Understanding what caused the reduction of Greenhouse Gas emission intensity of the steel industry to stagnate:

A System Dynamics Approach

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Radboud University

Academic year 2021-2022

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Master thesis

Academic year 2021-2022

Master's in Business Analysis and Modelling

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Contents

Abstract

The reduction in Greenhouse Gas (GHG) emission intensity of the steel industry has stagnated from 1995 onwards. This represents a concern since GHG emissions are the main driver of anthropogenic climate change. This study aims to understand how the progress of the GHG emission intensity reduction in the steel industry has stagnated by discovering the drivers of the emission intensity between 1960 and 2015.

Drivers of GHG emission intensity are extracted from literature, after qualitatively analyzing its content. By exploring the causal relationships embedded in the drivers of GHG emission intensity, this study synthesizes the system that determines the GHG emission intensity behavior. The method used is the System Dynamics approach, as it is developed to understand complex behavior and attain leverage points. It is relevant to understand the drivers of the GHG emission intensity, of the steel industry, to identify intervention points and implement measures that can steer toward further decreasing the GHG emission intensity.

The results indicate the steel industry has reached a state where several factors are not allowing the GHG emission intensity to decrease further. These are namely the research and development stage of technology, the scrap availability constraint, the degree of government intervention, and the development level phase out between countries.

Key Words: Steel industry; stagnation of GHG emission intensity; drivers of GHG emissions; System Dynamics approach.

1- Introduction

1.1- Context and Background

The emission of Greenhouse Gases (GHG) is the main driver of anthropogenic climate change (Olivier et.al, 2005). Climate change is one of the most concerning issues of modern society, as it is already becoming noticeable through the increase in frequency of extreme weather events. These range from heatwaves to heavy rainfalls, to extreme drought in agricultural and ecological lands (IPCC, 2021). Examples are the floods that occurred in July 2021 in Germany, Belgium, and the Netherlands, (Kreienkamp et.al, 2021), or the extreme heat waves that occurred in June 2021 in the Southwest of America and Canada (Philip et.al, 2021). Therefore, it is urgent to reduce GHG emissions by addressing the responsible actors.

The iron and steel industry[1] is the largest contributor to the GHG emission footprint of the heavy industry sector, it is responsible for about 7% of the total anthropogenic emissions (Kim & Worrel, 2002). The GHG emissions stem from direct processes at the production plants, such as the coke usage for combustion, and indirect processes outside the production plants, such as energy generation for the production process, or transportation of raw materials (Tian et.al, 2013).

At the same time, steel is a fundamental material for the current modern society (Smil, 2016). It is widely used in the construction of infrastructures, vehicles, engineering and medical tools, and many other applications (Smil, 2016). Production of steel in industrial volumes started in 1850 and has expanded ever since. The characteristics that have enabled such expansion of the use of steel are the availability of resources, low production costs, and the versatility and mechanical properties of steel (Cullen et.al, 2012). Currently, global steel demand is about 1.9 billion tonnes per year, and it is expected to grow to more than one third of the current demand by 2050 (IEA, 2020). The useful characteristics of steel and the forecasted rising steel demand indicate that the industry is not easily substitutable, and thus precludes shutting down the production of steel as a solution.

Not only is the steel industry a large contributor to the world's GHG emissions, but also, the industry is not achieving a further decrease in the GHG emission intensity since 1995 (see

[1] Iron and steel industry will be represented from here onward by the steel industry, as 'The most important use of iron ore (up to 98%) is as the primary input to steelmaking with the remainder used in applications such as coal washeries and cement manufacturing' (Indian Bureau of Mines, 2007; IBISWorld Industry Report, 2009, retrieved from Yellishetty et.al, 2010: p.1085).

Figure 1, Wang et.al, 2021). The stagnation of the decrease in GHG emission intensity means that the amount of GHG emission per unit volume has remained constant for about 25 years, i.e., there has not been a further decrease in the GHG emission intensity rate. This is of particular concern because it does not contribute to bringing the overall net GHG emission intensity down to zero, which is needed to stabilize the temperature anomaly that is triggering the occurrence of extreme weather events (Davis, 2018).

To be able to further decrease the GHG emission intensity, an understanding of what caused the progress to stagnate is needed. The decrease in emission intensity and gradual approach to a constant value shows a pattern that follows a goal-seeking type of behavior, i.e., reaching a limiting value (Sterman, 2000, p.108). This type of behavior is generated by an underlying balancing feedback mechanism, revealing that the GHG emission intensity pattern is dynamic (Sterman, 2000).

Additionally, the article of Wang et. al (2021) mentions that the reduction in emission intensity right before the stagnation relates to the 'improvement of energy efficiency through technological advancements'. The latter coincides with the transition from Open-Hearth Furnace (OHF) to the Basic Oxygen Furnace (BOF), saving about 3 GJ/ton of energy usage (Smil, 2016; p.148). The stagnating behavior is linked to the fact that while demand for steel production kept rising, 'the process efficiency of global steel production appeared to have stalled and levelled off' (Wang et.al, 2021). Although, the paper suggests an explanation for the stagnation, it does not provide the understanding on the dynamics that have led to a stagnating behavior. This knowledge is important, to gain control over the undesired behavior and to be able to change it (Sterman, 2000).

The steel industry is part of a complex environment where a multitude of interconnected factors, that involve environmental, social, technological, and economic aspects, have an effect on the GHG emission intensity level (Vögele et.al, 2020). Examples of such factors are government regulations, world trade, investments in knowledge development, and technology costs. In this way, to understand the behavior of the GHG emission intensity it becomes relevant to clarify and map the interaction between the multiple driving factors. The complexity of the industry is also described in the extended literature found in journals, across multiple disciplines (e.g., Journals of Management, Environment, Engineering, Economy, Political Science), that explore various factors that have influenced the global industry in terms of its GHG emissions. These literature pieces will be used to seek an explanation for the emergence of the stagnation (see Appendix V).

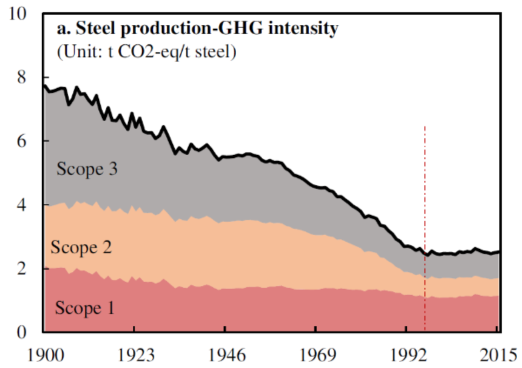


Figure 1- Empirical data of the GHG emission intensity of global steel production from 1900-2015. Retrieved from Wang et.al (2014). The red line shows the start of the stagnation period (1995-2015)

1.2- Research Objective and Research Questions

The research project aims to gain insight into the drivers that impact the steel industry's GHG emission intensity level and how these drivers interconnect. This is done to explain the stagnation of the emission intensity and to identify effective ways to intervene. This leads to the research question:

What are the main drivers of the GHG emission intensity of the steel industry and what caused the decrease of the GHG emission intensity to stagnate?

With the following sub-questions:

1- What are the drivers of the GHG emission intensity of the steel industry between 1960 and 2015?
2- How do the GHG emission intensity drivers interact with each other?
3- How does interaction between the GHG emission intensity drivers explain the stagnation of the decrease in GHG emission intensity?

To answer the main research question, a systems approach is taken, where the GHG emission intensity pattern will be looked at in terms of its dynamic causes, to be able to deal with the complexity of the system.

1.3- Societal and Academic Relevance

The societal relevance of this research lies within the urgency to take concrete actions toward minimizing the GHG emissions of the steel industry. Every insight that can help steer the steel industry towards sustainability, rather than stagnation, is needed. Since the steel industry has both a global scale and is emission intensive, it becomes relevant to understand how the current emission pattern came to be, and from there to be able to extract leverage points that reduce the GHG emission intensity. Furthermore, decision-makers can benefit from gaining a systems perspective of GHG emission intensity driving factors, and as a result, get insight into the origins of the stagnation. This understanding can lead to more informed decisions to create policies that steer towards the mitigation of the GHG emissions of the steel industry.

Academically it is relevant to pursue this research because the majority of the literature adopts a reductionist perspective. A reductionistic perspective focuses on explaining relationships between a small number of variables that are linear in nature, meaning that the mutual dependence among variables and its consequences are often not captured. This is in contrast with the holistic perspective that the SD approach provides, as it does incorporate mutual dependencies. And as such, SD allows identifying counterintuitive behavior and unforeseen side effects that play a role in the occurrence of complex phenomena. Examples of papers, that have a reductionistic perspective are Boomsma et.al (2020) that focuses on solutions for emission mitigation, Gosh (2006) that focuses on the economic growth of the steel industry, Conejo et.al (2020) that looks at environmental challenges of the steel industry and so on.

