, ("*Agence de* *l'Environnement et de la Maîtrise de l'Energie" [ADEME]*), which recommends to name SRFs according to their performances in 7 parameters, with 4 different scores for each (ADEME, 2015):

- NCV,
- Chlore, Fluor, & Bromine content,
- Sulphur content,
- Nitrogen content,
- Ash content,
- Density,
- Particle size.

As new end-uses are being researched (paragraph **3.2.3**), the ADEME also indicates that such nomenclature will help to build trust and facilitate supply and sales in value chains that are yet to be built.

In a nutshell, SRF is seen in the literature and in the industry as a more promising product than RDF because of more detailed quality insurance policies regarding technical specifications. Therefore, its inter-industry and international business is likely to be facilitated. However, this standard is quite new, and each country is to introduce regulations that transpose its requirement to local contexts, as it has been done for the European Committee standards. The choice of this research is to use the vocabulary and classification introduced by ISO standards. Nevertheless, more extensive environmental regulations, and possibly more various end-uses have led to a need for standardisation that encompasses more parameters. In the coming years, it may be of a decisive importance for the ISO/TC 300 to work on standardisations that can be coherent with up-to-date environmental regulations, and relevant for upcoming end-uses.

In this thesis, the nomenclature "RDF" will be used by default. "SRF" will describe high quality RDF, especially when the cited literature uses this terminology.

3.1.2. Technical specifications

The standard ISO-21640-2021, "*Solid recovered fuels - Specifications and classes"* (ISO, 2021a), defines limit values for SRF, and provides guidelines for classification. 3 main characteristics are used:

- **Net calorific value**: a performance indicator, hence an economical characteristic,
- **Chlorine content**, proven to cause corrosion (Persson et al., 2007), clogging (Chinyama, 2011) and other issues for some applications such as cement (Chinyama, 2011), hence a technical characteristic,
- **Mercury content**, an environmental characteristic, because of combustion pollution.

For each characteristic, the standard defines 5 classes. There are therefore 125 possible classes of SRF (**Table 3**).

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

Table 3: SRF classification (ISO, 2021a)

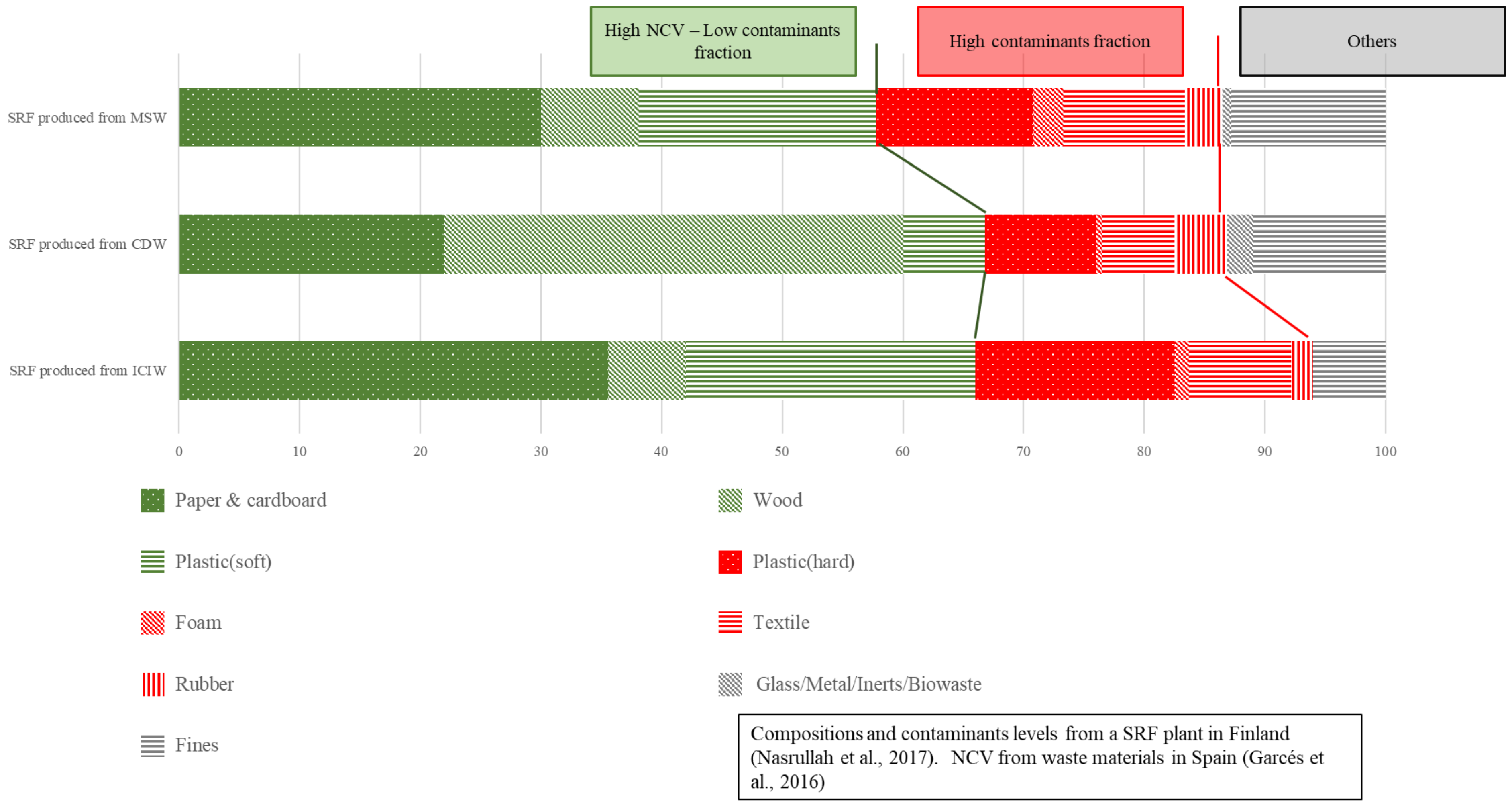
In addition to the class code that sorts the names the product according to the value of these 3 parameters, a SRF producer needs to specify the value of these additional parameters:

- Waste flow origin,
- Traded form (pellets, bales, briquettes, chips, flakes, fluff, or powder),
- Particle diameter,
- Ash content,
- Moisture content,
- Chemical content in 13 heavy metals, including Chlorine and Mercury.

3.1.3. RDF/SRF composition

As shown in the previous paragraph, the very definitions of RDFs and SRFs are related to their composition, which is strongly influenced by the composition of their feedstock. The European Commission (2002) observed that the location is a decisive factor, as local waste composition influence fuel composition, leading to high differences in RDF composition from one plant to another. The nature of the feedstock is another important factor, as RDF can be sourced from streams of MSW, ICIW, or CDW (IEA, 2020a). Agricultural waste can also provide an interesting feedstock (Hsu, 2021; Hussieny et al., 2019), although no reports of high scale use has been found. This may be due to the high organic content of such waste, which tends to be avoided by RDF manufacturers.

Figure 9 gives an example of the composition of a SRF produced in a Finnish facility. For achieving a good quality RDF, the most relevant materials are paper and cardboard, soft plastic and wood, which all have high NCV (Garcés et al., 2016) and low contaminant levels (Nasrullah et al., 2017). Hard plastics (such as PVC), foams, textiles and rubber have higher contaminants levels, which make them undesirable from RDF production (Nasrullah et al., 2017), although hard plastic also hold a high NCV (Garcés et al., 2016).



Compositions and contaminants levels from a SRF plant in Finland (Nasrullah et al., 2017). NCV from waste materials in Spain (Garcés et al., 2016)

Figure 9: Composition of SRF from various feedstock (wt%)

A SRF produced from MSW shows a higher recovery rate in a high-income country as Finland, as well as better energetic performances (**Table 4**) than SRF produced from CDW and ICIW. Nasrullah et al. (2017) indicates that the lower yields are caused by the nature of CDW and ICIW, which contain more inert (glass, stone, metal) and contaminated materials (PVC, rubber). For the average in Europe, the IEA (2020a) indicates lower yields, respectively 35%, 15% and 15% for MSW, CDW and ICIW. This difference is likely to be due to the higher source sorting in Finland (World Bank, 2012).

They also indicate that the lower NCV observed for SRF from CDW and ICIW is caused by a greater proportion of large size, highly moist, or irregularly shaped materials.

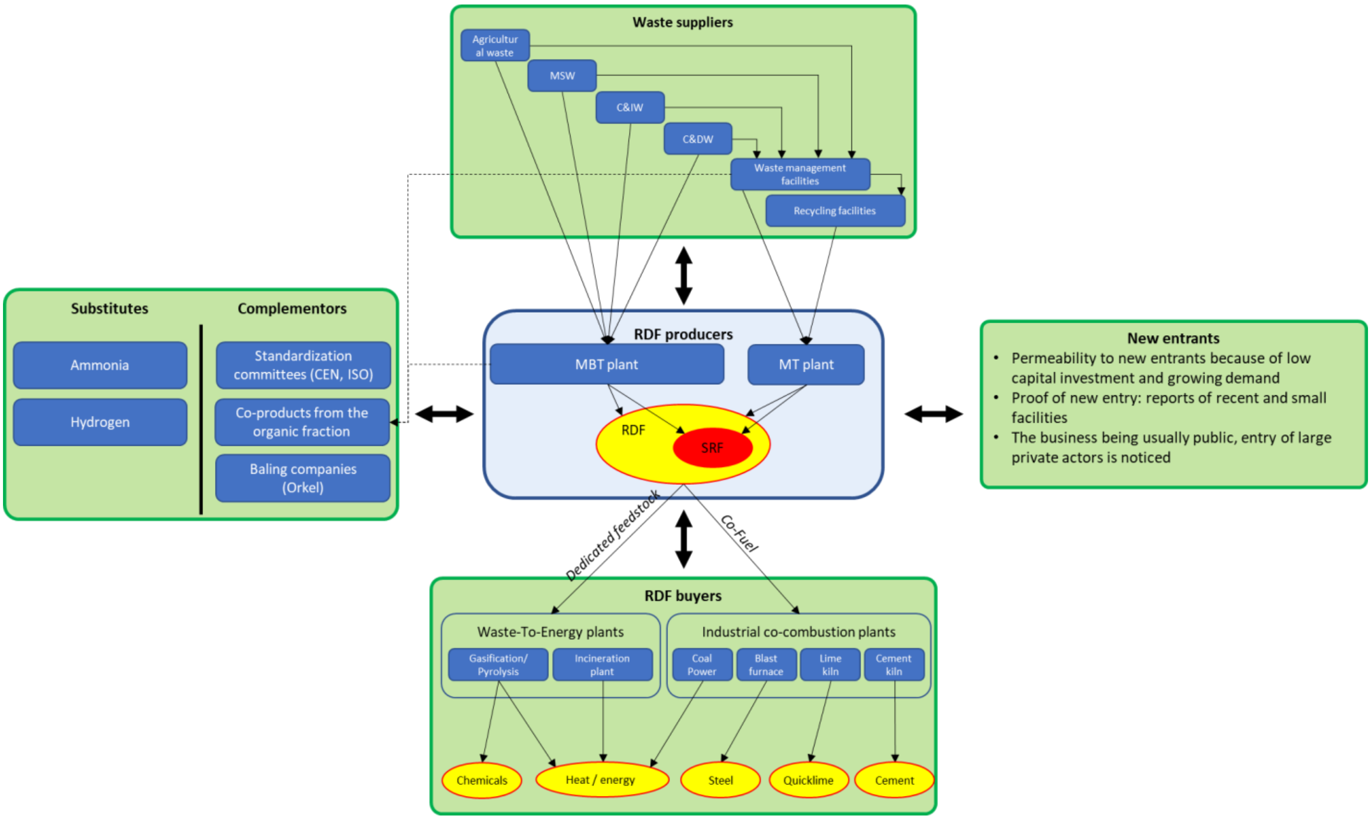
Feedstock	MSW	CDW	ICIW
Material recovery (wt%)	72%	44%	62%
NCV (MJ/kg)	20	18	18

Table 4: SRF yields and NCV by feedstock. Data from Finland (Nasrullah et al., 2017).

Sarc and Lorber (2013) stand that the type of waste input is *de facto* more important than the production process itself. Furthermore, the influence of feedstocks is likely to be different among countries, as the compositions are greatly different. For instance, the influence of the greater biowaste fraction in MSW observed in developing countries (World Bank, 2012) is yet to be studied.

3.2. Actors driving the industrial development.

As defined by Porter (1980) and used by De Wit (2020), an analysis of competitors, buyers, substitutes, potential new intrants, as well as the structural factors that influence their behaviour, is important for determining a successful strategy. They form the actors driving the industrial developments (**Figure 10**).



New entrants

- Permeability to new entrants because of low capital investment and growing demand
- Proof of new entry: reports of recent and small facilities
- The business being usually public, entry of large private actors is noticed

Figure 10: Drivers of industry development: actors and underlying factors (base on Porter (1980))

3.2.1. Waste suppliers

As shown in paragraph **3.1.3**, the initial feedstock for waste can be of 4 natures: MSW, CDW, ICIW, and Agricultural Waste. Similarly, the actors providing this waste can be of various natures: (ISO, 2021a)

- Municipal Solid Waste: house rubbish, waste from markets, waste from parks, etc. This waste is most often provided by municipalities, although more and more private actors are involved (Antonioli & Massarutto, 2012; World Bank, 2012).
- Industrial, Commercial & Institutional Waste: the main industries are agriculture (low-organic fractions), paper production, wood processing, textile industry, organic chemicals processes, plastic processing. Furthermore, high amounts of packaging waste can be recovered from any other industry.
- Construction & Demolition Waste: construction and demolition companies.
- Agricultural waste: agriculture industry (high-organic fractions).

- Waste from recycling and waste management facilities: either from mechanical treatment plants, or from vehicles end-of-life treatment plants. Such waste is therefore pre-processed, either in order to separate the recyclable fractions, or to provide an appropriate feedstock to the RDF facility (ADEME, 2015).

A wide range of industries in the waste supply is observed, which contributes to waste composition being highly variable depending on the companies. Furthermore, diversity can also be observed when it comes to companies' size and governance. For example, agricultural actors can encompass small farmers as well as international corporations. Similarly, municipal waste is handled by public institutions (cities) or private companies, according to the country.

3.2.2. RDF producers

The ADEME (2015) reported about a hundred of producers in Europe in 2015. Outside of this regions, the IEA (2020a) counted 50 plants in Japan, and 12 in Korea. India and China, although being major waste producers and the two biggest cement producers, don't disclose a number of plants nor a volume of RDF produced.

RDF facilities were developed mainly with a goal of producing a good suitable for combustion in cement kilns, as the main end-use is the cement industry (ADEME, 2015; Chavando et al., 2022; De Caevel et al., 2018; IEA, 2020a).

In Europe, the ADEME (2015) reports high variations of RDF composition between producers, but a steady composition for a given producer.

Mechanical Biological Treatment plants

In the literature and in the industry, RDF are produced, among other goods, in plants often named "*Mechanical Biological Treatment*" (MBT) (Garg et al., 2007; IEA, 2020a; Ragazzi & Rada, 2012). Processes involved are various, but they generally first separate biodegradable fraction and often process it directly into resources such as biogas or compost. Then, mechanical operations and/or sorting techniques to produce RDFs by separating inert materials and highly pollutant waste components:

- Shredding,
- Screening,
- Magnetic or Eddy current separation,
- Pneumatic separation,
- Optical sorting,
- Near infrared (NIR) sorting.

MBT plants usually use untreated waste (often MSW) as a feedstock, which results in high gate fee compensation being received (70-140€ in France). The yields are generally low (15-50% in France), and the gate fee of the RDF/SRF produced is often lower than 80€/ton (ADEME, 2015).

Mechanical Treatment (MT)

Mechanical Treatment plants are MBT facilities that only deal with the mechanical/sorting operations. They receive an input from which has already been withdrawn the biodegradable fraction, which results in a higher NCV. The output is often a high-quality RDF or SRF. In France, the ADEME (2015) describes high yields (between 50% and 80%) and high value added to the end product, with gate fees of 20-120€/ton of input (paid to the producers), while the SRF produced is sent for gate fees below 30€/ton, with situations where a sale of 15€/ton can be achieved.

3.2.3. Buyers: Utilisation of RDF

De Caevel et al. (2018) showed that the RDF end-users have in common to be motivated to use this good because of the following factors (ranked from most to least important):

- High and increasing fossil fuel prices, leading industries to seek for alternatives,
- Low waste derived fuel prices, resulting from landfill bans or taxes,
- CO2 quotas regulations,
- A regulation gap in some European countries, sorting RDF facilities in the incineration category, exonerating it from CO2 quotas and taxes.

Gendebien et al. (2003) and the IEA (2020a) identified a number of applications for RDF. Some end-uses are already well researched, and extensively used throughout industry. This paragraph will first describe the waste-dedicated facilities, then the cement and coal power plant industries. Afterwards, two little explored end-use will be described: steel and lime production.

Other end-uses have been used in the industry, but not documented sufficiently in the literature to these days: glass industry, chemical industry are highly energy intensive sectors that still use high amounts of fossil fuels (IEA, 2020). These sectors will therefore not be included in the analysis.

Waste-dedicated facilities

RDF can be used in various types of waste-dedicated processes:

- Combustion in an MSW-fed WTE plant,
- Combustion in a dedicated WTE plant,
- Gasification,
- Pyrolysis.

When compared to MSW, using SRF as a feedstock has mixed results. In a literature review focused on the UK's industrial context, Garg et al. (2009) found that substituting 10% of the weight input of MSW in a cogeneration WTE plant by SRF would result in similar GHG emissions, lower winter smog, and a higher acidification potential. MSW is already widely used in WTE plants, and is cheaper to produce than SRF, because less processed. Accordingly, Lombardi et al. (2015) showed that processing waste into SRF for an end-use in an Italian Waste to Energy plant is an irrelevant and unnecessary process, due to inherent system losses and additional energy costs.

RDF gasification (Arena & Di Gregorio, 2014; Lombardi et al., 2011) is where waste is converted into a gaseous fuel in presence of oxygen. It also creates a solid by-product containing carbonaceous compounds. There were already more than 100 waste gasification plants around the world in 2002 (Klein, 2002), for which RDF is particularly well suited because of the higher quality needed.

RDF pyrolysis is similar to gasification, except that the reaction occurs without oxygen. Waste pyrolysis is a more recent process than gasification, which produces a gas of a higher calorific value, and is more flexible in terms of temperature. Pyrolysis is often coupled with gasification in the same facility, because they don't target the same fraction of waste, and so that they can benefit from the heat created by the other process (Dehzen et al., 2014). Chakraborty et al. (2013) pointed out that the energy consumption due to RDF production greatly reduces the overall energy potential of this technique. However, benefits of RDF's high and consistent quality include availability to all reactor types, steady operation, and production of uniform outputs.

In a summary, when it comes to RDF dedicated use, direct WTE doesn't show to be more relevant in terms of emissions than direct use of MSW, while RDF has higher production-related costs and energy use. However, gasification and pyrolysis are interesting end-uses, as the high quality of RDF enables the production of gas usable for energy or chemical needs. The NCV of the RDF used in pyrolysis and gasification processes is at least of 17.9 MJ/kg (Dehzen et al., 2014), which corresponds to an ISO class 3 (see **Table 3**), similarly to the cement industry.

RDF for cement kilns

In 2021, 4.4 billion tons of cement were produced (U.S. Geological Survey, 2022). Coal is the main fuel currently used, with approximately 500g of coal needed to produce 1 kg of cement (World Coal Institute, 2009).

In 2016 already, secondary fuels were substituting fossil fuels in cement industry at a thermal rate of 17% globally, and 44% in Europe. German and Austrian cement kilns were supplied by more than 76% of RDF (Sarc et al., 2019a). The same study concluded that 100% of substitution ratio is theoretically possible, with fuels that comply with the Austrian regulation for SRF (Federal Ministry of Agriculture Forestry Environment and Water Management, 2010). This corresponds to a medium-quality SRF with ISO class code NCV 3; Cl 3; Hg 4 (**Table 5**). Some process improvements are needed, particularly to limit Chlorine value, which can be higher in the Austrian-produced RDF than what regulations limit. This is due to high quality RDFs containing a higher share of hard plastics, which can be a high source of chlorine (as explained in paragraph **3.1.3**).

Classification characteristic	Statistical measure	Unit	Limit values	ISO class
Net calorific value (NCV)	Mean	MJ/kg	≥16	3
Chlorine (Cl)	Mean	% in mass	≤ 1.0	3
Mercury (Hg)	Median	mg/MJ	≤0.075	4
	80th percentile	mg/MJ	≤0.15	4

Table 5: Technical requirements for SRF in the cement industry

As shown in **Table 6**, the quality of RDF used in the cement industry are similar in Italy (data from the RDF producers) and slightly stricter in Germany (data from the national standard RAL GZ 724, created by *Die Gütegemeinschaft Sekundärbrennstoffe und Recyclingholz e. V. (BGS)* which can be translated by *Quality Association for Secondary Fuels and Recycling Wood* (BGS e. V., 2015)).

Parameter	Unit	Italy (Producer 1) (1)		Italy (Producer 2) (1)		Germany (all producers) (2)	
		Limit value	ISO class	Limit value	ISO class	Limit value	ISO class
Net calorific value (NCV)	MJ/kg	15	3	16	3	18	3
Chlorine (Cl)	% in mass	1	3	0.8	3	1	3
Mercury (Hg)	mg/MJ	0.067	4	0.094	4	0.05	3

Sources:
(1): European Commission, 2002
(2): BGS e. V., 2015

Table 6: Quality requirements for RDF in the cement industry

RDF for coal power plants

The current use of RDF in Coal Power Plants is rather low compared to its use in cement kilns. This may be explained by policies in Europe that tend to prefer renewable sources for electricity generation and to reduce the production of their Coal Power Plants. Meanwhile, the cement, lime, and steel end-uses have a need for heating, for which green alternatives can’t be found as easily. However, the use of RDFs in Coal Thermal Plants can still be relevant. First, many countries outside of Europe rely heavily on coal for their electricity (as will be detailed in paragraph **4.2.2**). Second, novel processes such as co-generation may foster further development of Coal Power Plants.

Co-generation is the process of producing jointly electricity and useful heat in the same plant. Lombardi et al. (2015) showed that this is a profitable process in waste to energy plants, because the heat generation high yields are greatly useful, while electricity can be generated when less heat is needed (during summers, or low plant activity), without reducing the throughput. Some industries – mainly public owned - are furthermore connected to national energy grids, allowing a constant use for the heat generated (De Caevel et al., 2018; IEA, 2020a).

In 2020, the coal for industry sector generated 32 000 000 TJ of energy, which represents over 4.5 billion tons of coal combusted IEA (2022a). Fruergaard and Astrup (2011) demonstrated that substituting coal by SRF in Denmark had less impact in all 9 environmental categories considered (including global warming and acidification), for similar energy level produced. Similar results were found by Garg et al. (2009), to the difference of higher smog content for SRF combustion than for coal combustion (related to the high ash content). There is overall an interesting environmental impact.

The properties of a RDF suitable for a use in Cement Power Plants, as assessed by the German quality certification RAL GZ 724 (BGS e. V., 2015), corresponds to an ISO class code NCV 4; Cl 3; Hg 3, similar to the requirements for cement kilns, although the Chlorine content must be lower (**Table 7**). This confirms the comments of (Velis et al., 2010) about requirements being higher in coal power plants than the cement industry. The observed substitution rates are of 1.8-4% in German power plants, without significant impact on operational performance and emissions (Velis et al., 2010). A theorical substitution rate of maximum 10% has been estimated by Juniper, 2005.

Parameter	Unit	Quality requirement (RAL GZ 724)	
		Limit value	ISO class
Net calorific value (NCV)	MJ/kg	13	4
Chlorine (Cl)	% in mass	0.7	3
Mercury (Hg)	mg/MJ	0.038	3

Table 7: Quality requirement for RDF in the Coal Power Plant industry

RDF for steel work

After energy, cement, and lime, steel production is one of the main coal end-uses (IEA, 2022a). In 2021, 1.95 billion tons of crude steel were produced (World Steel Association, 2021). 70% of the steel produced is made using coal, although it is difficult to know precisely how much coal is used for a given amount of steel produced, as the technique (oxygen-blown converters) uses various shares of coal and natural gas among circumstances. In 2020, 1.1 billion tons of metallurgical coal were combusted (IEA, 2021).

It is therefore coherent that the use of RDF has been investigated. RDF is already used in steel plants in Austria **(**Buergler, 2008**)**, Germany **(**Buchwalder et al., 2006**;** Janz, 1995**)**, and Japan, where high quality RDF are manufactured from paper and plastic and have a particularly high calorific value **(**Ariyama & Sato, 2006**)**. Based on these examples, Kepplinger and Tappeiner (2011) assessed that RDF could replace fossil fuels and result in significantly lower emissions.

Regardless of the waste type, a 2-3% substitution rate is regarded as safe (Galko et al., 2023). In 2015, 200 000 tons of plastic waste were used to create a substitute carbon-derived coke used in Japanese blast furnaces, with a 1-1.5% mass substitution rate (Nomura, 2015).

Although little information on quality requirement is available in the literature, Sarc and Lorber (2013) describe a NCV requirement over 25 MJ/kg, which corresponds to an ISO class 1. Such a high value can explain the current limited use of RDFs in blast furnaces.

RDF for lime kilns

Lime kilns are used for the calcination of limestone into calcium oxide (also called quicklime), which is an essential chemical compound for a number of industries (Schorcht et al., 2013):

- It is an important agent in metal processing (the main use in Europe),
- It is used for various purposes in environmental protection, agriculture and forestry,
- It is a binder in building and construction,
- It is widely used in chemicals, paper, food, glass industries.

The worldwide lime production in 2021 was 430 million tons (U.S. Geological Survey, 2022). The fuels used for producing quicklime are mainly solid (coal, coke, etc…), as well as natural gas.

Lime kilns fed with RDF instead of fossil fuels are less documented that cement kilns. However, it is cited as one of the main potential applications (IEA, 2020a; ISO, 2021b). Furthermore, according to the European Commission, solid waste is already partly used in the industry (Schorcht et al., 2013), with 10% thermal substitution rate in a studied German plant in 2006. They indicate that a rate up to 60% is technically permitted. The same report indicates that quality insurance and warranty is needed for using more waste as fuels. They point out that the main limitations for waste use are physical and chemical properties, and fuel availability.

In Japan, Nomura (2015) found that RDF could be used to create coke intended for lime kilns, similarly as for steel. Gasified RDF can also be used to replace coke (Talebi & Van Goethem, 2014).

The properties of a RDF suitable for a use in lime kilns, as assessed by the German quality certification RAL GZ 724 (BGS e. V., 2015), corresponds to an ISO class code NCV 3; Cl 3; Hg 2 (**Table 8**).

Parameter	**Unit**	**Quality requirement (RAL GZ 724)**	
		Limit value	ISO class
Net calorific value (NCV)	MJ/kg	23	2
Chlorine (Cl)	% in mass	1	3
Mercury (Hg)	mg/MJ	0.022	2

Table 8: Quality requirement for RDF in the lime industry.

3.2.4. Substitutes and complementors

Brandeburger and Nalebuff (2021) provide a formal definition of industrial substitutes, based on the works of Edgeworth (1925), Fisher (1892), and Pareto (1909): firms are substitutes to each other if the willingness to pay of customers is lower for both their products together than for the separated products. In other words, in a market where these two products coexist, there will be a form of competition between both. In his framework for industry development, De Wit gives an insightful definition of substitutes for a company: "*resource that can be exploited separately to implement the same strategies*". They therefore recommend firms to develop resources that are "*rare and inimitable*". Conversely to this definition of substitutes, firms are complements to each other if the willingness to pay of customers is higher for both their products together than for the separated products. An important characteristic of substitutes and complementors is that they belong to a similar business model. Resources related to a different business model are to be categorized into "*New Entrants*" (paragraph **3.2.5**). Projecting these definitions in the scope of the RDF industry, substitutes can be understood as goods other than RDF that fulfil the same strategic purposes, and whose value to end users are lower together than apart.

In short, substitutes and complementors are resource from external companies that are involved in similar business models. Substitutes to a given resource are a threat as they can be purchased instead, while complementors are an opportunity as they offer more value added combined with the resource.

Substitutes

As explained in paragraph **3.2.3**, value in RDF for its buyers lies in 3 criteria: its secured availability, relatively low price and low CO2 emissions. All three of these criteria are extrinsic, as they are not inherent to the fuel itself. However, emissions are partly related to intrinsic properties (composition, density). Therefore, it will be assumed as the base property to compare resource that could present a threat of substitution; the next paragraph will compare low carbon fuels.

Biogas is a fuel that encompasses is made of waste, just as RDF (Cherubini et al., 2008). However, its emissions are severely variable depending on the production process and calculation method (Gnansounou et al., 2009), which makes it uncertain whether it can be categorized into "low-emission fuels". Additionally, Cherubini et al. (2008) showed that the cradle-to-grave emissions and energy used of biogas is more suitable when produced from the organic fraction separated from RDF in MBT plant, which makes it a suitable complementor for RDF. It can be noted that biogas is different from the gas obtained after gasification/pyrolysis, as it is produced from a different process named anaerobic digestion (Cherubini et al., 2008).

Other low-carbon fuels have been identified in the literature, although they mainly don't tackle waste management challenges: Ammonia and Hydrogen (IEA, 2022b). These energy vectors can be produced by chemical means from coal, natural gas, biomass and electrolysis. In a hypothesis without carbon capture involved, producing it from coal represents higher emissions than coal combustion. Electrolysis' emissions depend greatly on the country energy mix, so it will also be excluded from the scope. Because the biogas production processes often use RDF (IEA, 2020b; Paolini et al., 2018), this way is also not considered a substitute, rather a complementor. Because of emissions of similar magnitude than RDF and coal, natural gas-based Ammonia and Hydrogen can be considered substitutes to RDF (IEA, 2022b).

On a qualitative basis, a comment can be done that Ammonia and Hydrogen are innovation-based fuels, that need to be used in dedicated processes that have been recently developed, and yet to be mature (IEA, 2022b). As a result, they show little risk of influencing the RDF industry, aside from the public opinion that may consider them "greener".

In order to support these findings, quantitative analysis is conducted to determine the potential threat of the substitutes identified, in terms of cost and GHG emissions potential (**Figure 11**). The supporting data is available in **Appendix 4.** These charts show that RDF is to this date a competitive low carbon fuels, with prices per energy delivered lower than Ammonia, Hydrogen, or Coal, noticeably because of its nature of waste. The GHG emissions are also interestingly lower than these two "low carbons" fuels when they are sourced from natural gas. These figures therefore confirm the qualitative findings of RDF being a more interesting low carbon fuel than its potential substitutes.