Besides providing a holistic perspective, by having an SD approach this project also seeks to map the dynamics of a complex system, in this case of the drivers of the GHG emission intensity of the steel industry, which has not previously been done for the global industry. The current research using an SD approach and assessing the steel industry has revolved around particular geographical areas such as China and India (Wårell, 2014), Iran (Ansari & Seifi, 2012), and Korea (Kim et.al, 2014). For this particular research the model aims to compile existing literature, and encompass the global steel industry as a whole, rather than in separate geographical areas. There is one article, by Kumar et.al (2008), that has a systems approach for the global industry, however it does not seek to understand the GHG emission intensity stagnation, in particular.

1.4- <u>Overview of the project</u>

An overview of how the research will be conducted (Figure 2) follows next. Sub-question 1 will be answered by discovering the drivers of the GHG emission intensity found in the literature. These drivers are factors that change the GHG emission intensity level during the study period (between 1960 and 2015, further elaboration on the time boundary, in section I-Reference mode and System Boundaries). Once the drivers have been determined, they will be represented as a set of interactions in a qualitative SD model, answering sub-question 2. The above-mentioned steps will be conducted iteratively.

The third sub-question is answered in two steps (see green box in figure 2). First, the different hypotheses found in literature for the occurrence of the stagnating behavior will be explored, then the hypotheses will be contrasted with the findings of the model.

At the end, the results will be summarized and discussed, and further research possibilities pointed out.

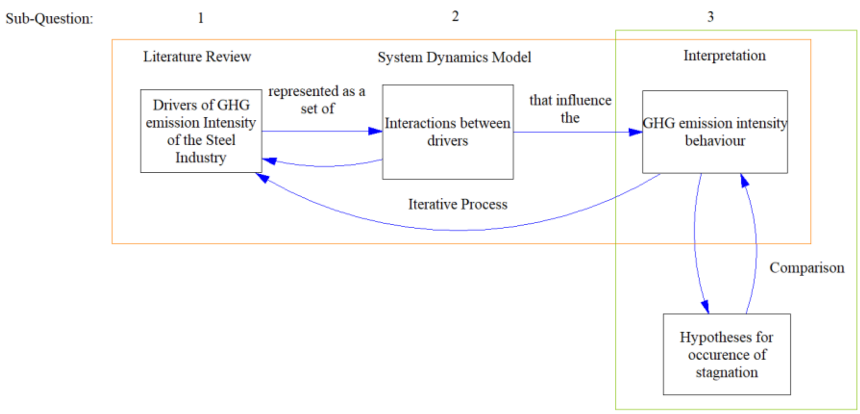


Figure 2 Conceptual Model of Research Project. The main steps of the research project are highlighted in orange. The steps that lead to the validation of the model and of the information retrieve from existing literature are highlighted in green. Each research sub-question should be answered in each step (Q1-Q3).

2- Theoretical Background

2.1- Steel Industry Context

Industrial steel production only began in the second half of the 19th century, with the appearance of the Bessemer converter (the first furnace that allowed massive steel production) in 1856 and the introduction of the Open-Hearth Furnace (OHF) in the late 1860s (Grübler, 1998; p.209). Steel became attractive due to its versatility and low production costs (Campbell, 2008), and thus became an important material for railways, transportation vehicles, and developments in the Energy Industry (Smil, 2016; p.35).

By 1960 the steel industry had already been impacted by several world events, like World War I (WWI) and World War II (WWII). These events led to the growth in steel production output as ‘large investments were made to re-build economies’ in countries damaged by war (Wårell, 2014, p.134). About this time, more than 100 Mt of steel was produced each year and with the world leaders in the production of pig iron and steel being the US, the USSR, and the UK (Smil, 2016; p. 235).

Between 1960 and 2015, several key historical events have shaped the industry’s development. Particularly the oil crisis, which led to an economic slowdown and the burst of the growth in Japanese and Chinese steel production, which dominated the market and changed the global economic scene (Smil, 2016). These have influenced the demand for steel, technological developments, and social and environmental norms.

Furthermore, the 1960s was the period when improvements in the production of steel led to a reduction of the GHG emission intensity (Smil, 2016; p. 190). These improvements happened mainly through: more efficient use of input materials, recycling, process and energy efficiency, and transitioning to cleaner energy (Smil, 2016). The most significant change was the gradual transition from Open-hearth Furnaces (OHF) to Basic Oxygen Furnaces (BOF) and Electric Arc Furnaces (EAF) and the implementation of Continuous Casting (CC) technology (Smil, 2016).

From 1995, the reduction in GHG emission intensity started to stagnate. Since this moment, several potential mitigation technologies have been developed that are able to decrease the emission intensity pattern even further, however, these have not yet been implemented. A few examples are Carbon, Capture, Usage Storage (CCUS), the use of hydrogen as fuel, and top gas recycling (Fischedick et. al, 2014).

These events and developments have shaped the steel industry to its current state.

2.2- GHG Intensity Observed Behavior

The observed GHG emission intensity pattern (Figure 1, see above) was retrieved from the article by Wang et.al (2021). It shows the emission intensity of the steel industry between 1900 and 2015. The GHG emission intensity gradually decreases until 1995 when the decrease of the GHG intensity stagnated. GHG emissions are measured in tons of Carbon Monoxide (CO_2) equivalents per ton of steel. As such, GHG emissions other than CO_2 (e.g. nitrous oxide, methane, and ozone) are measured by 'calculating the amount of CO_2 emission required to cause the same integrative radiative forcing or temperature change, over a given time horizon'. (IPCC, 2018; p.546). Radiative forcing is the measure of the energy flux change caused by external drivers of climate change (as anthropogenic emissions) in the atmosphere (IPCC, 2014; p.1460). It represents the amount of radiation that gets trapped within the earth's atmosphere contributing to the greenhouse effect.

Furthermore, the graph (seen in Figure 1) shows the GHG intensity for 3 different scopes. Scope 1 accounts for all the direct emissions coming from sources that the industry controls (e.g., production byproduct) which will be called *plant emissions*. Scope 2 accounts for emissions that stem indirectly from the processes of the industry but are controlled by the industry (e.g., electricity use), which will be mentioned as *energy emissions*. Scope 3 accounts for indirect emissions that are a consequence of the production of the industry but are not controlled by them (e.g., emissions from the transportation of raw material) (Tian et.al 2013), these indirect emissions fall outside the scope of this project.

2.3- Energy, Fossil fuels and GHG emissions

In order for iron ore and scrap to be transformed into steel, energy is required. Energy for steel production is provided by energy carriers. An energy carrier is either a substance or a phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes. (ISO, 1997).

Fossil fuels are a form of energy carrier. In the steel industry, they take part in the chemical process of steel production and also act as sources for the production of heat and electricity. The burning of fossil fuels produces electricity, but also produces heat in a blast furnace, while at the same time functioning as a reducing agent in the chemical reaction to produce steel from iron ore in a blast furnace. Fossil fuels are useful and hard to replace because they have a large accumulated energy content (Wang et al., 2021). Decomposing fossil fuels into smaller parts releases large amounts of energy that is used to process the initial raw materials (Falk et.al, 1983). Fossil fuels are composed primarily of hydrocarbons and when hydrocarbons react with oxygen a high amount of energy is released. It is this reaction that in the presence of a metallic material produces the GHG as a result (Campbell, 2008; p.351).

Steel production can utilize other energy carriers, that do not release GHG, such as hydrogen and electricity (Barbir, 2009). However, the generation of either one, still often involves fossil fuel combustion, contributing to indirect energy emissions (Reppelin-Hill, 1999).

2.4- Background of the Steel Production

2.4.1- Production Process

Steel is an iron alloy that contains elements such as carbon, magnesium, chromium, and nickel among others. One of the necessary conditions for a material to be considered steel is that it has a carbon percentage of less than 2% (Campbell, 2008; p.154). This means that steel has a very specific composition of elements, that confers steel the useful properties of strength, ductility, and durability. Steel cannot be found ready to use in nature but instead is produced by processing iron ore or scrap steel.

Steel can be processed and produced through two distinct routes: a primary production route that makes steel with iron ore as initial input and a secondary route that makes steel from scrap.

The production of steel requires several steps before steel is finished and ready to use (Figure 3). According to Cullen et. al (2012), these steps are reduction, steelmaking, casting, rolling/forming, and fabrication. The focus of this paper will be on the first two steps because they are responsible for the majority of the emissions (Cullen et. al, 2012; Holappa, 2020). However, the third step, casting, is going to be included only to acknowledge the impact of the implementation of the continuous casting technology in the reduction of the GHG emission intensity in the 1970s.

- *a) Step one: Reduction*

The reduction step sometimes called the 'iron-making step', is where raw iron ore is transformed into pig iron. Reduction is a chemical process in which iron ore reacts with reducing agents like carbon monoxide or hydrogen, which are responsible for making iron ore less rich in oxygen and closer to the desired chemical composition of steel (IEA, 2020). The enabling technology for this process is the Blast Furnace (BF) or Direct Reduced Iron (DRI) Process. The former technology is the most widely used (Cullen et. al, 2012). The reduction step belongs only to the primary production route since the secondary route already starts with steel scrap. Molten scrap is equivalent to pig iron in the production of steel.