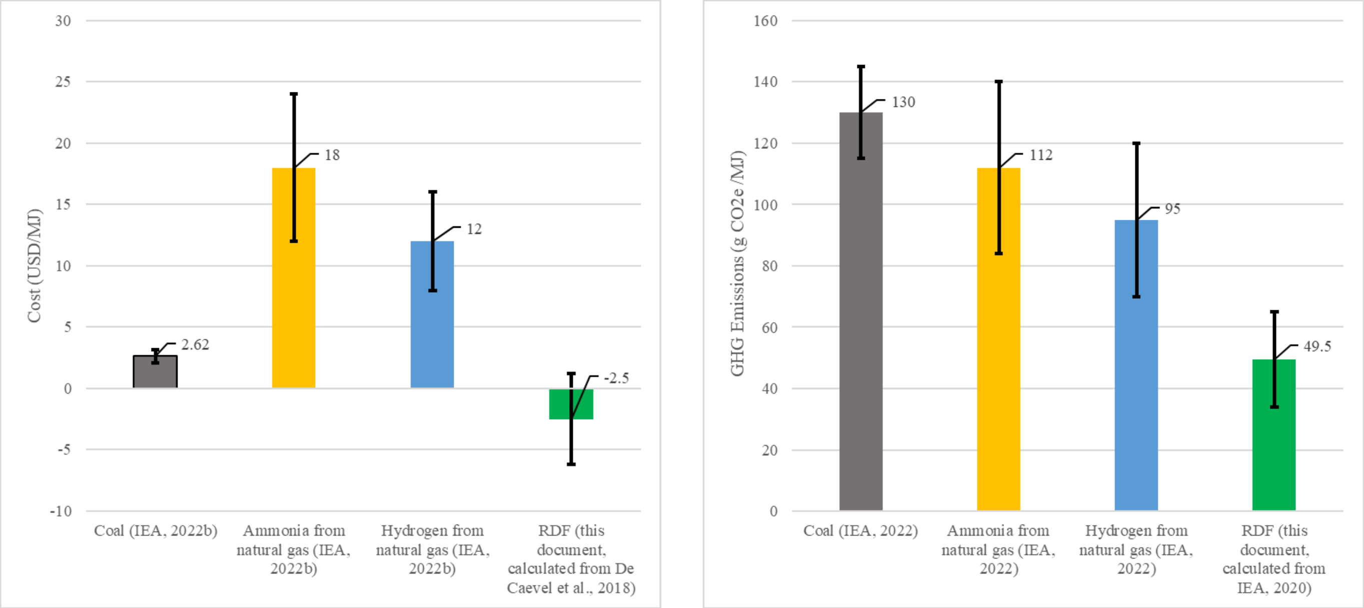


Figure 11: Costs and GHG emissions of RDF in Europe, compared to Coal, Ammonia, Hydrogen.

Complementors

According to the definition of Brandeburger and Nalebuff (2021), complementors are actors that produce a product or service that brings more value added to the original product or service. When it comes to RDFs, standard organisms can be considered as complementors, as standard help the whole industry develop (see paragraph **3.1.1**). Baling companies such as Orkel can also, to some extent be considered complementors, as a baled RDF comes with higher value for transporters and end-users (ORKEL AS, 2018). Co-products of RDF production can also act as complementors. For example, biogas from the organic fraction separated in MBT plant, can bring profit to the RDF producer (Cherubini et al., 2008).

3.2.5. New entrants

Porter (1980) describes "new entrants" as new competitors in the industry that can create a threat to existing firms. Other strategists, such as (Geroski, 1995) focus the threat on the specific entrants that survive in the industry enough years to become competitive, while specifying that entrants can be beneficial to the sector by making prices, products and process specifications right. Mccan (2010) additionally argue for considering entry an opportunity, as the agglomeration of industry cluster can trigger production economies and increased demand.

In all cases, the importance of the entry force is mainly determined by the entry barriers to the market: the hardest it is to enter an industry, the lower this force will be. Several indicators of an industry with low entry barriers were cited in literature (Harrigan, 1981).

- Few scale economies,
- New physical plants,
- Low market concentration,
- High labour intensity, hence low capital intensity,
- Industry-wide advertising outlets,
- Growing demand,
- Under capacity of existing plants.

Although these parameters are hardly objective, and their link to low entry levels is dependent on the industry studied and of the timely/regional context, they help grasping an overview of the likelihood for a number of new actors in the industry. Therefore, an analysis of each of them is conducted in this paragraph.

Scale economies

Scale economies are achieved if fixed costs can be amortized by building high-capacity production, enabling a lower cost for each product (Harrigan, 1981). There is little literature specifically on scale economies of the RDF industry. However, it is possible to assess roughly this parameter, using another view. The importance of scale economies is greater in industries that require complex technological development (such as airplane manufacturing) or high infrastructure investments (such as merchant shipping) (De Wit, 2020).

Focusing on standard RDF processes (which exclude gasification and pyrolysis), the machinery currently used for producing RDF is mostly mechanical (shredding, screening, sorting, see paragraph **3.2.2**), with intermediate technology complexity (Ouda et al., 2016). As explained by many sources (ADEME, 2015; Chavando et al., 2022; IEA, 2020a), the technologies used depend greatly on the end-use intended, and the biggest technological barrier is located downstream of the value chain, at the combustion phase. As for infrastructure, an upfront investment is needed for building a RDF facility, which represent a subsequent cost. Garg et al. (2007) reported capital costs of 12 to 36 M€ for the construction of a 105 000 ton/y MBT plant in Germany. This value can be compared to the production capacities of facilities across Europe. They have been reported to lie between 1,600 and 220,000 ton/y, with a median of 48,000 ton/y across 22 plants in Europe (European Commission, 2002), which shows that small plants do exist.

New physical plants

"Relatively new physical assets [are] expected to be found within environments where entry [is] more likely to occur" (Harrigan, 1981). No specific information on the age of RDF production facilities was found. However, the waste-to-energy sector in general is more documented. Montejo (2013) reported 180 MBT plants installed in Europe between 1990 and 2010. Downstream, De Caevel (2018), in a study on specific European RDF combustion plants, showed that most have been constructed since 2000, with a peak around 2010 that they explain by high energy prices (**Figure 12**). These results show that facilities in the RDF industries are quite new, although they suggest that this trend has lessened since 2010.

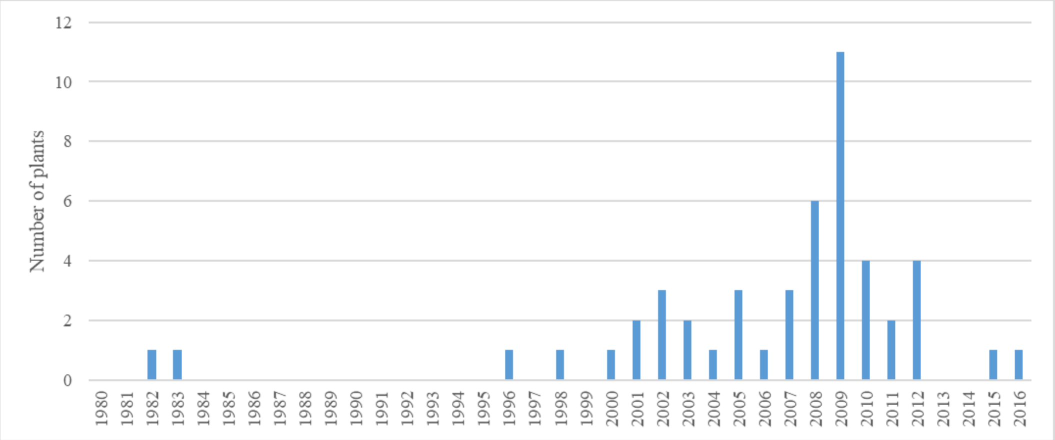


Figure 12: RDF combustion plants commissioning in Europe, from De Caevel (2018)

Low market concentration

A high concentration of firms, which means that few companies hold a large market share, is expected to discourage new entrants (Harrigan, 1981). As detailed further in paragraph **3.4.2**, the worldwide RDF market used to be fragmented between public regional actors, but the current trend is showing a more concentrated market.

High labour intensity

“Higher labour intensity [is] expected to be present among firms in industries where capital requirements, a traditional form of economical entry barrier [...], [is] relatively low” (Harrigan, 1981). In a literature review, Ouda et al. (2016) reported that RDF production has a high labour cost compared to capital costs, noticing that high skills are needed for these operations.

Industry-wide advertising outlets

“*New entrants [are] expected in industries where firms [can] capture the goodwill and customer recognition developed by past industry-wide expenditures on advertising” (*Harrigan, 1981*).* As the RDF deal is made Business-To-Business, the “goodwill” of customers can be understood as the willingness of end-users to use RDF. As suggested by De Caevel et al. (2018) and studied by De Beer et al. (2017), cement producers in Europe are highly willing to use more RDF. Less information is available on metallurgy, lime or coal-power stations actors. However, it can be expected that the drivers for RDF use (low price, low emissions, secured availability) are similar across industries. It is therefore likely that, as the business develops suitably in the cement industry, other end-use industries will perceive trust from this good.

Growing demand

“Rapid growth in demand would be expected to attract new entrants as would be evidence of successful performance by ongoing firms” (Harrigan, 1981). There is a consensus in the literature (De Caevel et al., 2018; IEA, 2020a), about estimating that the market will grow worldwide. Chavando et al. (2022) assessed that the current Compound Annual Growth Rate of the RDF industry is of 5%, noting that the expected highest growth lies in Africa and in Pacific Asia (excluding Japan).

Capacity utilization

“*The presence of several underutilized plants should deter yet another firm from entering”(*Harrigan, 1981*).* As detailed further in paragraph **4.2.2**, capacity levels are greatly variable across countries. Within Europe, countries such as England and Italy are today in situation of overproduction of RDF, while Germany, the Netherlands and Sweden’ cement industries are in need for RDF. In the long term, and as there is only a finite amount of waste recoverable from a given region, it is expected that new entrants will not be profitable in such contexts (IEA, 2020).

Summary of the barriers for new entry

Throughout this paragraph, a qualitative analysis of the RDF production industry’s barriers for new entrants was led. It emerged that the market is relatively permeable to arrival of new actors, especially because of a relatively low capital investment, and a growing demand in most markets. To a lesser extent, reports of small and recent facilities show that entry is fairly possible for new actors. The threat of new entrants is tightly linked to the relationship between private and public actors, as it will be discussed further in paragraph **3.4.2.**

3.3. Underlying factors of industry development

Surrounding the actors responsible for industry development, some factors and actors influence indirectly the businesses of an industry. It is possible to categorize them in 4 categories: economic, political/regulatory, technological, and socio-cultural drivers (De Wit, 2020).

3.3.1. Economic drivers

As shown by the IEA (2020a) and De Caevel et al. (2018), product cost is a major driver of development. For upstream actors, processing waste into RDF allows to reduce the gate fee (cost of disposing RDF to other firms), or even to get benefits from the disposal. For end-users, the price of RDF compared to other fuels is a main driver for development as well (see paragraph **3.2.3**).

As for international trade, RDF is influenced by exchange rates between currencies. Companies within a country will tend to reduce their exports if their currency becomes strong, or if the exchange rate with destination countries becomes more volatile (Auboin & Ruta, 2013). The only countries that don't suffer from these phenomena are the ones sharing a currency, such as EU countries. However, and as further detailed in paragraph **5.2.2**, most of the RDF trade happen between these countries and the UK, or with other countries. Currency strength and volatility is therefore an important aspect for RDF trading.

3.3.2. Political/regulatory drivers

Sound and sustainable trading of RDF, as for every commodity, needs a comprehensive legal framework. Flamme and Geiping (2012) assessed that the main legal requirements to be settled to ensure a proper value chain of SRF consists in two categories:

- **Waste legislation** whose purpose is "t*o avoid or reduce the negative impact of the production and management of waste materials, to reduce the overall impact of the exploitation of resources and to improve the efficiency of the use of resources"*,
- **Emission control and trading:** as waste combustion can have a negative impact on air, water and soil quality, and as the end-use industries of SRF are emission intensive industries (cement, energy…), they are affected by emission trading regulations, which allow GHG emission certificates to be traded. These certificates are pollution quotas given by authorities to pollutant actors of an industry. The possibility to trade represents an economic potential in case of emission reduction (Muller & Mestelman, 1998), as well as threat in case of emission increase (Staber et al., 2008).

As the regulatory context depends on the location, and the time, it is useful to study a particulate case to better understand this topic. Taking as example the United Kingdom, Garg et al. (2007) showed that regulations can both enable and constrain the SRF business. Most of the relevant waste legislation applying to the UK was focused on the diversion of waste from landfill, hence encouraging the energy recovery via waste combustion. However, this framework supports waste combustion when it is considered a recovery process, yet some regulations consider it a disposal process, hence hampering the RDF business.

When it comes to emission control, regulations have mixed effects. Using RDF instead of coal reduces GHG emissions, meaning there is a positive impact. However, the combustion of low quality RDF can liberate high amounts of Nitrogen oxides (NOx) and Sulphur dioxide (SO_2), responsible for air acidification and winter smog, respectively (Garg et al., 2009). Regulations on NOx and SO_2 emissions hamper the development of SRF as a substitute fuel, as the process-equipment should be upgraded in order to comply with such regulation. Similarly, emission trading of GHG is beneficial to the SRF to energy business, while NOx and SO_2 trading would be hampering its development.

Eventually, these regulations have organizational consequences on RDF actors. Some European regulations create bureaucratic barriers (IEA, 2020a): newly built combustion or co-combustion plant need several types of permits, licences, and appraisal to be commissioned (Garg et al., 2007). Furthermore, to comply with emission control regulations, facilities will need to invest in pollution abatement equipment. This parameter is decisive, as Lee et al. (2005) noted a rather short commissioning time for MBT plants in the U.K. (3 years on average), which can be correlated with the development of the RDF industry there.

Regulation also influences exporting trends. As shown by the "*Chartered Institution of Wastes Managements"* (CIWM, 2018), exports from the U.K. and Ireland (the main exporters in Europe nowadays) could only start when it was made legal by national authorities. Similarly, national regulations can condition the possibility of exporting, or importing waste (such as the plastic import ban in China in 2018) (IEA, 2020a).

3.3.3. Technological drivers

The most advanced, and by definition complex technologies are located at the combustion stage of the value chain. De Caevel et al. (2018) showed that for high quality fuels with low impurities, there is little technological challenge for co-combustion (which is one of the reasons for the establishment of such industry), although some barrier might be present for middle to middle to low-income countries (Chavando et al., 2022). However, more issues start to appear for lower quality fuels and with greater substitution rates: technologies for the treatment of ashes (ADEME, 2015) and pollutant such as NOx and SO2 (Garg et al., 2007) are needed to comply with regulations. In this perspective a consensus emerges (De Caevel et al., 2018; IEA, 2020a) that specific, broadly used standard will help end-user and producers to tailor RDFs to the technologies needed.

Emerging technologies such as gasification and pyrolysis show promising insights in manufacturing methanol, ammonia, biomethane and liquid hydrocarbons from RDF/SRF (Chavando et al., 2022) but are the most complex technologies to date. However, several sources testify of an interest in these technologies for the middle to long term and emphasize the need for more research (Chavando et al., 2022; Dehzen et al., 2014; IEA, 2020a).

Waste treatment capacity is also pointed out as a driver for RDF exports (CIWM, 2018; De Caevel et al., 2018). RDF is often exported because it the end-uses need a regular amount of good quality RDF, while local MBT plants are not able to deliver it. This is what happened in Germany until 2020 (CIWM, 2018), triggering imports.

3.3.4. Socio-cultural drivers

Public acceptance plays an important role in the RDF business development (IEA, 2020a). Population can influence the political decisions (especially in high-income countries), which via regulations influence all companies playing in the market, especially public firms, which still run a significant part of the waste management industry (Antonioli & Massarutto, 2012).

De Beer et al. (2017) showed that public acceptance in Europe towards waste co-processing is inequal depending on the countries, with some where a mistrust towards waste combustion near populated areas prevails. It is furthermore shown that countries with high public acceptation are often the biggest producing countries.

3.4. Dimensions of industrial development

De Wit (2020) writes that the rules of the industrial context are constantly changing, evolving along the "*dimensions of industry development"*. Based on the work of Porter (1980), a selection of dimensions is highlighted as most relevant to study in order to understand the changes of a given industry:

- Convergence-divergence,
- Concentration-fragmentation,
- Vertical integration-fragmentation,
- Horizontal integration-fragmentation,
- International integration-fragmentation,
- Expansion-contraction.

These 6 dimensions are described in this paragraph, and the direction of current trends along each of these directions are then assessed.

3.4.1. Convergence-divergence

Convergence is a phenomenon where business models in an industry start to resemble each other, divergence being about business models diversifying (De Wit, 2020). The first part of this paragraph is about defining what a "*business model"* is. This appellation started to be used widely in the late 1990s, when (Lewis, 1999) defined it simply as "*How you planned to make money"*. Drucker (1994) refers to the "*assumptions about what a company gets paid for*", underlying that the perceived, or presumed business model is sometimes different from the way they in fact create benefits. Finally, a more organized definition was provided by Osterwalder (2013) through his canvas specifying 9 parameters:

- Value proposition,
- Customer segments,
- Channels of distribution, sales & communication,
- Customer relationships,
- Key activities,
- Key resources,
- Key partners,
- Revenue sources and amounts,
- Cost structure.

Each of these parameters will be evaluated regarding the MBT facilities point of view.

Value proposition

The end product delivered is a fuel that satisfies technical, economic, and legal requirements (see paragraph **3.1.1**), higher than unprocessed waste. The value is found in different levels of parameters according to the customers. Calorific value is expected to be gradually higher for power plants, cement kilns, lime kilns and blast furnaces (paragraph **3.2.3**). The levels of contaminants are a different concern for the customers according to which technologies are used (ADEME, 2015; IEA, 2020a). Therefore, the value proposition evolves towards divergence.

Customer segments

As shown in paragraph **3.2.3**, customer segments are expected to diversify, encompassing in addition to the cement producers, coal power plants, and eventually possibly the metallurgic and lime industries.

Channels of distribution, sales & communication,

The supply channels of waste input are most often local (World Bank, 2012). It can be explained by the low production yields, although high-income country shows more source-sorting that allow higher yields (see paragraph **3.1.2**). Low yields and cheap price make unrealistic to supply untreated waste from a long distance. Distribution occurs often up to 300km aways (De Caevel et al., 2018). Diversification in distribution appeared recently with exports that started in 2010 from Ireland and the U.K. (CIWM, 2018), while export volumes are expected to grow overtime until they reach a peak (see paragraph **4.2**). When it comes to information channels however, convergence is expected, because the improvement of marketing induced by broad standardization will be based on shared similar references (Chavando et al., 2022; Paolo & Paola, 2015).

Customer relationship

Little information on customer relationships was found in the literature. However, De Caevel et al. (2018) indicates that RDF combustion sites have a small amount of RDF suppliers. They also mention that such combustion sites are often owned partially by both the energy end user (often a municipality), and the RDF supplier. Therefore, a strong relationship seems to exist.

Key activities

In all business models encountered during the writing of this paper, the activities encountered had for purpose to process waste through a series of operations that are shaped according to the requirements of the end-users (IEA, 2020a). As explained in paragraph **3.2.3**, end-users tend to diversify, hence the techniques used can be expected to become more diverse across, or even inside firms. However, the standardisation of characteristics brought up by the new ISO standards can have an impact on firms and push them to adopt similar technologies in order to achieve characteristics that are more precisely measured, using more parameters.

Key resources

Key resources are used to perform the activities. The best-known examples are the machines used, as well as the labour. As more specialized and specific activities are expected to be used for RDF production overtime, more specialized and specific labour and machines can be expected, while still belonging to the same categories: resources used for sorting, screening, shredding (see paragraph **3.2.2**).

Key partners

Key partners are getting more and more diversified. While the first input for RDF was MSW (Alter, 1987), they nowadays can be processed for various other sources, as shown in paragraph **3.2.1**. Long term transportation implies to deal with actors that have great power induced from concentrated market: exporting companies (10 companies held 76% of England's RDF exports in 2017), ports (81% of England's RDF exported in 2017 went through 6 ports), and administrations (CIWM, 2018; IEA, 2020a). With further transportation also comes the need for appropriate packing, hence the developments of compacting and baling actors such as Orkel in recent years.

Revenue sources and amounts.

Revenue comes from the compensation the company is given to take charge of its input, unprocessed waste. This revenue decreases if waste is pre-treated upstream (**paragraph 3.2.2**). Despite being waste, some producers are able to sell high quality RDFs, therefore unlocking another source of revenue. This possibility however depends on the markets, as only a few, high income countries don't consider this resource completely as waste (ADEME, 2015; De Caevel et al., 2018). Along with regulations evolution, and higher quality fuels to fit new applications, this diversified source of revenue can be expected to be more common.

Cost structure

The main costs identified in the literature are, from highest to lowest:

- Operating costs (Ouda et al., 2016): 22-75€/ton of SRF were reported in Germany (Garg et al., 2007),
- Gate fee to end-users (ADEME, 2015; De Caevel et al., 2018): can vary from 80€/ton of RDF to none,
- Production technique improvement (IEA, 2020a),
- Infrastructure investment (IEA, 2020a),
- Raw waste collection, transportation if done by the RDF producer (IEA, 2020a),
- Elimination of refusal from the sorting process (ADEME, 2015).

Among these 6 identified costs, convergence is expected for 4:

- Collection and transportation costs can be minimized using logistics 4.0 in every market. A more urbanized population trend is moreover observed across countries, improving the density of waste sources, hence reducing the costs for collection and transportation

(Nowakowski & Wala, 2020). Convergence in cost reduction is therefore observed and expected.
- Although small capacity companies operate nowadays, large volume firms gain a competitive advantage on fixed costs (see paragraph **3.2.5**), which seem to be the converging trend happening.
- As RDF production is a growing industry, operating costs can be reduced by building up experience (Wright, 1936), a trend that is also converging for all types of actors.

With regards to the 2 other parameters, the industry can be considered to evolve toward divergence:

- As shown earlier, the gate fee is expected to disappear for high quality RDFs (including SRFs), while staying similar for low quality RDF. Two distinct cost structures could therefore emerge from the distinct products businesses.
- The elimination of sorting refusals costs has hardly expectable evolution, because societies evolve towards waste with less organic and more paper content (less sorting required), but more heavy metal contaminants, particularly from plastics and electronics (more sorting required) (World Bank, 2012).

Table 9 summarises the main costs for RDF producers, as well as the expected trends.

Cost source	Importance	Fixed/Variable	Convergence/Divergence	Evolution anticipated	Trigger
Operating costs	High	Variable	Convergence	Reduced	Experience
Gate fee to end-users	None to High	Variable	Divergence	Reduced & Steady	Depends on RDF quality
Production techniques improvement	Moderate	Fixed	Convergence	Reduced	Scale economies
Infrastructure investment	Moderate	Fixed	Convergence	Reduced	Scale economies
Raw waste collection and transportation	Moderate	Variable	Convergence	Reduced	Logistics 4.0 and urbanisation
Eliminating sorting refusal	Low	Variable	Divergence	Difficult to assess	Depends on waste composition

Table 9: Main cost sources for RDF producers

Summary of the paragraph

As shown through this paragraph, RDF producers' business models are evolving towards divergence, notably through their customer segments that are diversifying. As a consequence, and, also driven by more specific standards, the value proposition of their products is diversifying to fit these customers. Partners are going to be more diverse, as supply can come from various waste flows, new techniques are being developed and transportation firms are key when it comes to RDF exports. However, these changes are staying within a framework of producing a similar product (RDF), using similar techniques (Mechanical and/or biological processing and high labour), to achieve similar goals (providing a low cost, low emissions waste-derived fuel).

As a result, the RDF industry as a whole has not been assessed to clearly evolve towards complete convergence nor diversification.

3.4.2. Concentration-fragmentation

Concentration is the trend of a market whose shares are increasingly held by few companies, while fragmentation is where those large companies start to lose market shares, for the benefit of smaller companies (De Wit, 2020). Within this context, it is needed to introduce the concept of market, which is a notion with many definitions. We will use here the one given by De Wit (2020): "*a group of customers with similar needs*". In this paper, the customer can be downstream (energy consumers, as they use the product), and upstream (waste suppliers, as they pay to get rid of it). As the main actors in RDF and SRF are firms already specialized in MSW management (Chavando et al., 2022), this paragraph will describe the concentration trends of MSW management, precising when possible if RDF is specifically mentioned.

The needs of upstream customers are to dispose waste at low cost **3.2.1**, while the needs of downstream customers are to get a low price, low emissions and available fuel (paragraph **3.2.3**). The end-user often source RDF regionally, less than 300km (De Caevel et al., 2018). Similarly upstream, Antonioli and Massarutto (2012) showed that high transportation cost led to MSW treatment plants being located close to the waste collection clusters in Europe. Using this regional segmentation of markets, Di Foggia and Beccarello (2021) determined that the regional WTE market in Italy is moderately concentrated. Similarly, the ADEME (2015) showed that many facilities are owned by municipalities in France, leading to local concentration, and national fragmentation.

For high quality RDFs such as SRF, market segmentation can be made at the national, or international scale, because their energy-recovery value beat the costs of transportation (Antonioli & Massarutto, 2012). Within this segmentation, the waste management market is clearly concentrated, with the domination of roughly 5 actors per national market in Europe, alongside a few international companies. This mix of large national and international firms is also identified by Chavando et al. (2022). **Table 10** summarizes some of these companies:

- Large firms are present on the market, including national (from China, India, Finland) and international companies such as the world leader in waste management, *Veolia*.
- There is also a coexistence of private and public companies, which confirms the findings of Antonioli and Massarutto (2012) that both types of firms are growing bigger.
- Companies with a small number of employees are assumed to be purely active in trade and dealing, such as *Andusia* and *Seneca*, both cited by the CIWM (2018) as major exporting actors in the U.K.

Although the presence of small and middle enterprises is noticed, the general trend goes toward a concentrated market, which seems to be a consequence of vertical integration strategies (Antonioli & Massarutto, 2012; Di Foggia & Beccarello, 2021) where large upstream or downstream companies acquire RDF production facilities. Such results are confirmed by the presence of the Japanese firm *JFE Holdings* among the main waste management actors, a world leader in steel production (**Table 10**).

Name	Country	Status	Employees	Turnover/Revenue (MUSD)	Source
Capital Environment Holdings	China	Public	3,670	681	[1]
Jinjiang environment	China	Public	2,450	605	[1]
TPI Polene Power	Thailand	Public	740	290	[1]
Veolia	France	Public	220,000	45,090	[1]
PAPREC	France	Private	13,000		[1]
Advanced Disposal Services	United States	Private	6,000		[1]
Clean Harbors, Inc. US 1987	United States	Public	20,260	5,166	[1]
Covanta Holding Corp	United States	Private	2,280		[1]
Waste Management Inc.	United States	Public	49,500	19,698	[1]
3R Management	India	Private	6		[1]
Biffa Group	United Kingdom	Private	10,000	1,700	[2]
SUEZ UK	United Kingdom	Private	6,000	1,155	[3]
Andusia Holdings	United Kingdom	Private	13		[1]
Seneca Environmental Solutions	United Kingdom	Private	8		[1]
Renewi PLC	United Kingdom	Public	7,000	2,171	[1]
BMH Technology Oy	Finland	Private	160	34	[4]
Herambiente	Italy	Private	9,400	20,082	[5]
JFE Engineering	Japan	Private	60,430	30,500	[6]
Hitachi Zosen	Japan	Public	11,540	3,933	[1]
Beauparc Group	Ireland	Private	3,000	530	[7]
Enva	Ireland	Private	1,600	435	[8]

[1] www.pitchbook.com
[2] www.biffa.co.uk/about-us
[3] www.suez.co.uk/en-gb/who-we-are/suez-in-the-uk/about-us
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[6] www.jfe-holdings.co.jp
[7] www.irishtimes.com/business/retail-and-services/beauparc-utilities-sees-pretax-profits-jump-23-to-34m-1.4714314
[8] www.enva.com

Table 10: Top RDF, SRF and MSW management players (from Chavando et al., 2022)

3.4.3. Vertical integration-fragmentation

Vertical integration occurs where firms are becoming involved in more value adding activities in the industry column, while fragmentation occurs where firms are withdrawing from various value-adding activities (De Wit, 2020).

Antonioli and Massarutto (2012) indicate a clear trend towards vertical integration in the MSW treatment industry in Europe: it becomes a stake for both public and private actors to secure availability of waste supply upstream, and of solutions downstream. They outline that this trend is driven by the growth of private actors, in a market with a limited supply capacity where it becomes an advantage to internalize scarcity rent (the cost of competing for a limited resource proportional to land use).

Yet, Antonioli and Massarutto (2012) also show that a residual fragmentation is observed: despite large actors acquire high value-added phases as economies of scale are more important for technological complex tasks (see paragraph **3.2.5**), easier tasks are done by local actors, often public. Therefore, it can be understood that these easier tasks, which correspond often to the sorting activities upstream, are still held by nationally fragmented municipalities.

3.4.4. Horizontal integration-fragmentation

Horizontal integration is where the boundaries between businesses in an industry become fuzzier, while horizontal fragmentation is the trend of firms becoming more strictly confined to their own businesses (De Wit, 2020). When it comes to the waste treatment industry, the various businesses can be described upstream (by sources: ICIW, CDW, MSW), at the RDF producers' stage (Mechanical or Mechanical-Biological Treatment), and downstream (dedicated solutions and co-combustion solutions). As shown by Antonioli and Massarutto (2012), the vertical integration observed has been coupled with horizontal integration of activities, where large groups acquire various techniques in order to achieve economies of scope. Yet, there seem to be a partitioning downstream, between historical waste actors handling dedicated activities (incineration, pyrolysis, gasification) and material producers owning the facilities that receive RDF for an industrial incineration purpose (cement, lime, metallurgy).

3.4.5. International integration-fragmentation

International integration is the trend of "*international boundaries separating various geographic segments of an industry becoming increasingly less important",* while with international integration, the businesses become confined within countries or regions (De Wit, 2020).

In 2016, considerable amounts of plastic waste were exported in the world, with a clear trend of flow from high income to low-income countries (Gregson & Crang, 2015). As an example, G7 countries export mainly to Asian middle-income countries (IEA, 2020a). Some 14 million tons of plastic waste were exported around the world in 2016. Although the plastic & paper waste ban set by China in 2017 reduced this amount, such trade is still important, and mainly driven by a under capacity of treatment facilities inland (IEA, 2020a). Concerning RDFs, favourable costs differences are also driving such trade.

However, the fact that RDF is a fuel allows excess products to be sent to closer countries than untreated plastic, because there is more demand for it. As shown by the IEA (2020a), most international trade occurs within Europe, or within South-East Asia, with little business between these regions. Regulations about waste exports can also hamper long-distance RDF trading, as did EU regulations for extra-Europe waste exports (Gregson & Crang, 2015).

A limitation of this assessment is that most of the research found on waste trade trends is scoped on Europe. As shown by the World Bank (2012), the biggest producers of waste are outside of Europe, and these countries will produce much bigger amounts, while European nations are leaning towards waste reduction incentives (IEA, 2020a). The drivers of international waste exports in Europe (capacity unbalances, cost differences) (De Caevel, 2018), can be expected to repeat in these countries: unsynchronized regulations requalifying RDF as a resource across countries, demand for low-carbon fuels and capacity mismatch within countries are phenomena than can be expected to occur in countries in Asia, Africa and South America.