- *b) Step two: Steelmaking*

Steelmaking transforms pig iron or molten scrap into crude steel. In this step, oxygen is blown into the furnace to allow the input to attain the steel composition. Three main steelmaking furnaces dominated the market between 1960 and 2014. These are Open-Hearth Furnace (OHF), Basic Oxygen Furnace (BOF), and Electric-Arc Furnace (EAF) (Appendix I). These will be described in more detail, in terms of their characteristics and developments in the market.

Open-hearth furnaces (OHF). A steelmaking technology that is coupled to the iron-making BF technology. This type of furnace was widely used between 1900 and 1960. The furnace is mainly used to remove the excess of carbon by burning coal.

From 1960, there was a transition from OHF to BOF, when the OHF process started a sharp decline in usage. The transition took place until 1990 when it was almost completely out of use in the steel industry (see Appendix I). During this period, the OHF was gradually substituted by BOF technology since this was more energy efficient, had lower capital costs, and had higher productivity, (Yellishetty et.al, 2010; Worrell et.al, 1997, Reppelin-Hill, 1999). The transition to the BOF technology was a result of the need for higher capacity and more cost-efficient solutions, as demand was growing quickly (Smil, 2016; p.99)

Basic Oxygen Furnace (BOF). A technology that is responsible for processing pig iron. Like the OHF process, the BOF is coupled to the BF process. The BOF is 70-90% charged with pig iron and 10-30% with scrap (Yellishetty et.al, 2010).

Electric-Arc Furnaces (EAF). The last technology to integrate into the market, although EAF had existed since the 1940s, its wide use only started around the 1970s. The main input for the EAF is recycled scrap and it uses mainly electricity to produce steel (Yellishetty et. al, 2010).

- *c) Step three: Casting*

Casting is the process of solidification of steel, as when crude steel comes out of the steelmaking process it finds itself in liquid form. It is then either molded into discrete ingots or cast continuously, i.e., melted steel can either be cast in discrete batches or into a continuous molding chain (Campbell, 2008; p.356). The transition into a continuous cast technology was responsible for major yield improvements that led to a reduction in emission intensity.

2.4.2- Steel production blocks

The production of steel has three essential blocks: an input, a transformation process, and an output. The input for the production process is *raw materials*. The transformation process occurs with the *consumption of energy* and a chain of production technology (i.e. a *production route*) for the raw materials to be processed. The *production output* results from the transformation process. Each of these aspects will briefly be elaborated upon, next.

- *Raw Materials: Feedstock*

To produce steel, iron-based materials need to be used as feedstock for the process. The two most used input materials are iron ore and scrap. Around 70% of the total metal input comes from iron ore (IEA, 2020). The production of steel by the primary route produces a lot of waste. Yellishetty et.al (2011), mentions ‘according to an estimate by World Steel Association scrap recycling can offset the use of over 1200 kg of iron ore, 7 kg of coal and 51 kg of limestone for a tonne of steel scrap used’, showing the benefits of using scrap.

- *Production routes*

The integrated route is a primary production process that starts with the iron making step. The most common combination of technology in this route is the BF together with the BOF (about 90%) (Appendix II). Plant emissions of the integrated route rise due to the usage of fossil fuel reducing agents, like pulverized carbon and coal (Yellishetty et.al, 2010). Furthermore, energy emissions of this route stem from the requirement of energy generation for heat and electricity. The usage of fossil fuels as primary source for energy generation determines the amount of energy emissions. 70% of the total emissions of this route come from the iron making step (Holappa, 2020). The integrated route has always been the dominant production route, currently representing 60% of the fleet (Swalec & Shearer, 2021). In this document, the terms ‘integrated plant’, ‘primary production process’, and ‘BF/BOF plant’ are used interchangeably.

The secondary route starts with the steelmaking step. This is because scrap is used as input, allowing for the iron-making step to be skipped (Kim & Worrel, 2002). The main steelmaking technology that is used in this step is the EAF (Cullen et. al, 2012). GHG emissions from EAF technology mainly stem from the usage of electricity, as the process does not require the usage of reducing agents. This means that external energy emissions (scope 2), play a larger role than plant emissions (scope 1) (Yellishetty et.al, 2010). The terms ‘secondary plant’ and ‘EAF plant’ are also used interchangeably.

The fact that the secondary route uses scrap as input and electricity as an energy source makes it less emission intensive than the integrated route (IEA, 2020).

- <u>*Energy Consumption*</u>

Yellishetty et.al (2011), mentions that ‘EAF steelmaking is far less energy-intensive when compared with BOF steelmaking from both resource use and CO_2 emission perspective’. Continuing, the same article mentions that ‘steel produced from primary ore uses two and half times more energy than steel produced from melting scrap as one tonne of steel through the EAF route consumes 9–12.5 GJ/t of crude steel whereas the BOF steel consumes 28– 31 GJ/t of crude steel’. The reason for this discrepancy is the usage of coke in the primary route, and the saving of using scrap in the secondary route (Strezov & Evans, 2013).

Other sources like Lyakishev & Nikolaev (2003), mention that the energy content of steel products of secondary plants is 2.5 times lower than of integrated plants, and labor productivity is 3-5 times higher than that of integrated plants. The IEA (2020) report mentions that the secondary route is 1/8 as intensive as the primary route.

- <u>*Production output*</u>

The production output of steel is directly influenced by demand. According to Cullen et.al, the steel demand has increased 4-fold since the 1960s and is expected to continue to increase (Cullen et.al, 2012). The reason for the increase in demand has been the gradual industrialization, the increase in the standard of living, and population growth (Holappa, 2020; Wang et. al, 2021; Neelis & Patel, 2006). The IEA (2020) and Yellishetty et.al (2010) also estimate an ongoing increase in demand due to the role of steel in the energy transition and to the wide amount of useful properties that steel has (e.g., strength, recyclability, durability, low cost).

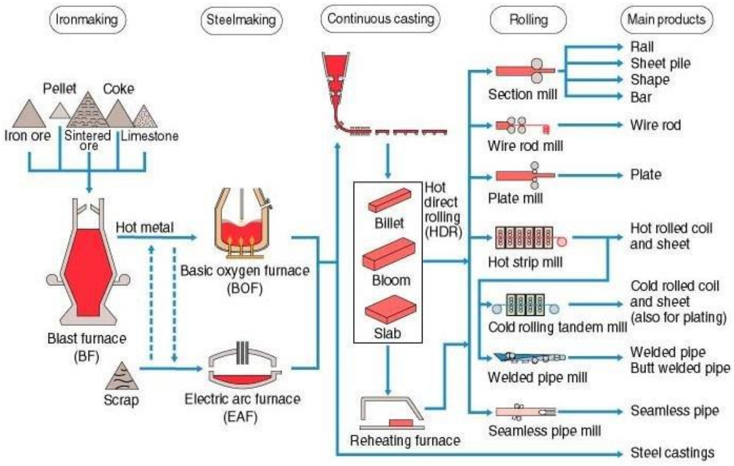


Figure 3- Overview of the main steel production process with the two main routes, integrated (BF/BOF) and secondary (scrap-EAF route). Retrieved from Arvola (2018).

2.5- GHG emission intensity drivers: Themes

In order to describe the drivers of GHG emission intensity in a structured way, it was necessary to find themes that included them all. Thus, during the literature review, three themes were found that met the above criteria. The themes identified are used in the literature as dimensions to define the concept of 'environmental quality'. This section serves to explain the relationship between the construct of 'environmental quality' and GHG emissions, and to introduce the themes that will structure the description of the GHG emission intensity drivers.

'Environmental Quality' is a construct that comes from theory that connects economic growth to environmental pollution. Several indicators measure environmental quality, for e.g., the amount of energy consumption, municipal waste, GHG emissions, suspended particles matter, and change in forest area (Shafik, 1994; Cole et.al, 1997). GHG emissions are thus one of the indicators of environmental quality.

The interest of this construct is mainly in the key dimensions that determine environmental quality: scale effect, technology effect, and composition effect. (Reppelin-Hill, 1999). These are used in literature to evaluate the degree of environmental pollution (Tsurumi & Managi, 2010). The paper of Tsurumi & Managi (2010), measures environmental quality in terms of emissions of sulfur dioxide and carbon dioxide, and energy use. The description of the three dimensions used in this paper will be adapted to the study of the drivers of GHG emission intensity of the steel industry.

Scale effect, according to Copeland & Taylor (2004; p.15) 'measures the increase in pollution that would be generated if the economy were simply scaled up, holding constant the mix of goods produced and production techniques.' GHG emission intensity is the amount of GHG emission that is released into the atmosphere per ton of steel produced. This means that if the same technology would be used throughout the years and the number of steel plants would keep increasing (scale factor increase) then there would not be a change in GHG emission intensity level at all. This might lead to thinking that scale does not affect the GHG emission intensity behavior, more specifically: that it does not contribute to the GHG emission stagnation phenomena. However, this is not the case because scaling up the number of steel plants as a consequence of a rise in demand provides an opportunity to create new steel plants with different technology. It creates a decision moment where companies can choose to either implement green technology that decreases GHG emission intensity or continue using technology that perpetuates the GHG intensity as it is.

Technology effects represent the changes in production technology that determine the amount of emissions generated with the production of each ton of steel (Tsurumi & Managi, 2010). The technology effect has the most direct connection to the behavior of the GHG intensity, as a change in production technology determines the emission per ton of steel.

The *Composition effect* 'is captured by the change in the share of the dirty good in national income… if we hold the scale of the economy and emissions intensities constant, then an economy that devotes more of its resources to producing the polluting good will pollute more' (Copeland & Taylor, 2004; p.15). This represents drivers that can induce a change in the structure of the production process. These determine the composition of technology used in the industry and thus have a large role in the behavior of the GHG emission intensity.

3- Methodology

3.1- Research Approach

This research project will make use of the System Dynamics methodology. As mentioned in the article of de Gooyert (2019; p.654), System Dynamics is aimed at understanding 'the behavior of a phenomena over time by mapping the underlying causal relations.'

The research strategy adopted is the 'Phenomenon Replicating Explanation'. This means the project seeks to prove and explain the behavior of a phenomenon (de Gooyert, 2019), in this case, the GHG emissions intensity pattern. This research project will perform the initial steps of the Phenomenon Replicating Explanation as described in Sterman et. al (1997, p.504). First, the construction of an overview of the drivers that influenced the GHG intensity of the steel industry between 1960 and 2015, by performing a literature review. Second, the generation of feedback structures that incorporate the drivers of GHG intensity described in literature and of hypotheses that explain the occurrence of the observed phenomena.

In sum, the use of the system dynamics approach for this project uses two research methods, a literature review, and a formulation of a qualitative SD model.

3.1.1- Systems Dynamics Approach

System Dynamics (SD) is an approach that is useful when learning about complex systems (Vennix, 1996). Complex systems are characterized by having multiple variables that result in interactions that involve feedback loops (i.e., dynamic interactions), and thus show non-linear behavior. Also, complex systems are history-dependent, characterized by trade-offs and counterintuitive behavior (Sterman, 2000). The main premise of the SD approach is that the behavior of the system is determined by the structure and functioning of the system as a whole and not by its individual components (Vennix, 1996).

According to Sterman (2000, p.4), 'System Dynamics is a perspective and a set of conceptual tools that enable to understand the structure and dynamics of complex systems.' The SD approach entails the formulation of a visual model that serves the following purposes: synthesizing the existent literature in a single visual representation and explaining the stagnation behavior through the interpretation of the model (Harrison et.al, 2007). The system dynamics approach is 'an iterative approach' (Luna-Reyes, 2003; p.271).

The suitability of the SD approach for this particular research comes from the fact that the method has been developed to understand systems that are dynamically complex. Dynamically complex systems are systems that are influenced by a multitude of variables that are tightly coupled, generating structures that are governed by feedback loops (Sterman, 2000, p.22). This is the case for the phenomenon in question, the emission intensity behavior is dynamic (goal-seeking pattern, Figure 4) and the industry is framed in a complex context where many interconnected factors play a role (Section 1.1).

Other methods that deal with complex systems such as: Strategic Operations Development and Analysis (SODA), Group Model Building (GMB), Soft System Method (SSM), and flow mapping, are less suitable than the established method for this project. First, the SODA approach focuses on a means-end approach resulting in a tree of connections, not providing the understanding of the structure behind a balancing phenomenon which is circular in nature (Eden & Ackermann, 2001). Second, a GMB, although it uses SD, it is a participatory approach, and as such requires the involvement of participants in the formulation of the model (Vennix, 1996). This study does not use participants since the aim is to focus on the global industry and to understand what current theory reveals about the GHG behavior pattern. Third, the SSM method also aims to include participants and is based on the belief that systems are social constructs created by logical human thinking (Rodríguez-Ulloa & Paucar-Caceres, 2005). This is not useful for this research as the drivers of GHG emission intensity should reflect the empirically observed reality. Lastly, creating a flow map of the GHG emissions structure follows sequential steps in a linear manner to map the material/carbon flow in order to grasp its origins. The goal of understanding the dynamics involved in the GHG emission intensity stagnation phenomena is best suited with the combination of literature review and formulation of a qualitative SD model

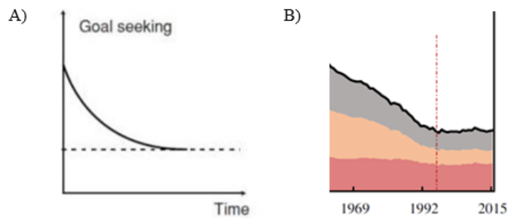


Figure 4- A) Example of a goal-seeking pattern: approach a limit value B) Partial graph from the empirical observed GHG emission intensity pattern retrieved from Wang et. al (2021), that follows a goal-seeking behavior.

3.2- Research Process

To use the SD approach, Luna-Reyes (2003) describes four modeling stages:

A- *Conceptualization Stage:* sets the reference mode of behavior, the boundaries of the model, and the conceptualization of the system;

B- *Formulation Stage:* retrieves the detailed structure of the system; for a quantitative model, this stage would entail the parametrization of the variables;

C- *Testing Stage:* consists of the model evaluation and analysis of the model behavior;

D- *Implementation Stage:* provides the relevant insights that can be extracted from the model.

In this section we clarify and explain these stages in-depth. Following, we introduce the notation that will be used in the SD model. Finally, we discuss the underlying assumptions and approximations that were made in this analysis.

3.2.1- Conceptualizing Stage

The first step in the process of building an SD model is the problem articulation and the definition of the system's boundaries. This is followed by the conceptualization of the system that requires identifying factors that cause the problematic behavior (Luna-Reyes, 2003).

- *I- Reference mode and System Boundaries*

The reference mode of behavior represents the problematic behavior (Vennix, 1996). In this case, the problematic behavior is: the stagnation of the GHG emission intensity level of the steel industry. The reference mode of behavior represents the empirically observed pattern that seeks to be explained. For the project at hand, it is only relevant to keep in mind as reference mode, the section of the graph that starts in 1960 (Figure 1).

The time horizon of this project will be from 1960 until 2015. This choice is made because from about 1960 onwards the emission intensity decreased approximately in a linear manner before the stagnation. According to Vennix (1996), the boundaries need to be determined given the purpose of the study. In this case, to understand what caused the stagnating behavior, the boundary consists of representing the drivers that have impacted the emission intensity level right before and during the stagnation. The period before the stagnation lasted for 35 years and the stagnation itself was reached in 1995 and remained at least until 2015 (the year that marks the end of the graph). In total, the time interval counts 55 years, whereby 35 years before the stagnation and 20 years during the stagnation. The start of the time framework, 1960, coincides with the start of the implementation in the market of the Basic Oxygen Furnace (BOF), and the burst in China's production growth (Smil, 2016; p.190 and p.236).

The model will be developed for the industry at a global level since the emission intensity graph is referent to the cumulative emission intensity of all the global production sites. The construction of the model, its boundaries, and aggregation level are determined by the analysis of the information retrieved from the sources of the literature review. The criteria to incorporate a certain variable in the model is based on how frequent it appears in statements retrieved from literature that relate to the behavior of the GHG emission intensity of the steel industry. In the end, each GHG driver will translate into a set of relationships that have an influence on the amount of GHG emission intensity of the steel industry between 1960 and 2015.

- *II- System Conceptualization: Literature review*

The literature review is done to map out the main drivers of GHG emission intensity behavior and as such to identify the factors that are causing the current GHG intensity observed pattern. This is a method that is inserted in the SD approach and is a necessary step to collect data to answer the main research question. The type of review performed is an integrative literature review. The purpose of an integrative review is to 'assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge' (Snyder, 2019; p.335). In line with this type of literature review, the sample selection procedure attempts to include a group of articles that allow an overview of the existing knowledge in the literature by including articles from different fields (Snyder, 2019). The articles have been selected based on their connection to the global steel industry while addressing the issue of GHG emissions intensity over the period between 1960 and 2015. The sources include various reports and scientific articles. The sources were selected by using the Google Scholar search engine, the Radboud University literature base, and some were included by the suggestion of the supervisor or by snowballing from reference lists.

Different types of sources were included with varying degrees of reliability in order to have a complete overview of the information that is available. In the discussion section, the information retrieved from sources with different degrees of reliability will be contrasted in terms of consistency. To reduce the snowball effect and selection bias, the sample selection process was performed by looking at different search terms, making sure that the articles were of different types (scientific papers and reports) and from different fields. Further clarification of the sample selection process and the overview of the selected literature can be found in Appendix IV and Appendix V.

The analysis of the information from the articles is done through a coding process, based on grounded theory. It is split up into three coding stages: open, axial, and selective. Open coding is described as the process of 'breaking down, examining, conceptualizing and categorizing data' (Strauss & Corbin, 2007; p.61). Open coding will be used as a method to extract relevant text segments from literature. As a result, a set of text segments (quotations) will emerge, that contain information about the drivers of GHG intensity of the steel industry, coupled with an initial code. Following the open coding, is the axial coding process, which relates the initial codes, by merging similar quotations and defining themes (Boeije, 2010). The result is a list of quotation sets, each set representing a driver of the GHG emission intensity (see Appendix VI). Lastly, a selective coding process is used to find overarching themes that allow integrating the different drivers in a small group of themes to organize and structure the information (Boeije, 2010). It is important to note that the coding process is iterative, moving between text, quotes, and themes interchangeably.