In short, RDF trade is expected to slowly grow to the mid-term until a peak and a decrease in Europe, while it is likely to expand greatly in middle and low-income countries, then will represent a huge share of the volumes considered. The international trend can therefore be considered to become increasingly integrated. RDF international trade is discussed further in paragraph **5.2.**

3.4.6. Expansion-contraction

Expansion and contraction are terms related to the increase and decrease in demand of an industry (De Wit, 2020). As described by De Caevel et al. (2018), the IEA (2020a), and Chavando et al. (2022), the volumes of RDF produced, traded and used are expected to grow, mainly driven by increasing input volumes (waste), low cost (permitted by legislations, standardization, scale economies), and low emissions (related to the product properties and to technological development).

3.4.7. Industrial development results

As shown throughout this paragraph of the thesis, the RDF industry is experiencing acute industry developments, along most of the dimensions analysed. A radical expansion of the business is observed and expected, while moderate horizontal, vertical and international integrations are occurring. The industry is clearly evolving towards a concentrated market, partly because of these integrations. Finally, the diversification of customer segments leads to the emergence of specific business models with dedicated key activities and key partners while cost structures are following two main models, according to whether RDF can be sold, or has to be taken in charge for a gate fee. A summary of the industry development indicators is displayed in **Figure 13.** These changes are likely to be driven by continuous forces such as the gradual use of standardization, technological innovation, while the introduction of national regulations on waste-derived fuels will stimulate discontinuous development, where actors can take advantage of temporary legal unbalances across markets.

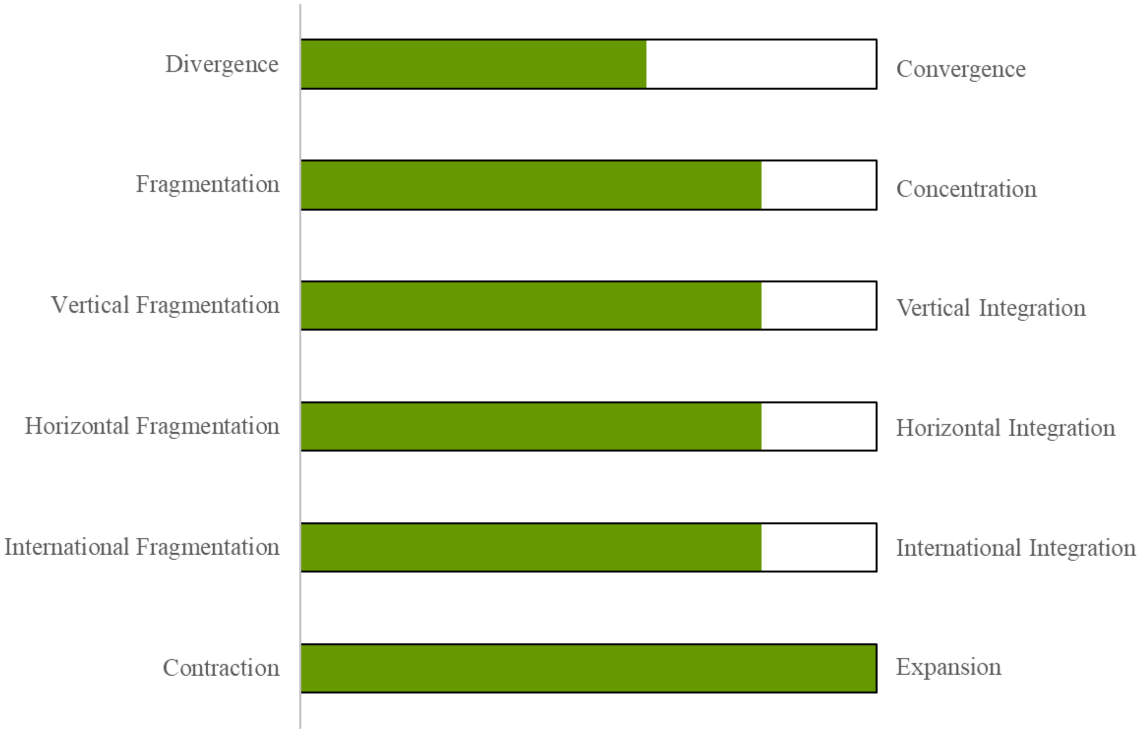


Figure 13: Industry Development indicators

4. Quantitative multi-case study: RDF potential by region and by country

The literature review conducted in chapter **3** highlighted that the RDF industry development is greatly various across countries, showing a concentration of production and trade in specific regions, or even countries. In order to develop a grasp of the overall industrial context, there is therefore a need to study each national context. Paragraph **4.1** consists in a quantitative analysis of RDF production potential by region, while **0** is quantitative multi-case study of RDF production and use potential in 39 selected countries.

4.1. RDF potential production by region

RDF potential production has been calculated, based on the data of Error! Reference source not found.**.** The results can be found in **Figure 14.** The total amount of RDF that could potentially be produced worldwide by 2025 is of 630 million tons, with a high polarization towards high-income countries, which is a result of a high amount of paper and plastic in their waste, as well as higher collection rates.

The OECD, which concentrates most of the current producing countries (Europe, Japan, the U.S.), can contribute to 50% to the worldwide RDF potential production. The East Asian and Pacific countries also represent a huge potential for RDF production. This region including China, Thailand, for example, shows high yields of plastic and paper, as well as interesting MSW collecting ratio. When it comes to comparing with current RDF production volumes, the most promising region is Latin American and Caribbean: greatly populated middle-income countries (Mexico, Brazil, Columbia) of which most don't produce RDF yet, as will be detailed in the next paragraph.

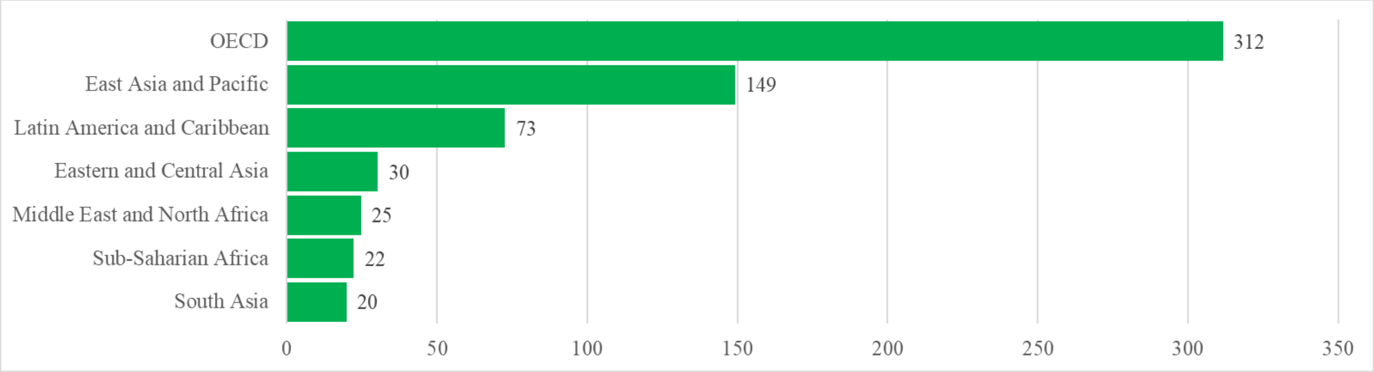


Figure 14: Potential RDF production in 2025 by region (MT/Yr)

4.2. RDF production and use potential by country

After studying a wide scope, it is relevant to dive into the specific contexts of the RDF industry state and potential by country.

4.2.1. Case categories

Alongside the systematic literature review conducted for chapter 3, a list of 39 countries was constituted, formed by every country encountered. They were divided into three categories (**Figure 15**).

Countries with relatively mature RDF industry (16 countries)

The first category noticed is a group of high-income countries, all from the OECD group, where RDF production techniques are known and used on a great scale. They include mainly high-income countries from 3 regions:

- Western and Northern Europe countries (such as Sweden, France, Poland, Germany),
- East Asian countries (Taiwan, South Korea, Japan),
- The United States.

In some of these markets, the production trends of RDF have been observed to stagnate or decrease over the past few years. In some rare cases, such evolution is mainly caused by a shortage of available waste (Austria, Germany) (IEA, 2020a). Among these countries, the United States stagnate at low production levels although the technology is mastered, a phenomenon that seems to be due to a lack of governmental support. Lower population density may explain the lesser extent of the *"Not In My Back Yard" (NIMBY)* effect that triggered regulations in other countries (De Beer et al., 2017). Most of these countries have adopted landfill bans or taxes, which is likely a driver for the development of RDF, as assessed in paragraph **3.3.2.**

Country with emerging RDF industry (18 countries)

This category consists of all the countries cited in the literature that produce RDFs and whose production is expected to grow, as they started to invest in this industry only a few years ago. Most of these countries have middle-income levels. They consist in:

- Eastern Europe countries (Bulgaria, Greece, Turkey),
- Middle East countries (Egypt, Iran),
- Highly populated Asian countries (China, India, Thailand, Pakistan),
- Mexico.

Countries with potential for an RDF industry (5 countries)

This category corresponds to countries where research on potential RDF implementation has been conducted, without an industrial scale physical implementation. These are Canada, Brazil, Singapore, Jordan, Kazakhstan.

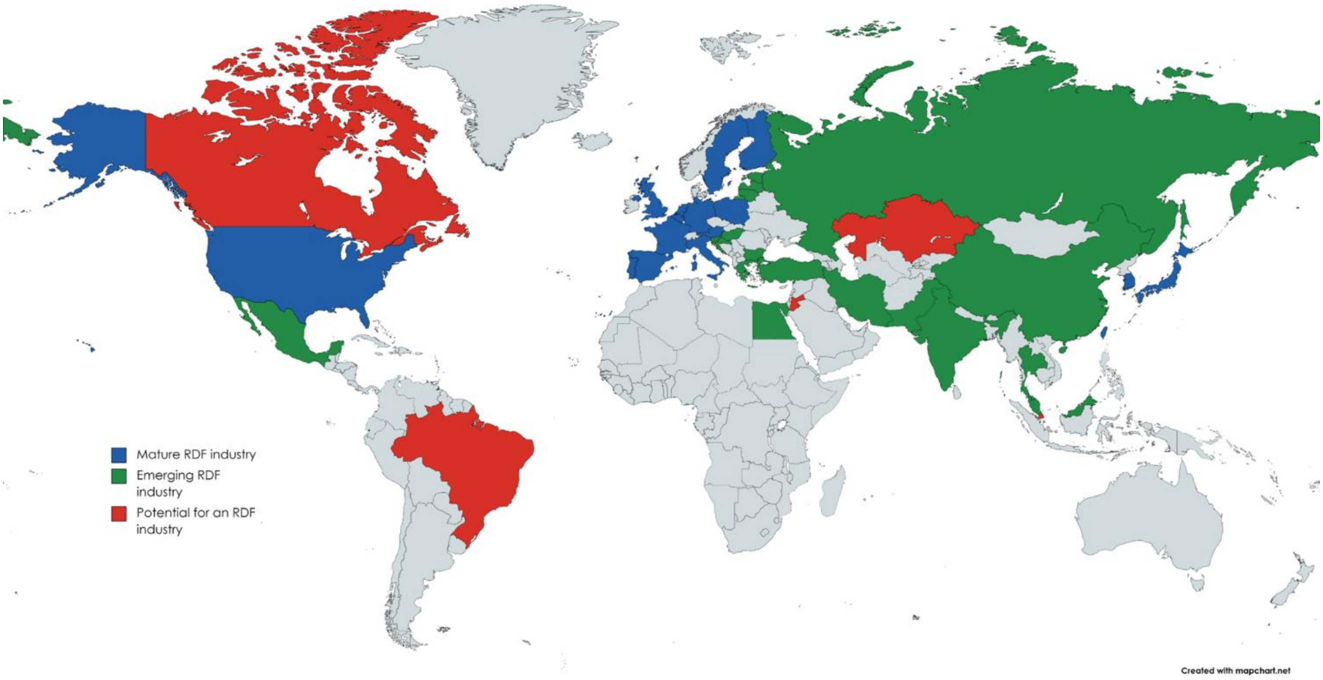


Figure 15: The 39 countries considered in the multi-case study.

4.2.2. Result of the case study

A multi-case study was handled, with a two-sided perspective. First, the upstream section of the value chain was analysed, gathering the amount of MSW produced (as this is the most common input for RDF according to the IEA (2020a)), and calculating the maximum RDF production capacity. Then, the downstream section of the value chain was analysed, calculating the importance (absolute and relative to their CO2 emissions) of the end-use industries. Following the findings of paragraph **3.2.3,** only coal-intensive industries were considered: cement, steel, lime, and coal power plants. Dedicated uses (gasification, pyrolysis, combustion in WTE plants) were not considered as there is less obvious advantages of using RDF in terms of emissions and availability. Furthermore, their production capacity is hard to predict as it depends on local and national policies, whereas the coal-based end-uses are driven by specific demand volumes. The results are illustrated in **Figure 16**. The supporting data is available in **Appendix 5** and **Appendix 6.**

These graphs confirm that the emerging countries are big producers of cement, which has been highlighted as the main end-use in most of research found. Furthermore, one can notice that many of these countries also produce also high amounts of coal-fired steel, which is promising for diversified end uses. Particularly, China appears as the country with the highest potential for RDF production and use in all industries considered. Highly populated middle-income countries are also highlighted: India, Thailand, Turkey, Pakistan, Egypt.

The sizes of the bubbles correspond to the national production of the end use, in kT/yr for cement, lime and steel, and in TWh/yr for coal power plants

Figure 16: Potential RDF prod. and importance of end-use industries for the selected countries.

Mature countries show low emissions related to cement, which can be a result of their diversified industry and use of alternative fuels such as RDF. Noticeably, their shares due to the steel and coal thermal plant industries are relatively high, showing a potential for more end-use. However, for these countries, as shown by the IEA (2020a), the availability of enough waste is starting to be an issue.

Among the potential countries, Brazil shows favourable signs for the development of an RDF industry, as it is a major producer of steel, cement and lime. Although not being highlighted by these graphs, Canada and Singapore can also develop industries rapidly, as they are the only high-income countries not categorized in the “mature” section. High income countries produce a MSW with high shares of plastic and paper, which can provide high yields for RDF manufacturing.

5. Qualitative case study: baling within the RDF/SRF industry

The second research question of this thesis deals with the impact that baling technologies can have on the RDF industry. This part is related to the company Orkel, that manufactures compacter/balers. Paragraph **5.1** analysis the company Orkel on a manufacturing point of view. Because baling is of great support when it comes to long transportation of goods, paragraph **5.2** will study the trading trends of RDF. Then, paragraph **5.3** will contain a description of how can baling be useful also for local use of RDF.

5.1. Orkel AS: manufacturing analysis

The information that follows is provided by contacts at Orkel, otherwise the source is cited.

5.1.1. Market and customers

Orkel is selling its units in a B2B (Business-to-business) system, to companies and local authorities. The contracts run for a small number of units. Orkel has sold in 2021 around 130 units, with a rapid growth in sales. The sales occurred with several dozens of customers so far, but the potential market is much bigger, and expected to grow over the years. The country in which are located most of their actual customers is the United Kingdom. However, they have sold industrial compactors intended to process RDF countries all over the world: Portugal, Belgium, South Africa, Romania… These units are also sold in facilities that handle other types of waste, as in a landfill in Taiwan for example. As every ETO (Engineering-to-Order) business, demand quantity is highly variable, but there is an ongoing increasing trend for utilities dealing waste for energy, which means growing demand is expected. Their main competitor in northern Europe on the industrial compactor market is Flexus Balasystem, a Swedish company which manufacture bigger, stationary industrial compactor-ballers.

5.1.2. Product

Orkel's main activity is about producing compactors-balers. For industrial and agricultural purposes, this process opens several advantages for the baled material:

- The volume is reduced from 50 to 70%,
- It makes them easier to handle, store and transport,
- There is a decreased risk of contamination from and to the material,
- It is easier to stack.

The production time is of 600 to 1000 hours, with a delivery lead time below 10 weeks for most units. The manufacturing strategy is Engineer-To-Order, characterized by high product variety, and low volume. Most of the structure and optional modules are pre-engineered, and solutions are usually tailored using this basis. Projects with more specific requirements, therefore more customization, can be accepted. The engineering takes from a few days to a few weeks. The product is sold at a price that can vary from approximately 500 000 NOK to several millions NOK.

They have two product families: agricultural compactors and industrial compactors. The latter has been developed on the basis of agricultural compactors, modifying some elements to fit waste products. RDF is one of the possible uses, among others such as saw dust, animal waste, etc.

Contrary to some of their competition, their units are mobile so that they can move between locations. This characteristic was already integrated in the agricultural compactors, as the need to move to and in the fields is important. Industrial compactors are often embedded to fixed processing lines so that this point is less critically relevant. However, this characteristic is useful for customers that intend to use the compactors for mobile purposes, such as compacting waste directly from landfills.

The size of their units makes it possible to transport them inside standard containers, with few preparations processing. This ensures a cheap, quick and reliable delivery. As sales operate at a worldwide scale, most of the transportation occurs by ship. Before that, units are first delivered to the ports by truck, or by rail. Once they arrive at the customers, the units can be ready to operate after a day of assembly on site.

5.1.3. Manufacturing operations

The manufacturing layout is a mix of functional layout and a cell layout. The process is labour intensive, with approximately 40 workers involved in production, as well as welding robots. The units are processed into each cell, then moved to the others (through welding, structure mounting, painting, assembly, testing, transport preparation). The facility is using some technologies related to industry 4.0: facility mapping, automobile robots, etc.

5.1.4. Competitive priorities

One of the drivers for the expected growth in sales is the promising competitive situation of Orkel. First, the ease of use, mobility and smaller size of their units allow them to reach other types of customers than their competitors. Compared to much bigger products, Orkel's units are sold at a cheaper cost, and easier to maintenance. Furthermore, the quality materials (Norwegian-sourced stainless steel, rubber conveyor bands) and their highly skilled labour makes their compactors reliable overtime, with a life expectancy of up to 1 million bales. Orkel is a company that is technology driven, with high trust and importance given to R&D. Product development is triggered by customer requirement, but also pushed by internal concerns on ways to improve product characteristics and quality.

5.2. Baling within RDF trade

5.2.1. Trade characteristics

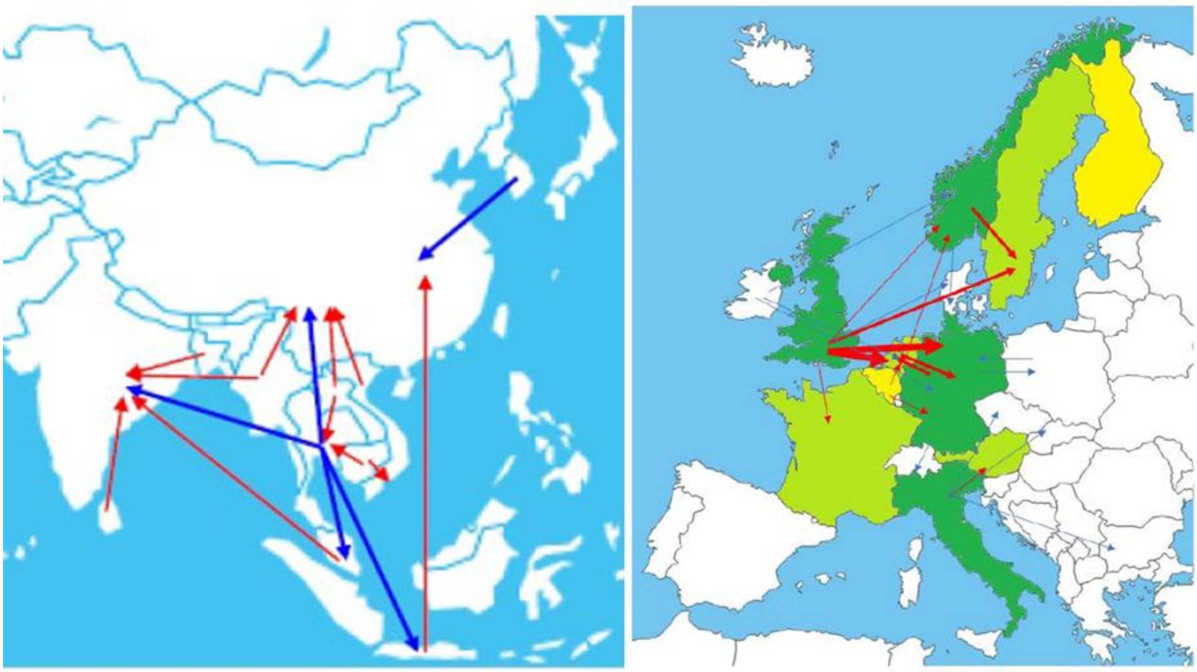
Nowadays, baling in the waste industry mostly happens when there is a need for long transportation, as the baling advantages (identified in paragraph **5.1.2**), such as smaller volume and easy handling overcome the costs (**Table 11**).

Operation	**Cost (€/ton)**
Producing RDF	15-20
Baling & wrapping	5-10
On-land transportation (up to 65km)	10
Administration & port costs	5-10
Sea Transportation costs	0-15
Gate fee	40-60
Total	*75-125*

Table 11: Costs related to RDF exports, for a shipment U.K. - mainland Europe (AMEC, 2013)

As shown in paragraph **3.4.5**, international business of RDFs is well developed, as for other waste types. However, offshore business seems to mainly thrive within neighbouring countries. As illustrated in **Figure 17,** two exporting clusters have been identified in the literature: Europe (De Caevel et al., 2018) and South-East Asia (Ishigaki, 2017).

The market evolution is described as “dynamic” by the RDF Industry Group (2022): high variations of exports and imports volumes have been observed in the last few years. They indicate that some former importers have become net exporters (Germany since 2020) while other countries like the U.K. have decreased their exports since 2017. Undeniably, the main exporting countries are often among the main producers identified in paragraph **4.2.2**: Thailand (0.5 MT exported in 2013), the United Kingdom (3.2 MT in 2016), South Korea (1.8 MT in 2013) are some examples (AMEC, 2013; RDF Industry Group, 2021). The main importing countries are the ones that host the biggest end-use industries: China and India are the two single main cement producers, while Germany is the main in Europe (IEA, 2020)



Ishigaki, 2017

De Caevel et al. (2018)

Figure 17: RDF trading trends in South-East Asia and in Europe

5.2.2. Trade trends in Europe

The AMEC (2013) describes that the exports of RDFs from the British Isles were specifically triggered by a capacity mismatch between production and end-use (waste is constantly created, while energy needs can vary), and facilitated by regulations. De Caevel et al. (2018) explains furthermore that the mismatch in RDF sectors between countries led to a wide scope of prices. Consequently, exports from countries with high gate fees became profitable. When it comes to regulations, both national and international policy frameworks influence the exporting industry. European regulations aiming at sustainability goals have changed the status of waste derived fuels, leading to easier business. Furthermore, a waste of high quality has become easier to obtain legal permission to export, as shown in the British Isles where RDF exports have been allowed in 2010 (AMEC, 2013).

De Caevel et al. (2018) and the IEA (2020a) report that RDF trade has increased in the last decades and is expecting to grow bigger as production and end use capacity increase, while regulations evolve in a facilitating way. However, international trade of RDFs can be expected to eventually become irrelevant for mature markets such as Western Europe. Indeed, the European regulations, pressure of public and national goals for sustainability will probably lead to similar regulations on landfills and gate fees, which will hamper the wide scope of costs observed (De Caevel et al., 2018). Furthermore, governments should aim at finding a domestic alternative (AMEC, 2013).

Margins may decrease, while high exporting costs are expected to be constant (see **Table 8**) and new national regulations on imports are introduced, that aim at protecting a country's industry, such as a 31€/ton tax on waste imports deployed by the Netherlands (Chavando et al., 2022). In this perspective, in Europe, the need of baling equipment, for long-distance transportation is expected to grow in the next decades and decrease in the long term for a mature market.

5.2.3. Trade trends outside of Europe

Trade of RDF occurs between two countries when they have both started to develop an RDF sector. This paragraph will study the clusters of countries from the "*emerging*" category identified in paragraph **4.2**, because it is the countries where most RDF production increase is expected (**Figure 18**). Three main cluster have been identified.

- Countries from the South-East Asian cluster can be expected to develop more trade, as they are far from the possible RDF production capacity. The countries identified as having an RDF sector are Thailand, Malaysia, India and China. There is a potential for 124 Mt/Yr of RDF produced within this cluster.
- A new potential cluster around the East-Mediterranean coast can be identified. Greece, Turkey, Egypt, and Hungary are part of this cluster. Jordan (part of the "*potential*" category) could also be included in this cluster. The potential is of 22 Mt/Yr of RDF.
- Another potential cluster is between Iran, Pakistan and India. Although this is only 3 countries, they all show proofs of existing RDF sectors and account for 36 Mt/Yr of potential RDF production.

Two minor clusters can also be identified. They represent smaller amounts of potential RDF production, and less of a need for shipping, as reliable road networks link them.

- Central Europe cluster: RDF industries exist in Slovenia, Croatia, and Bulgaria, for a total of 2Mt/Yr of potential RDF production.
- Baltic cluster: Estonia, Latvia, Lithuania account for a total of 1 Mt/Yr of potential RDF production.

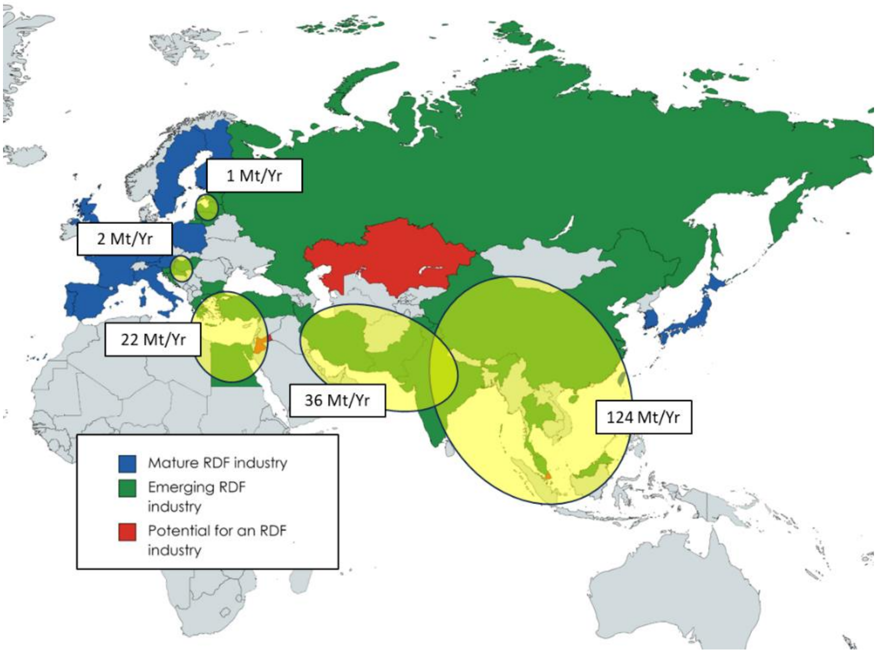


Figure 18: Expected trade clusters among the RDF "emerging" countries

5.3. Baling within local use

Moreover, baling is also relevant for RDF local use.

- The advantages of baling regarding handling and contamination risks are still key criteria for local actors, although not as important as for long distance travel.
- As RDF developments remain unpredictable, Velis et al. (2010) showed that baling had to be used in Germany when production exceeded consumption in cement kilns.
- For end uses such as waste-to-energy, seasonal demand has led some countries, particularly Sweden, to sporadically build RDF stocks by baling and storing it in the summer months in order to provide a sufficient stock in the winter months (AMEC, 2013)

These arguments indicate that baling is in general likely to be used where RDF is produced in general, Therefore, the findings of paragraph **4.2** about the potential producing countries are also valid for considering them potential place where bale users for RDF will be found.

The development of RDF and SRF standards can benefit to baler-compacter manufacturers, as the production process of these units involve a relatively heavy design phase in order to fit their characteristics to the good handled. Potentially, a broad use of ISO standards could help to reduce this design stage. By conceiving units that have proven to be suitable for a specific class, replicability of process can be achieved, reducing lead time and engineering costs.

6. Results & Discussion

The objective of this research has been to characterize the industrial context of Refuse Derived Fuels (RDF) and Secondary Recovered Fuels (SRF), on a worldwide scale. On a secondary basis, the trends that can influence and be influenced by baling technologies have been described.

6.1. R.Q.1 Industrial context of Refuse Derived Fuels

R.Q.1: Which key parameters define the industrial context of Refuse Derived Fuels and Solid Recovered Fuels across markets?

As showed by the analysis conducted in chapter **3.1.1**, RDF tend to be defined by qualitative characteristics such as their calorific value and contaminants levels. Recent standardisation named SRF as an RDF that complies with specific content and processes. The most influential is undeniably a set of ISO standards published since 2021, although some scholars recommend developing standards based on more criteria, with more classes.

Noticeably, standards facilitate the description of this product through its composition. Indeed, greatly various compositions are found, depending on:

- Its source stream: MSW, CDW, ICIW, agricultural waste (paragraphs **3.1.2** and **3.2.1**). Most literature focuses on MSW, as does this thesis.
- The geographical location of this stream, with significantly higher amount of plastic and paper materials in MSW of high-income countries than in low-income countries (paragraph **2.2.2**)
- The end-use intended (paragraph **3.2.3**)

The most promising end-uses for RDF and SRF are industries that require fuel with high quality, (characterised by the calorific value and the composition in contaminants), and consistent characteristics overtime. Two categories of end-uses were identified in paragraph **3.2.3**.

In the first category of end-uses, RDF can be used as a co-fuel in industrial co-combustion plants. These industries existed already prior to the use of waste as a fuel.

- The cement industry has adapted its processes and is using RDF in most European producing countries. The quality requirements for RDF in this end-use are medium, with noticeably a NCV over 15 MJ/kg (ISO class 3), and the potential substitution rate are up to 77% in practice, 100% in theory.
- Coal power plants can use RDF in co-combustion with up to 10% substitution rate. Low quality requirements such as a NCV of 13 MJ/kg (ISO class 4) can fit this industry.
- The steel industry is promising, and RDF is already used in such plants in Japan, Austria and Germany. However, it requires RDF of a very high quality: NCV over 25 MJ/kg (ISO class 1), with rather low substitution rate achieved to this date (up to 3%).
- Lime kilns represent an interesting industry to explore, although they use quite less coal than the three others. Lime is used for many purposes, such as metal processing, construction, chemicals. The quality requirements for RDF are high (NCV of 23MJ/kg, ISO class 2), and the substitution rate attains 10% in practice, up to 60% in theory.

In the second category of end-uses, RDF can be used as a dedicated feedstock.