In the end, the iterative coding process, provides a list of drivers of the GHG emission intensity, under three overarching themes (further elaboration of the process of finding the drivers can be found in Appendix III). This is the point where the system dynamics approach builds on the literature review to generate a model.

3.2.2- Formulation, Testing and Implementation Stage

- *I- Formulation Stage*

After analyzing the information from literature and after finding the GHG intensity drivers, the SD model will be generated. This is done by first translating the set of quotations, that represent each driver, into their underlying causal relationships. And then, by joining all the causal relationships found into a small model. This process is repeated for all the sets of quotations.

The book of Vennix (1996; Chapter 2), describes how to translate statements (in this case quotations) into causal relationships (Table 1). From the quotations it is possible to pinpoint causal relationships between two or more variables, i.e., to recognize if a change in one of the identified variables induces a change in the other variable in the same or opposite direction.

The construction of the model was done through an iterative process. The causal relationships found in literature retrieved a long list of variables that need to be revised. The variables were incorporated in separate models that represent one or more drivers. In each iteration, the variables needed to be adjusted to reach consistency among models. In the end, the separate models were joined into a final model.

To understand how the drivers of GHG emissions intensity influence its observed pattern, first, it is necessary to understand where GHG emissions come from in the steel industry and how GHG emission intensity can be changed. This requires an initial construction of a model that shows what determines the GHG emission intensity in the steel industry. The result section will start by mapping this structure prior to the description of the GHG emission intensity drivers (section 4.1- Origin of GHG emission in the steel industry). After that, the effects of the drivers on the GHG emission intensity behavior can be looked into, the causal relationships can be defined and the model that connects all the variables can be formulated.

Table 1 Example of translation of a piece of text into a causal relationship. Retrieved from Vennix (1996; p.52)

Statement	Relationship	Direction	Description
More cars will lead to more air pollution	Cars→+Air pollution	Same: Positive	When the amount of cars increases, air pollution increases as well.
More cars lead to fewer train travelers.	Cars→- Train travelers	Opposite: Negative	When the amount of cars increases, train travelers decrease.

- *II- Testing Stage:*

The Testing Stage has the purpose of critically assessing the model. Sterman (2000; p.859), presents a guide with 10 tests that enable checking the validity and reliability of simulation models. However, as the model is qualitative in nature, not all the tests are possible (e.g., integration error, sensitivity analysis, or statistical analysis tests), and as such only a brief assessment will be done, this can be found in Appendix IX.

- *III- Implementation Stage:*

From the papers used in the literature review, four possible reasons for the stagnation phenomena were pointed out. These are looked into and contrasted to the model findings, in order to have a more thorough understanding of the stagnating phenomenon.

In the end, the model allows identifying the struggle points of the industry that have led to stagnation and what are the available opportunities to intervene in order to overcome the stagnation.

3.2.3- Notation for the Qualitative SD model

The basic structure of an SD model consists of stock and flows (see Figure 5). The inflow is the additive quantity per unit of time, and the outflow is the subtractive quantity per unit of time. Both can be represented by functions over time, f(t). The stock is the quantity accumulated at each moment in time. The value of the stocks is altered by the amount determined by the in/outflow.

Furthermore, the SD approach uses auxiliary variables, to clarify the system behavior (Sterman, 2000). They can represent constant, exogenous or intermediate variables. In a model, these variables are connected by arrows with positive polarity, i.e., the two connected variables change in the same direction; or negative polarity, i.e., the two connected variables change in the opposite direction (Sterman, 2000). The polarity of the arrow identifies the direction of the causal relationship described above (Table 1).

Feedback loops are structures that make systems dynamic and non-linear (Sterman, 2000). The emergence of feedback loops in a model occurs when variables are connected in such a way that the change of the initial variable ends up changing its own state (Vennix, 1996). There are two types of loops, reinforcing loops that induce an exponential growth/decline to the initial state; and balancing loops that are characterized by a goal-seeking behavior, or a counteracting behavior to the induced variance of a particular state (Forrester, 1965).

Figure 5-Representation of the stock and flow structure.

3.2.4- Underlying assumptions, Approximations and Clarifications

As part of the analysis, some assumptions and approximations have been made to simplify the construction of the model. These approximations need to be taken into account when interpreting the results. As such, they need to be clarified and will follow up next.

- The EAF plants stand for a secondary route production process where the input is scrap because 76% of EAF plants follow this route Appendix II). According to a different source, as of late 1980, almost all EAF plants were running on scrap input, as of now, the non-scrap input is about 20% of the EAF input. (Neelis and Patel, 2006)
- There is a small portion of EAF technology used in the primary route that starts with iron ore or direct reduced iron, however, this percentage is quite small (about ~10%) (see Appendix II), that it is safe to represent EAF furnaces in the model as secondary steel production plants, coupling the production of steel through EAF to the usage of scrap as input (Yellishetty et.al, 2010).
- There is one country (Mexico) that has a relatively high share of EAF coupled with DRI (60%). However, Mexico it is not included in the largest steel producing countries and the GHG emissions resulting from this production process are small due to the usage of natural gas as energy fuel (Kim & Worrell, 2002). In this way, it is still safe to assume that EAF technology can be represented as secondary route.
- The opposite does not hold the same way because integrated plants use scrap as input, representing about 25 % of the total metallic input in integrated plants. (IEA, 2020)
- Minimill is sometimes mentioned in literature to refer to EAF that produces steel from scrap.

- This study aims to understand the stagnation of the emission intensity that started in 1995, and because there were almost no active OHF plants since the early 1990s (Appendix I), the model will not include the transition from OHF to BOF.
- CO_2 is responsible for the highest emissions that induce the greenhouse effect, as such CO_2 emissions constitute a large part of total GHG emissions (Holappa, 2020). In that way, articles that refer to CO_2 emissions instead of GHG emissions also contain information regarding GHG emission intensity drivers.
- In the text, the variables that are included in the model are written in italic.

4- Results

The Results Chapter starts by describing the origin of GHG emissions within the steel industry, and how that determines the behavior of GHG emission intensity. Followed by the description of the main drivers of GHG emissions and the causal relationships that each entails. The main drivers will be divided into three main categories, scale effect, technology effect, and composition effect. This allows answering the first and second research questions. This section ends with the description of stagnation factors found in literature, and the interpretation and analysis of the consequences of each factor on the GHG emission intensity behavior in the final model.

4.1- Origin of GHG emission in the steel industry

GHG emissions come from the production of steel. Steel is produced through two production routes: the integrated (BF/BOF) and the secondary route (EAF). The proportion of each type of steel plant changed between 1960 and 2015 (see Appendix I). This proportion plays a role in the GHG emission intensity behavior, as EAF plants are less emission intensive than BF/BOF plants (Swalec and Shearer, 2021). Moreover, each production process differs significantly in the type of feedstock used, the amount and type of energy used, and the steps involved in the steel production (Conejo et. al, 2020). As such, each production process will be represented by two stocks (Figure 6), one for *EAF plants* and one for *BOF plants*. The stock increases with new plants built and decreases with the retirement of plants. The size of the stock of each production process together with its *production capacity* determines the amount of steel produced, described as the *production activity* of each plant (Figure 6). The amount of active steel plants is determined by the *Gap between demand and production capacity*, this will be further elaborated in the results chapter (section 4.2.1- Scale effect). The higher the amount of steel produced the higher the usage of raw material and the higher the *energy consumed* to produce steel. The latter can be improved by having a higher *energy consumption efficiency*.

Fossil fuels are used as raw materials (to function as a reducing agent), and as energy sources (to produce heat and electricity) (see section 2.3- Energy, Fossil fuels and GHG emissions). In good approximation, the emissions from each route are proportional to the amount of *fossil fuel material* used in the production of steel (Conejo et.al, 2020).

The usage of *fossil fuel material* <u>within</u> the steel producing plants gives rise to *Plant emissions* (scope 1). In the BF-BOF route plant emissions rise from the amount of raw material used as a reducing agent and from the energy required for heating. The EAF route uses less *fossil fuel material* due to the *use of scrap* (Figure 6). Scrap eliminates the need for fossil fuel material that would be needed for the iron-making step. Thus, the higher the *scrap usage* the lower the *fossil fuel material* used, and as a consequence reduces the *EAF plant emissions* (Lyakishev & Nikolaev, 2003).

The usage of fossil fuels, as a source to produce electricity, <u>outside</u> the steel plants gives rise to *indirect energy emissions*. The *indirect energy emissions* are proportional to the *external energy consumed* times the ratio of *fossil fuel sources* used in the external energy grid. The amount of *electricity* consumed in each plant determines the *external energy consumption*. Together *external energy* and *plant emissions* are responsible for the full GHG emission of the steel industry, not accounting for scope 3 emissions.

The *GHG emission intensity* is a measure of GHG emissions per unit of steel produced, and in that way, it is determined by the total industry's *GHG emissions* divided by the overall *production activity*.