- The usual Waste-To-Energy industry shows mixed results in terms of potential for RDF, particularly because the energy increase and emission savings of using RDF instead of MSW can hardly compensate the energy and emissions related to the production of RDF.
- More advanced processes such as gasification and pyrolysis are encouraging processes to produce gaseous fuels or chemicals from RDF. The quality requirements for RDF use are medium (NVC of 18 MJ/kg, ISO class 3)

The growth in RDF production (as studied in paragraph **3.3**), is mainly triggered by:

- National and international policy drivers, noticeably landfill bans/taxes and emission trading. Although bureaucratic obstacles can lessen this driver, they are in some contexts lower than for other waste facility types, with short commissioning times found in the U.K. for example.
- Economic drivers: cost compared to other treatment solutions (upstream) and other fuels (downstream). These are also influenced by taxes and exchange rates.

To a lesser extent, these two categories of factors also influence the RDF industry developments.

- Socio-cultural drives: public perspective towards waste combustion influences policies, even more considering that many actors are public.
- Technical drivers: technology readiness allow RDF to be produced easier, as well as it enables new end-uses, as the main technological barriers are located downstream. Mismatch in capacity also triggers trade between regions or countries.

Paragraph **3.4** studied the evolution trends of the RDF business:

- Business models are differentiating in end-uses and cost structures, while converging in activities thanks to standardised methods.
- The market becomes more vertically, and horizontally integrated, as international private firms acquire similar activities across countries (horizontal integrations), and different activities along supply chains (vertical integrations). However, tasks with low value added, and lower entry barrier due to their low capital costs, are still let to local municipalities.
- The volumes are expected to expand. This phenomenon will be triggered by trends in both the waste management industry (upstream), and the energy/material recovery industries (downstream). In waste management, environmental regulations both push waste recovery, and facilitate waste trading. In energy/material recovery, environmental regulations on fossil fuels-related emissions, and uncertainties in supply due to resource scarcity and geopolitical events makes waste-related fuels more and more relevant. In Europe, this growth will be limited first by the capacity of RDF production facilities, then by the amount of feedstock (MSW, CDW and ICIW) that will decline due to less generation and more recycling.

One of the findings of the literature review led in chapter **3** is that the development of the industry will not happen simultaneously, leading to RDF production volume evolutions greatly varying across countries. The multi-case study conducted in chapter **4** shows that among 39 countries identified in the RDF literature,

- 16 can be categorized as “*mature”* countries, mainly from the OECD, that will evolve towards stagnation in production,
- 18 can be categorized as “*emergent”* countries, mainly in Asia and Eastern Europe, that are expected to show the greatest evolution trends in the next decades,
- 5 can be categorized as “*potential”* countries, as they show literature on RDF without traces of an industrial sector.

The results from the chapter **4** confirm the emerging countries may be driven by high expenses and emissions in the cement industry, and also shows that new end-uses such as coal-fired blast furnace for steel production lead to more need for RDF in mature countries.

Chapter **4** also shows that potentially 630 million tons of RDF per year could be produced in the world by 2025.

6.2. R.Q.2: Orkel scope of action

RQ2: Which parameters can influence Orkel impact on the value chain?

Orkel is producing industrial compactors. Therefore, their technology is intended to be used at the RDF/SRF producers (**Figure 19**). Orkel technologies are intended to bale and wrap material, which allows a seamless handling, storage and transportation. Whether there is an interesting context depends highly on the product characteristics, and on the need for RDF/SRF producers to transport their products.

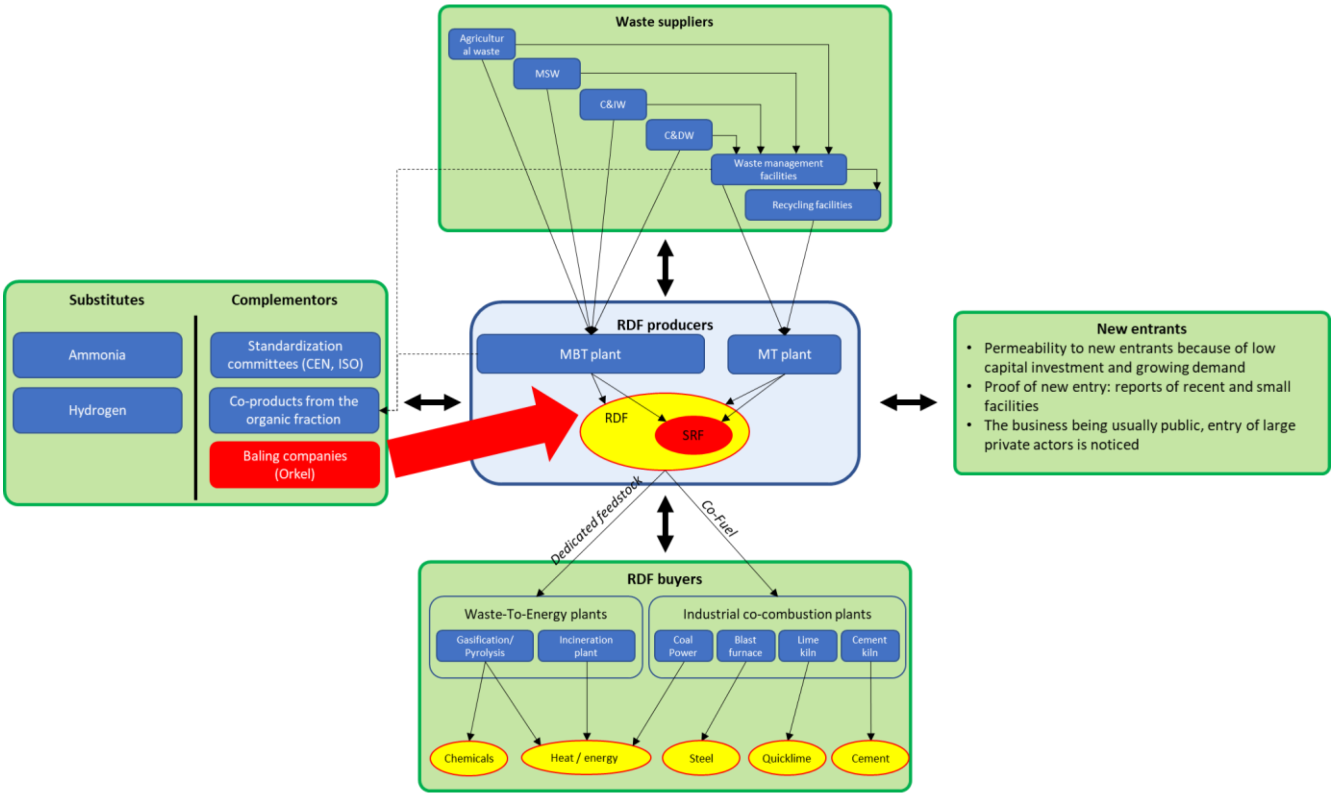


Figure 19: Orkel scope of action within the RDF/SRF industrial context

Chapter **5** helped identifying relationships between baling technologies such as Orkel's, and the industry characteristics.

First, the main use for baled RDF is when there is a long-distance transportation, as the price of baling is small compared to other costs. As RDF trade has been observed mainly in geographical clusters of countries that have a RDF sector, potential clusters for trade have been identified. Excluding the European cluster that is assumed to cap in a few years, the most important clusters are:

- South-East-Asia, with a potential RDF production of 124 Mt/Yr,
- East-Mediterranean coast, with a potential RDF production of 22 Mt/Yr,
- Iran-Pakistan-India, with a potential RDF production of 36 Mt/Yr.

Second, RDF has also been proven to be used in the RDF industry in general, a finding that indicate that the countries expected to develop a sector will represent potential markets for baler-compacters.

Third, the development of international standards for RDF/SRF, will be directly beneficial to Orkel as they will be able to cover several markets with few designs' effort. Indeed, their manufacturing strategy is based on customizing standard structures with optional modules to fit their customer. With RDF dimensions, density, and contaminants level that are similar for their current and future customers, this will help reducing design cost, as well as delivery lead time.

6.3. Limitations of the results

The research conducted for this thesis was limited by a number of aspects, that will be discussed in this paragraph.

Although extensive research was found about countries with mature RDF industries (Europe, Japan, Korea), more sparse information was found for countries with emerging RDF industries. Most literature for these countries consists either of specific case studies on one plant, or qualitative literature reviews. Particularly, the lack of nation-wide quantitative information made complex to gather the data used for the case studies. Consequently, the lowest available estimations were considered for MSW generation, and RDF production.

Most of the literature focuses in MSW, while CDW and ICIW are considered in a small number of research sources. Agricultural waste is mentioned in even fewer papers. The composition, and actors involved in these waste sources being different from one to another, more research on RDF produced from these feedstocks could help understanding how supply chains are built for CDW, ICIW, and agricultural waste.

For end-uses of RDF, some authors mention a use in the industry, but a limited number of papers study the possible use in terms of substitution rate, and quality requirement. This issue arises particularly for the steel and lime industry. An explanation for it can be the confidentiality of data on a low-carbon fuel such as RDF, in coal-intensive industries where emissions become a competitive advantage thanks to regulations and emission trading.

The quantitative data compared has been gathered from secondary sources, that measure waste volumes with various indicators. As a result, comparisons between countries' industrial context are made particularly complex. The focus on MSW (a waste stream whose characteristics have a broad consensus), and the use of ISO classification were aimed at reducing the impact of this limitation.

7. Conclusion

This thesis has explored the developments in play in the RDF (Refuse Derived Fuels) and SRF (Solid Recovered Fuels) industry.

A literature review showed that recent RDF have various composition and are made through various processes, depending on local contexts:

- It can be made from various waste streams, although most literature focuses on Municipal Solid Waste,
- For a given waste stream, the composition varies dramatically depending on the country, impacting the production process and final composition of the RDF,
- Because of its nature of fuel, RDF is often manufactured to correspond to the quality requirements of a specific end-use.

Promising end-use sectors are:

- Co-fuel for the cement industry, most developed to this date, with medium quality RDF,
- Co-fuel in coal power plants, suitable for RDF of low quality,
- Co-fuel in the lime industry, suitable for RDF of high quality,
- Co-fuel in the steel industry, suitable for RDF of very high quality,
- Dedicated feedstock for gasification/pyrolysis plants, that can produce gaseous fuels or chemicals, suitable for RDF of medium quality.

The review also highlighted that producing RDF in order to incinerate it in regular Waste-To-Energy plants is hardly relevant, because the emissions and energy used for RDF processing offset the benefits of combusting it compared to regular waste. In fact, RDF main strengths in a life-cycle perspective turned out to be industries that specifically require high-quality solid fuels: coal-intensive industries, and dedicated gasification/pyrolysis facilities.

Another major finding of the literature review is that the main factor influencing the industry development is economical (low cost of RDF compared to other fuels), heavily influenced by regulations (landfill bans/taxes, gate fees, taxes on combustion). Public pressure and technology readiness level were also identified as triggers for RDF expansion.

As studied further in a multi-case study, the development trends are varied across 39 countries studied:

- 16 "*mature*" countries show a potential capping of production volumes to the mid-term perspective, although the development of the steel and lime end-use might represent a bounce in demand,
- 18 "*emergent*" countries produce RDF and could potentially ramp up to high amounts of RDF. They also concentrate a large portion of the end-use industries,
- 5 *"potential"* countries that don't produce RDF yet were identified.

In total, 630 million tons of RDF could be produced from nowadays Municipal Solid Waste streams worldwide.

RDF international trade has been identified when countries with a sector are located close to each other’s. Two main clusters are described in the literature: Western Europe and South-East Asia. The multi-case study confirmed the possible growth of the South-East Asia cluster, while identifying two potential main cluster for RDF trade: East-Mediterranean coast and Iran-Pakistan-India.

It is found that RDF/SRF development will be beneficial to Orkel’s solutions related to waste:

- Direct influence: standardised product characteristics will shorten design time and cost to deliver suitable units,
- Indirect influence: the growing local, national and international business will lead to more demand for Orkel units as they make handling, storage and transportation easier and cheaper.

Along the research conducted for this thesis, some limitations were encountered:

- Most literature focuses on countries from Europe, which led to most of data used for other countries being sparse. Particularly, a lack of literature reviews based on nation-wide quantitative data was identified.
- Similarly, most of the literature found focuses on Municipal Solid Waste, which represents a fraction of all waste emitted. There is therefore a potential for literature reviews on Institutional, Commercial and Industrial Waste, as well as on Construction and Demolition Waste.
- The end-use processes are often subjected to company confidentiality, making the feasibility assessment complex for indicators such as theorical substitution rates.
- The definitions used across literature for MSW, and RDF can be varied. This result in potential errors in the quantitative case-studies, especially with production volumes.

This thesis contributed to existing research by highlighting the tight relationship between RDF use, and standardisation, as well as by describing the industrial trends first worldwide, then by country group, finally by identifying specific countries where the industry is mature, emergent or potential. A relevant finding is that the trends are simultaneously different across these categories, because they are experiencing the same industry development stages (introduction, growth, maturing, decline), but not at the same time. Finally, potential new clusters for RDF production, use and trade were identified.

Further research can be conducted on new end-uses such as furnace in paper manufacturing, or ceramics. Another trigger for RDF demand can be the viability of technologies such as gasification and pyrolysis, for which large-scale industrialization is only starting.

Appendixes

Appendix 1: International standards and Solid Recovered Fuels

The two international standard organizations mentioned in this thesis are CEN (European Committee for Standardization) and ISO (International Organization for Standardization). Both organisms produce several types of documents, of which three are used in this thesis (boss.cen.eu; iso.org).

- TR: Technical Report. This abbreviation describes an informative document and contains data such as a survey results, an informative report, or information of the perceived "state of the art". Such document's code contains CEN/TR or ISO/TR
- TS: Technical Specification. This abbreviation addresses work that acts as a "pre-standard". It is immediately published. It can evolve into a proper standard, which is why feedback is allowed to potentially develop the most appropriate standard. Such document's code contains CEN/TS or ISO/TS
- EN and ISO: European Standard and International Standard. This document contains rules, guidelines or characteristics. While ISO standards are purely informative and can lead to conflicts with national standards, EN standards replace any conflicting national standards emitted within their member states. Such document's code contains CEN/EN or ISO.

ISO and CEN standards are named with the document type, the reference number and the year of publication in a subsequent order.

- CEN/TR 14745:2003 is a technical report published by CEN in 2003.
- ISO 21640:2021 is an international standard published by ISO in 2021

When a document is published or endorsed at the European, or national level, its name takes an abbreviation related to the country/region:

- EN ISO 21640:2021 is the endorsement of the previous standard in Europe, by CEN
- NS-EN ISO 21640:2021 is the endorsement of the previous standard in Norway, by NS (Norsk Standard)

Appendix 2: About Heating Value and Calorific Value

In this thesis, the notion of Net Calorific Value (NCV) is used to describe the property of a fuel to deliver energy when combusted: (ISO, 2016).

- Gross Calorific Value (GCV) = High Heating Value (HHV) corresponds to the "*amount of heat […] released by the complete combustion with oxygen*" of a substance, considering all the products returing to the same specified temperature, except for water which is left at the gaseous state.
- Net Calorific Value (NCV) = Low Heating Value (LHV) corresponds to the "*amount of heat […] released by the complete combustion with oxygen*" of a substance, considering all the products, including water, returning to the same specified temperature.

The GCV of a substance is lower than its NCV because more heat is created during the condensing of the water vapor producing during the combustion process. Across literature, HHV, LHV and NCV are the units found most often. For this document, a choice was made of using only NCV.

Appendix 3: Characteristics of RDF and RDF_Q as introduced by UNI 9903:1-14 (adapted from Ragazzi & Rada, 2012)

Type	**Charact.**	**Units**	**RDF**	**RDF_Q (high quality**
Performance	Moisture	% as is	max. 25	max. 18
Performance	NCV	MJ/kg as is	min. 15	min. 20
Performance	Ash content	% d.m.	max. 20	max. 15
Hazardous	As	mg/kg d.m.	max. 9	max. 5
Hazardous	Cd	-	-	max. 3
Hazardous	Hg	-	-	max. 1
Hazardous	Cd+Hg	mg/kg d.m.	max. 7	-
Hazardous	Total Cl	% as is	max. 0.9	max. 0.7
Hazardous	Cr	mg/kg d.m.	max. 100	max. 70
Hazardous	Soluble Cu	mg/kg d.m.	max. 300	max. 50
Hazardous	Mn	mg/kg d.m.	max. 400	max. 200
Hazardous	Ni	mg/kg d.m.	max. 40	max. 30
Hazardous	Volatile Pb	mg/kg d.m.	max. 200	max. 100
Hazardous	S	% as is	max. 0.6	max. 0.3
Performance	Glass content	% d.m.	*	*
Performance	Fe	% d.m.	*	*
Hazardous	Fluorine	% d.m.	*	*
Performance	Al	% d.m.	*	*
Performance	Sn	% d.m.	*	*
Performance	Zn	% d.m.	*	*
Performance	Exterior aspect	-	*	*
Performance	Dimensions	mm	*	*
Performance	Ash softening	°C	*	*

*: for this parameter a limit is not set.
d.m.: dry matter

Appendix 4: Supporting data for substitutes quantitative analysis

Cost calculations for comparison with substitutes

- Coal: 52-79 USD/ton = 2.08-3.16 USD/GJ (IEA, 2022b),
- Low carbon hydrogen: 8-16 USD/GJ (IEA, 2022b),
- Ammonia: 12-24 USD/GJ (IEA, 2022b),
- RDF: Price between -80 and 15€ for end users (De Caevel et al., 2018). With an average exchange rate of 1.16 USD/EUR the last ten years and considering a medium quality RDF (ISO class 3, NCV = 15MJ/kg), as it is the minimal requirements for co-firing in cement kilns, it correspond to a price of between -6.2 and 1.2 USD/GJ.

GHG emission calculations for comparison with substitutes

- Coal: 115-145 gCO2e/MJ (IEA, 2022b),
- H2 from natural gas: 95 gCO2e/MJ (IEA, 2022b),
- Ammonia: 112 gCO2e/MJ (IEA, 2022b),
- RDF: (Genon & Brizio, 2008) calculated 490 gCO2e/kg combusted, with an RDF of NCV >15MJ/kg (ISO class 3). This corresponds to emissions of 33 gCO2e/MJ. The same article shows that the two other gases usually considered in CO2 equivalent calculations (CH4 and N2O), represent between 0.8% and 3.8% of the total CO2e emissions. This suggest that the CO2 equivalent emissions are roughly equal to the CO2 emissions, which simplifies our research process as most literature on RDF emissions is based on CO2 emissions. Accordingly, the IEA (2020a) gathered values of 34-65 gCO2/MJ, that we use in this analysis as similar value with 34-65 gCO2e/MJ.

Appendix 5: MSW production and RDF industry by country

Group	Country	MSW production (kT, 2005-2021) (1)	RDF potential production (kT) (2)	Reported RDF production		Reported SRF production		Share of potential/reported production	Domestic end-use industries	Source
				Prod. (kT)	Yr	Prod. (kT)	Yr			
Mature RDF Industry	Austria	7,440	2,604	-	-	2,800	2015	108%	Cement, WTE, Co-combustion	IEA (2020a)
	Belgium	8,410	2,944	400	2008	-	-	14%	Cement, WTE, Co-combustion	IEA (2020a)
	Finland	3,380	1,183	250	2014	250	2014	42%	WTE	IEA (2020a); Le Bihan et al. (2018)
	France	34,340	12,019	230	2015	-	-	2%	Cement	IEA (2020a); Le Bihan et al. (2018)
	Germany	53,322	18,663	6,000	2015	3,000	2016	48%	Cement, WTE, Co-combustion	IEA (2020a)
	Italy	28,950	10,133	-	-	1,340	2017	13%	Cement, WTE, Co-combustion	IEA (2020a)
	Japan	41,700	14,595	300	2015	1,280	2016	11%	Cement, WTE, Lime, Steel	IEA (2020a)
	Netherlands	9,300	3,255	400	2020	-	-	12%	WTE	IEA (2020); Le Bihan et al. (2018)
	Poland	13,670	4,785	2,500	2020	-	-	52%	Cement, WTE	Nowak (2023)
	Portugal	5,310	1,859	1	2017	-	-	<1%	Cement, Co-combustion	IEA (2020a)
	South Korea	22,540	7,889	-	-	Yes	2020	N.A.	WTE, Co-combustion	Yang et al. (2020)
	Spain	21,990	7,697	Yes	2020	-	-	N.A.	Cement, WTE	IEA (2020a)
	Sweden	4,350	1,523	400	2012	-	-	26%	Cement, WTE, Co-combustion	IEA (2020a)
	Taiwan	10,050	3,518	Yes	2023	-	-	N.A.	WTE	Tsai (2023)
	United Kingdom	31,000	10,850	3,200	2020	-	-	29%	WTE, Co-combustion	IEA (2020a)
	United States	265,220	92,827	Yes	2008	-	-	N.A.	WTE, Co-combustion	Ko & Chang (2008)
Emerging RDF Industry	Bulgaria	2,840	994	Yes	2016	-	-	N.A.	WTE	Milutinović et al. (2016)
	China	215,210	75,324	-	-	Yes	2020	N.A.	Cement, WTE, Co-combustion	IEA (2020a)
	Croatia	1,720	602	Yes	2020	Yes	2020	N.A.	Cement	IEA (2020a)
	Egypt	21,000	7,350	223	2015	-	-	3%	Cement	IEA (2020a)
	Estonia	530	186	Yes	2011	-	-	N.A.	WTE	European Commission (2011)
	Greece	5,610	1,964	220	2020	-	-	10%	Not used yet	Psomopoulos & Themelis (2015)
	Hungary	4,040	1,414	156	2013	-	-	11%	WTE	Pintacsi & Bihari (2015)
	India	68,800	24,080	Yes	2020	-	-	N.A.	Cement, WTE, Co-combustion	IEA (2020a)
	Iran	15,600	5,460	150	2020	-	-	3%	Cement	Shumal et al. (2020)
	Latvia	870	305	26	2018	-	-	9%	Cement	Arina et al. (2020)
	Lithuania	1,350	473	Yes	2018	-	-	N.A.	WTE	Arina et al. (2020)
	Malaysia	18,130	6,346	Yes	2013	-	-	N.A.	WTE	Yong et al. (2019)
	Mexico	42,100	14,735	Yes	2021	-	-	N.A.	Cement	Rueda-Avellaneda et al. (2021)
	Pakistan	20,080	7,028	180	2020	-	-	N.A.	Cement, WTE, Co-combustion	Azam et al. (2020)
	Russian federation	80,560	28,196	Yes	2022	-	-	N.A.	WTE	Vinitskaia et al. (2021)
	Slovenia	1,080	378	Yes	2019	-	-	N.A.	WTE, Co-combustion	Sarc et al. (2019b)
	Thailand	24,980	8,743	1,800	2017	-	-	21%	WTE, Co-combustion	IEA (2020a)
	Turkey	34,580	12,103	Yes	2016	-	-	N.A.	Cement	Agdag et al. (2016)
Potential for an RDF Industry	Brazil	78,400	27,440	-	-	-	-	0%	Not used yet	Liikanen (2018)
	Canada	35,600	12,460	-	-	-	-	0%	Not used yet	Reza et al. (2013)
	Jordan	2,700	945	-	-	-	-	0%	Not used yet	Hemidat et al. (2019)
	Kazakhstan	5,000	1,750	-	-	-	-	0%	Not used yet	Kuspangaliyeva et al. (2021)
	Singapore	7,390	2,587	-	-	-	-	0%	Not used yet	Zhao et al. (2016)

(1) OECD, 2023

(2) Theorical yield from MSW to RDF: 35 wt% (IEA, 2020a)

Other sources: (Akdag et al., 2016; Arina et al., 2020; Azam et al., 2020; European Commission, 2011; Hemidat et al., 2019; Ko & Chang, 2008; Kuspangaliyeva et al., 2021; Le Bihan et al., 2018; Liikanen, 2018; Milutinovic et al., 2016; Nowak, 2023; Pintacsi & Bihari, 2015; Psomopoulos & Themelis, 2015; Reza et al., 2013; Rueda-Avellaneda et al., 2021; Sarc et al., 2019b; Shumal et al., 2020; Tsai, 2023; Vinitskaia et al., 2021; Yang et al., 2020; Yong et al., 2019; Zhao et al., 2016)

Appendix 6: CO2 emissions and end-use industries by country

Group	Country	CO2 emissions (3)		Cement			Coal-based steel			Lime			Coal		
		CO2 emissions (kT,2017)	CO2 emissions (kT,2021)	Prod. (kT, 2020) (4)	CO2 Emissions (kT, 2021) (5)	Share of national emissions	Prod. (kT, 2017) (6)	CO2 Emissions (kT,2018) (7)	Share of national emissions	Prod.(kT, 2021) (8)	CO2 Emissions (kT, 2021) (9)	Share of national emissions	Power generation (TWh, 2022) (10)	Emissions (kT, 2022) (10)	Share of national emissions
Mature RDF Industry	Austria	69,600	64,000	5,100	2,805.00	4%	7,400	14,703.80	21%	780	1,014.00	2%	-	-	0%
	Belgium	99,000	95,000	6,820	3,751.00	4%	5,400	10,729.80	11%	1,500	1,950.00	2%	-	-	0%
	Finland	44,600	37,000	1,350	742.50	2%	2,700	5,364.90	12%	490	637.00	2%	3	1,404.00	4%
	France	337,500	305,000	15,200	8,360.00	3%	10,600	21,062.20	6%	2,600	3,380.00	1%	4	1,872.00	1%
	Germany	785,600	674,000	33,600	18,480.00	3%	30,300	60,206.10	8%	5,600	7,280.00	1%	181	84,708.00	13%
	Italy	352,700	329,000	18,500	10,175.00	3%	4,700	9,338.90	3%	3,600	4,680.00	1%	21	9,828.00	3%
	Japan	1,188,400	1,067,000	50,905	27,997.75	3%	96,300	191,348.10	16%	6,653	8,648.90	1%	312	146,016.00	14%
	Netherlands	162,500	141,000	2,980	1,639.00	1%	6,800	13,511.60	8%	N.A.	N.A.	N.A.	16	7,488.00	5%
	Poland	337,700	329,000	18,900	10,395.00	3%	5,700	11,325.90	3%	1,700	2,210.00	1%	124	58,032.00	18%
	Portugal	55,200	41,000	4,290	2,359.50	6%	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	-	-	0%
	South Korea	654,600	616,000	48,000	26,400.00	4%	70,600	140,282.20	21%	790	1,027.00	0%	210	98,280.00	16%
	Spain	275,000	234,000	15,600	8,580.00	4%	4,800	9,537.60	3%	1,800	2,340.00	1%	9	4,212.00	2%
	Sweden	42,700	36,000	3,000	1,650.00	5%	3,100	6,159.70	14%	640	832.00	2%	-	-	0%
	Taiwan	284,800	283,000	11,786	6,482.30	2%	23,300	46,297.10	16%	326	423.80	0%	130	60,840.00	21%
	United Kingdom	387,400	347,000	8,240	4,532.00	1%	6,000	11,922.00	3%	1,500	1,950.00	1%	6	2,808.00	1%
	United States	5,211,000	5,007,000	89,000	48,950.00	1%	25,800	51,264.60	1%	4,800	6,240.00	0%	898	420,264.00	8%
Emerging RDF Industry	Bulgaria	47600	42600	2,000	1,100.00	3%	-	-	0%	1,521	1,977.30	5%	21	9,828.00	23%
	China	10,011,100	11,472,400	2,380,000	1,309,000.00	11%	754,000	1,498,198.00	15%	310,000	403,000.00	4%	5,339	2,498,652.00	22%
	Croatia	18,800	17,700	2,729	1,500.95	8%	-	-	0%	170	221.00	1%	2	936.00	5%
	Egypt	260,100	250,000	41,700	22,935.00	9%	600	1,192.20	0%	870	1,131.00	0%	-	-	0%
	Estonia	18,800	10,400	258	141.90	1%	-	-	0%	N.A.	N.A.	N.A.	-	-	0%
	Greece	74,800	56,300	5,450	2,997.50	5%	-	-	0%	N.A.	N.A.	N.A.	5	2,340.00	4%
	Hungary	49,500	48,500	2,300	1,265.00	3%	1,600	3,179.20	6%	280	364.00	1%	3	1,404.00	3%
	India	2,434,900	2,709,700	295,000	162,250.00	6%	43,800	87,030.60	4%	16,000	20,800.00	1%	1,271	594,828.00	22%
	Iran	685,400	748,900	64,800	35,640.00	5%	2,200	4,371.40	1%	3,900	5,070.00	1%	1	468.00	0%
	Latvia	7,200	7,300	1,100	605.00	8%	-	-	0%	N.A.	N.A.	N.A.	-	-	0%
	Lithuania	13,600	13,900	1,221	671.55	5%	-	-	0%	N.A.	N.A.	N.A.	-	-	0%
	Malaysia	248,200	256,000	15,600	8,580.00	3%	-	-	0%	1,500	1,950.00	1%	77	36,036.00	14%
	Mexico	465,600	407,200	47,800	26,290.00	6%	4,700	9,338.90	2%	N.A.	N.A.	N.A.	13	6,084.00	1%
	Pakistan	216,100	229,500	40,100	22,055.00	10%	-	-	0%	N.A.	N.A.	N.A.	17	7,956.00	3%
	Russian federation	1,654,100	1,755,600	56,000	30,800.00	2%	47,800	94,978.60	6%	N.A.	N.A.	N.A.	192	89,856.00	5%
	Slovenia	14,600	12,500	920	506.00	4%	-	-	0%	1,118	1,453.40	12%	3	1,404.00	11%
	Thailand	293,100	278,500	35,700	19,635.00	7%	-	-	0%	790	1,027.00	0%	38	17,784.00	6%
	Turkey	430,200	446,200	72,299	39,764.45	9%	11,600	23,049.20	5%	4,800	6,240.00	1%	102	47,736.00	11%
Potential for an RDF Industry	Brazil	497,400	488,900	61,052	33,578.60	7%	26,700	53,052.90	11%	8,400	10,920.00	2%	25	11,700.00	2%
	Canada (Vancouver)	571,500	545,600	13,000	7,150.00	1%	7,300	14,505.10	3%	1,594	2,072.20	0%	37	17,316.00	3%
	Jordan	25,400	25,600	2,900	1,595.00	6%	-	-	0%	N.A.	N.A.	N.A.	-	-	0%
	Kazakhstan	320,800	276,700	10,810	5,945.50	2%	4,400	8,742.80	3%	830	1,079.00	0%	77	36,036.00	13%
	Singapore	37,200	32,500	-	-	0%	-	-	0%	N.A.	N.A.	N.A.	-	-	0%

(3) Our World in Data (2022)

(4) U.S. Geological Survey (2022)

(5) Emissions of cement production: 0.55 kT/kT (IEA, 2020b)

(6) World Steel Association (2022)

(7) Emissions of coal-based steel production: 1.987kT/kT (NSC, 2010)

(8) U.S. Geological Survey (2023)

(9) Emissions of lime production: 1.3kT/kT (Flannery & Mares, 2022)

(10) BP (2023)

(11) Emissions of Coal: 130g/MJ = 468kT/TWh (IEA, 2022a)

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