The *production activity* of each steel plant determines the total *production output*. The environmental impact of a high *production activity* can be decreased by increasing the *yield*. As an increase in *yield* reduces the *production activity* necessary to generate the same *production output*, less scrap and energy are consumed as a consequence.

Furthermore, alterations in the composition of the steel industry plants change the level of both process and energy emissions. The composition of the *total amount of plants* changes the GHG emission intensities level because the EAF technology is less emission intensive than the BF/BOF process, and so the contribution of plant emissions from EAF plants weigh less than that from BF/ BOF plants.

The relationships described in this section show the origins of GHG emissions in the steel industry. It serves as a basis to understand the influence of the drivers of the GHG emission intensity on its behavior. The model that translates these relationships can be seen in Figure 6. The left side shows the contribution of the EAF route, and the right side shows the contribution of the BF/BOF route to the GHG emission intensity. The variables in green influence the overall GHG emission intensity of both routes.

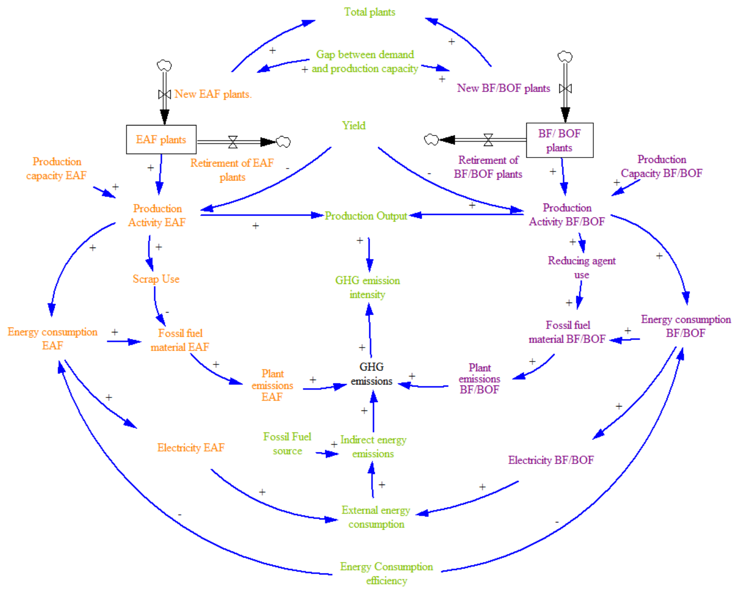


Figure 6 - Origin of steel industry emissions. The variables in orange represent the contribution of the EAF route, in purple the contribution from BF/BOF route to the GHG emission intensity behavior. Green variables influence the GHG emission intensity independently of the production route.

4.2- Drivers of GHG emission in the steel industry

The Scale, Technology and Composition effects are going to be used to introduce the main drivers of GHG emission intensity. Each of these effects relates to the GHG emission intensity behavior, as described previously in the theoretical background section 2.52.5- . Each driver that has influenced the GHG emission intensity of the steel industry between 1960 and 2015 falls under one of the three effects. How these drivers are connected to each effect and how they determine the GHG emission intensity will be described in the following sections. Additionally, the causal relationships that rise from each driver will gradually be presented in small SD models, which will be part of the final model at the end of the section (4.2.4- Overall Final model).

The quotations that backup the information written in this chapter are noted behind each sentence in the following format (1:3). The first number refers to the number of the source, e.g., Wang et. al (2021), and the second number refers to the quotation number within the paper, in this case, it refers to quotation number 3. The quotations are presented Appendix VI, grouped by each driver, and the numbering of the sources can be found in Appendix V.

4.2.1- Scale effect

The scale of the steel industry influences the amount of GHG emissions produced. Scaling up or down provides opportunities to change the composition of technology and thus alters the prospect of the GHG emission intensity level. Demand is a factor that drives the direction of the scaling rate, as demand determines the need for construction or retirement of industrial plants. In this way changes in demand can alter the scale of the steel industry. The demand level is influenced by different factors that change the required steel production, such as quality requirements and the usage of alternative materials to steel.

The first section will start with a description of how demand determines the scale of the steel industry, followed by the consequence of having a global scale industry. In the second section, a zoom-in will be done into the factors that change demand and affect the scale of the industry.

I – Development of Industry Scale and Consequences of Global Scale

With regards to the scale of the steel industry, it started with an exponential growth in several countries in the 1970s. It began to expand and reached a global scale. The biggest breakthrough was from China in the 1990s. For other countries (e.g. Germany and the U.S.) however, the steel growth stagnated and even reached a point of overcapacity, where descaling was required. Furthermore, the steel industry reaching a global scale, led to the fragmentation of the industry. These aspects will be elaborated upon next.

- *I a- Initial demand growth: Industry expansion*

After WWII (the 1940s) and until the 1970s there was a burst in the production of steel (4:20, 11:14). The main steel producing regions at the time, were Western Europe, the U.S, the former Soviet Union and Japan (Wårell, 2014). The burst in the production of steel was driven by the need to recover economically from the war and to keep the country at the forefront of development (Wårell, 2014). This period starts before the time interval under study, its relevancy lies in the fact that it determines the number of existing steel plants and sets the composition of the type of steel producing plants for a long period, as the lifetime of a steel production process is about 40 years (2:7).

A higher demand stimulates the production of steel and new plants are made when there is not enough capacity to produce according to demand. This translates into the following, a positive

Gap between demand and production capacity increases the creation of *New plants.* In turn, this changes the *total number of plants*, which determines the existing *production capacity* and in the end, it will decrease the *gap between demand and production capacity*. The relationships described here are found in Table 2. It represents a balancing feedback loop, B1 (Figure 7), meaning that the construction of new plants allows closing the gap between demand and production capacity.

The decision to generate EAF or BF/BOF plants depends on considerations like investment attractiveness, viability (e.g., degree of required modification, the lifetime of technology), government intervention, and so on. These considerations will be further looked into as they belong to technology effects and composition effects. It is important to note however, that in this period the preferred plants to build were the integrated plants (BF/BOF plants), as they were the successors of the OHF in terms of capacity and energy usage and were more attractive than EAF technology (17:4, 18:9). As a consequence, the steel production capacity grew to have the integrated route as the dominant production process (7:4).

Table 2- Causal Relationships that translate the development of the initial growth of the industry.

Higher demand for steel$\rightarrow^{+}$ Gap between demand and production capacity$\rightarrow^{+}$ New plants$\rightarrow^{+}$ Total number of plants$\rightarrow^{+}$ Production capacity$\rightarrow^{-}$ Gap demand and production capacity

- *<u>I b- Demand and Economic Growth</u>*

The development of the steel industry is intertwined with economic development. The growth of economy is only possible due to the expansion of steel production and the other way around also holds (3:28). The element that connects the number of industry plants and economic growth is demand. The degree of economic development influences the demand for steel, and the latter determines the amount of steel produced.

In the report of the IEA (2020), it mentions that since 1970 steel demand has tripled due to the ongoing requirement for steel to build infrastructure, which sets forth the country's development (3:1). The growth of a country's economy has an effect on the creation of new plants that are responsible for the emission of GHG gases.

In China, the burst in economic growth started around the 1990s, and this led to a burst in the BOF production sites which only contributed to an increase in GHG emissions. To illustrate China increased from producing about 70 Mt per year in 1990 to about 820 Mt per year in 2015 (11:13). As the growth rate was high, the technology implemented in this period, was the available mainstream technology. In this way, as the BF-BOF was the predominant technology, a large amount of BF/BOF plants were built, establishing a large part of the composition of steel plants (1:13, 10:14, 2:2). China became the largest producer in the mid-1990s and currently has 50% of the production share (12:17, 11:16, 13:42). However, its economic development outpaced the growth of steel production sites which made China the largest importer of steel (13:43).

This leads to the following causal relationships (Table 3). The higher the *Growth rate* of a country, the higher the *Demand* and thus the higher the *Gap between demand and production capacity* and thus the higher the requirement for *New plants* to create more capacity, which generates a higher *Production output* and consequently raises the country's *GDP (Gross Domestic Product)*. This allows the country to develop further in a reinforcing feedback behavior (feedback loop R1 in Figure 7).

Relevant to note is that in the 1990s several other countries were thriving in the steel market, namely the Republic of Korea, Brazil, and Mexico. These countries together with China and Japan were responsible for 40% of the total steel production (12:1).

Table 3 Causal Relationships that translate the interaction between economic growth and demand.

Growth rate $\rightarrow^{+}$ Demand$\rightarrow^{+}$ … Production output... $\rightarrow^{+}$ Growth Rate $\rightarrow^{+}$ GDP

- *<u>I c- Decrease in demand: Overcapacity</u>*

The industry kept on growing in the steel producing countries until the 1990s when the steel demand declined steeply, especially in Europe (13:40). This happened simultaneously with the burst in the development of the Chinese industry. The decrease in demand together with a broad steel offer had an effect on the steel prices and in the long run, led to a situation of overcapacity (3:29). Overcapacity is a problem for the steel producing companies as it leads to trade wars and disputes, but it also represents an opportunity to close emission intensive plants and to keep production sites that are less harmful (3:4, 2:12, 2:5). Eventually overcapacity also caught up with China, when the economic growth rate started to stabilize, becoming a global issue.

The ongoing decline of demand makes the *Gap between demand and production capacity* reverse its direction, as *production capacity* starts to become larger than the *demand for steel*. If the demand keeps decreasing for a long time, then the steel industry faces *Overcapacity*, causing an increase in the *Retirement rate* of steel plants. This decreases the *total number of plants*, and thus the *production capacity*, leading to a decrease in the *gap between demand and production capacity*. The relationships described here can be found in Table 4, these generate another balancing feedback loop, as it closes the gap between demand and production capacity, in the opposite direction from the first balancing loop (B1, Figure 7).

Table 4 Causal Relationships that translate the occurrence of a decrease in demand leading to overcapacity.

Lower Demand for steel→+ Gap between demand and production capacity→- Overcapacity→+ Plant Retirement →- Total number of plants→+ Production Capacity→- Gap between demand and production capacity

Note: Currently, global steelmaking capacity is 25% higher than demand (2:5). Also, according to Swalec & Shearer (2021), China in particular has around 350 Mtpa of operating excess (2:14). As mentioned above, descaling provides an opportunity to significantly reduce emissions and decrease emission intensity (2:13).

- *I d- Global scale: Fragmentation of the steel industry*

Between 1960 and 2015 the steel production industry expanded to a wide range of countries and led to the first wave of globalization. It was stimulated by the fact that steel has a wide range of applications and is a fundamental component for the development of societies, which makes it attractive for countries to generate their own steel plants (3:8). Both effects, industrial growth and globalization, have led to a fragmentation of the industry (3:29). As mentioned in the IEA report (2020), 'The top 10 companies account for just over a quarter of global output, with the top 25 and top 50 accounting for 42% and 56% respectively'. Consequently, the industry is highly competitive due to the broad offer of steel products (3:30, 13:03). As such steel prices have remained low and accordingly the profit margin as well. The implications of having small profit margins are that choices to invest in production processes are preferably low-cost (26:15).

A high amount of *total plants* reflects the fragmentation of the steel industry and thus affects the *steel price* negatively, this, in turn, lowers the economic *growth rate*. As such, it translates into lower *demand* and lower *capital for investments*. Both constrain the creation of *new plants* and lower the amount of *total plants*. This describes two balancing feedback loops (B3 and B4, see Figure 7), that limit the expansion of the industry.

Table 5 Causal Relationships that translate the fragmentation of the industry.

Total plants→ - Steel Price→ + Growth rate →+ GDP→+ Capital for investment →+ New plants→+ Total plants
Total plants→- Steel Price→ + Growth rate →+ Demand→ Gap between demand and production capacity →+ New plants→+ Total plants

- *I Model – Representation of causal relationships*

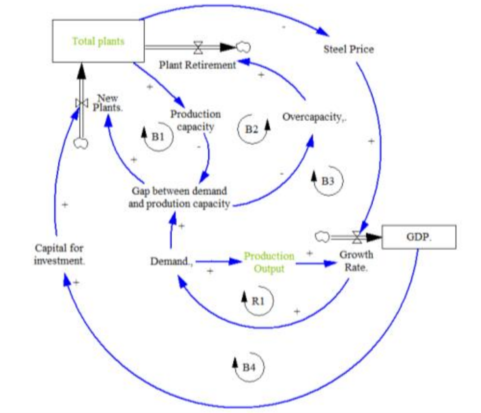


Figure 7 Model retrieved from joining the causal relationships from the scale effect, in terms of the Development of Industry Scale and Consequences of Global scale. In green are the variables that interfere with the GHG emission intensity level.

From the causal relationships explored above, the resulting model is presented in Figure 7. There are 5 feedback loops present, mainly balancing in nature. What can be seen here is the effect of a change in demand on the scale of the industry and the opportunities that rise to either create or retire plants, due to a change in the gap between demand and production capacity (B1 and B2). Additionally, the effect of a high amount of steel plants on the steel price is represented and as a result its effect on the economic growth (R1, B3, and B4).

Note: In the final model the stock structure presented here was unfolded in two separate stocks the EAF plants and BF/BOF plants (see model considerations in Appendix VIII).

II- Changes in the scale of the industry

Demand for steel has been increasing ever since 1940 until 2015 (4:20). However there have been several factors that have limited the demand for steel. These are namely the requirement for high-quality steel due to competitive alternatives and material efficiency demands from consumers.

II a- Requirement for Quality Materials

As mentioned above the development of the industry is intertwined with economic development (3:28). Economic development is a reflection of infrastructure development, which is strongly dependent on steel, especially at an initial stage. When the infrastructure has been settled in broad terms, there is a lesser need to expand in size and the requirement for quality materials takes over (4:19). As such, the steel-consuming sectors, (such as the automotive, aviation, and construction sectors), continuously keep seeking for the most advanced materials with maximum performance for the lowest cost. This raises two effects. Firstly, the requirement for advanced materials provides an opportunity for other materials such as aluminum and plastic to enter the steel market. This is due to the attractive properties of these materials, as the possibility to get into complex geometries, higher material efficiency and lower corrosion rate, and shape flexibility (25:2, 3:25, 14:14). Therefore, the increasing value of steel alternatives has consequences for the steel demand, as was visible in the U.S. between 1971 and 1991 when the steel demand decreased 15%, plastics increased 300% and aluminum 55% (14:16).

Secondly, it forces the steel industry to focus on investing in higher quality steel to be able to compete in the market. This was the case in the U.S, Germany, and Japan, in the 1970s, where the focus shifted to produce steel with higher quality (14:17). The consequence of having a higher quality material is that it increases the material efficiency, and the lifetime of a product. The latter means that steel takes longer to reach its end of life, and thus induces a delay in the need for new steel, reducing the overall demand (9:35).

The causal relationships that rise from the requirement for quality materials are translated into the following (see Table 6): the higher the *GDP*, the higher the *Material quality requirement*, and as seen before the higher the *Capital investment*. These two effects, stimulate the *investment in quality* steel. The investment in quality keeps steel in a competing position in the market increasing or at least maintaining the *Steel market share*. However, the fact that the *lifetime of steel* increases leads to a decrease in *demand* (9:28). Also, the *Material quality requirement* has a direct negative effect on the *Steel market share*, as it represents the decrease in steel use due to the availability and rise of alternative high-quality materials. The *Steel market share* relates to *demand* positively as a higher share of steel products in the market reflects upon a higher demand for steel products. Furthermore, the decrease in *Steel market share* by itself also stimulates the *investment in quality* products.

Table 6-Causal Relationships connected to factors that influence demand.

GDP→+ Material quality requirement + Capital for investment→+ Investment in quality→+ Steel market share
Investment in quality →+ Life-time of steel products→- Demand
GDP→+ Material quality requirement →- Steel market share→+ Demand
Steel market share→+ Investment in quality

- *II Model - Representation of causal relationships*

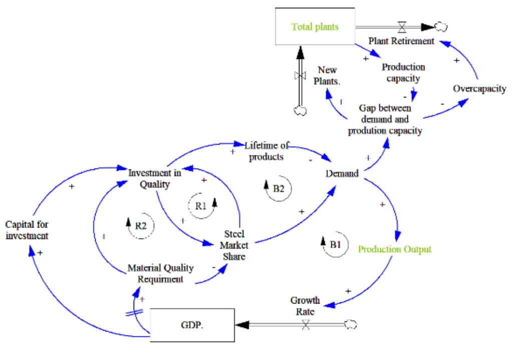


Figure 8 Model retrieved from joining the causal relationships from the scale effect, in terms of the factors that affect the scale of the industry. In green are the variables that interfere with GHG emission intensity level.

The model generated from the factors that affect the scale of the industry can be seen in Figure 8. It retrieves 4 feedback loops, two reinforcing (R1 and R2) and two balancing loops (B1 and B2). It shows how the requirement for quality materials and the investment in the lifetime of steel products, has limiting and reinforcing effects on demand and as a consequence on the total amount of plants.

4.2.2- Technology effects

Technology effects are reflected in the diffusion and implementation of technology that changes the emission intensity of the steel production process. The changes that are implemented in the production process structure are usually of two types, either continuous improvements that can be implemented within existing steel plants, or disruptive improvements where the ratio of plants is altered.

This distinction is relevant because the decision to choose for a certain mitigation option has different consequences. Continuous improvements do not need to take sunk costs into account and are often safer in the short run. On the other hand, the implementation of disruptive technology needs to be considered more thoroughly, as it entails a higher investment risk but might be more beneficial in the long run, especially when it benefits the environment significantly.

Continuous improvements are thus technology implementations that do not change the proportion of the types of existent production plants (primary or secondary), i.e., the production processes still follow the same route. Instead, the changes cause a higher efficiency of the process, making it less GHG emission intensive. Disruptive technology changes are characterized by radical changes in the production route. Inefficient production routes are changed by implementing new production technology which will fundamentally change the production process, as in the number of production phases, the type of fuel needed, the type of feedstock used... During the period between 1970 and 2015, one disruptive transition took place, the transition between the integrated route and the secondary route. The transition rate was influenced by several factors, such as scrap availability and quality requirements. These technological changes will be explored in the same order in the remaining part of this section.

Besides the implementation of the improvements, the type of feedstock used impacts the GHG emission intensity, this aspect will end the section.

I- Implementation of Continuous technology - Process efficiency

The major developments that led to a higher process efficiency were mainly: the increase in the share of the usage of the continuous casting method, and the increase of the OHF retirement rate. This change happened around the 1970s when the need for more efficient technology rose, both in terms of production capacity and energy efficiency. This need was driven by the growth of the industry and later by the energy crisis. The consequence of having a higher process efficiency is that less fossil fuels are used to produce a ton of steel which ultimately lead to less GHG emission intensity.

- *I a- Energy Crisis -R1*

In the 1970s, due to the overall growth of industries, energy consumption rose very quickly, this induced a spiked increase in prices that led to the energy crisis (14:8). The *energy price* is not controlled by the industry, however, it impacts the *energy costs* directly. To be able to cope with the increase in *energy costs* the consumption of energy needed to be reduced. *Energy costs* compose about 20-40% of the steel *production costs* (26:33, 7:14). Therefore, there was a high incentive to implement energy-efficient technologies, that would decrease the energy required to produce steel (1:25, 7:34, 14:08). This was done in several ways, through the *investment in the Best Available Technologies* (BAT), through the implementation of continuous casting technology, through the transition from OHF to BOF, and the decarbonization of electricity grid (12:14, 12:29, 1:16). The transition from OHF to BOF will be included in the investment in Best Available Technology, and the decarbonization of the grid is not directly influenced by the steel industry itself. This translates into the causal relationships found in Table 7.

Table 7 - Causal Relationships connected to the occurrence of the Energy Crisis in the 1970s.

Energy Price →+ Energy Costs→ + Production Costs →+ Investment in BAT

- *Implementation of BAT – R2*

Since the integrated route, at the time, was the predominant production process, the main energy efficiency investments were made by *improving* the *BF-BOF production route* through the *investment in Best Available Technology* (BAT) (1:26, 10:14). Meanwhile the *price of steel* went up to compensate the increase in *production costs* in the short run. This had a negative influence on *demand* (1:27). The interactions described here are presented in Table 8.

Note: Best Available Technologies (BAT) 'mainly refers to proven technologies and processes available at a commercial scale that transform waste heat to useful energy, thus lowering the energy intensity of the steelmaking process' (Swalec & Shearer 2021, p.23).

Table 8- Causal Relationships connected to the implementation of BAT.

Investment in BAT →+ Improvement of BF/BOF →- Energy Required BOF →+ Energy Consumption BOF
Energy price→+ Energy costs →+ Production Costs→+ Steel price →-Demand

- *Implementation of Continuous Casting technology – R3*

Continuous Casting (CC) machines penetrated the market heavily since the 1970s (9:20). The introduction of this technology came with the need to increase the *yield*. An increase in yield means that less raw material input is needed to produce a certain amount of output (14:05). In that way the *implementation of the CC method* diminishes the material losses, which not only reduces the raw materials used (represented by *scrap use* and *reducing agents*) to produce steel but also the energy consumed per ton of steel (*energy consumption efficiency*) (9:30). In the 1990s, already more than half (~60%) of the steel casting was done with the CC method (17:8). It is relevant to note that the penetration level of CC casting in China and India is still very low, however in Korea, U.S. and Mexico the CC process is extensively used (12:22). The causal relationships embedded are represented in Table 9.

Table 9 Causal Relationships connected to the implementation of CC technology.

Investment in BAT→ + CC implementation→ + Yield → - (Scrap + Reducing agent)
CC implementation→ + Yield→ + Energy consumption efficiency → Energy consumption BOF + EAF→ -Fossil fuel Material

- <u>*I b- Efficiency limit -B1*</u>

In order to produce steel, there is a thermodynamic *minimum required energy*, to melt iron ore. With each improvement of the BF/BOF route in terms of the *energy required per ton of steel*, the *gap between the energy consumed and minimum required* energy becomes smaller. This means that it is only possible to improve the BF/BOF route until it reaches the threshold of *minimum required energy*. Described here is the leveling off of the gain in efficiency attainable by implementing continuous adjustments to existing technology. When this phase is reached the only way to progress to a less energy-intensive industry is by transitioning to a new production process.

This is the case for the integrated route, where the state-of-the-art equipment is already reaching the minimum required energy consumption (3:7). When the gain in energy saving becomes very small, the implementation of a disruptive technology becomes more attractive and viable. Although it is still possible to increase energy efficiency in the BOF/BF route (about 10%-15%), it is not a long-term viable option (9:10, 11:24).

For the time interval that is being looked at, the *disruptive transition* refers to the transition from an integrated (BF/BOF plant) to a secondary production route (EAF plant). The causal relationships that represent the effect of approaching the limit of continuous technology adjustments are represented in Table 10.

Table 10 Causal Relationships connected to the implementation of CC technology.

Energy Required BOF→ + Gap between consumption and minimum required - ← Minimum required energy
Gap between consumption and minimum required →+ Improvement of BOF/BF→- Disruptive transition Rate

- *I Model- Representation of causal relationships*

The model presented in Figure 9, shows how the implementation of continuous improvements affects the usage of fossil fuels, which in turn are responsible for the GHG emission intensity. It shows 4 balancing loops, representing the reduction in technology efficiency gain (B1), the improvement of energy efficiency in the BOF route and the CC implementation stimulated by the energy crisis (B2 and B3), and the decrease in demand for steel due to high energy costs (B4). Fossil fuel material represents the overall usage of fossil fuels, joining the contribution of EAF and BF/BOF plants.

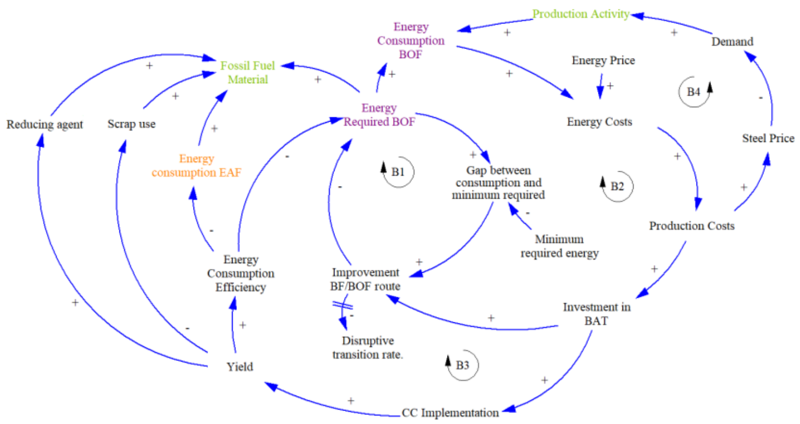


Figure 9- Model retrieved from joining the causal relationships from the technology effect, in terms of the factors that affect the implementation of continuous improvements.

II- Disruptive technology implementation

As mentioned previously the EAF technology is better for the environment as GHG emissions are much less than with the BOF furnace (15:6). Besides, according to Wang et.al (2021; p.2), there has been a 'decrease in the share of EAF production from 30% in 1995 to 21% in 2015, contributing partly to the increase of the sectoral GHG emissions.'

Implementing a new production process has to consider different aspects in two distinct contexts. When a new production plant is built from scratch, the choice of the type of production route depends solely on the implementation costs and attractiveness of each of the production routes. When a steel production plant already has an existing production process built-in, an additional aspect requires consideration: the sunk costs involved. Sunk costs are capital that that is lost when for example, technology that is still uprunning needs to be substituted before the expected moment of retirement.

The following section will look further into the effects that played a role in the transition from the primary route (with BOF technology) to the secondary route (with EAF technology), by starting with sunk costs and then zooming into the attractiveness factors.

- *II a- Sunk Costs and Retirement Rate*

The transition to the secondary production process is an option that significantly reduces the GHG emission intensity. However, the costs of replacing existing technology with new technology are high, for instance: reducing emissions by 20% in the U.S. costs about 3.6 trillion dollars (14:11, 2:4). The high amount of capital needed is connected to the implementation costs but also to the sunk costs involved.

The higher the progress of a *plant's lifetime* the lower the stranded risk of substitution. In this way, the closer the *BF/BOF plants* are to retirement, the lower the *sunk costs* when investing in new technology. This provides an opportunity to close inefficient plants, as such the *disruptive transition rate* increases and as a consequence the *implementation of EAF technology* (12:38) (Table 11).

What happened in China was that the burst in the economy led to the creation of a large number of BF/BOF plants. Since investment in new plants is costly, the expectation is that the technology lasts for a few decades. The BOF fleet, for example, has an estimated lifetime of about 40 years (2:7). As the 'boom' in the construction of BOF technology only happened in the 1990s, it means that China has a young production fleet and a transition to cleaner technology is delayed until the BOF fleet is at the end of its lifetime (3:5).

Table 11- Causal Relationships connected to the influence of sunk costs on the implementation of EAF technology.

Plant Life-time→+ BOF plants→+ Sunk costs→- Disruptive Transition Rate→+ EAF implementation

- *II b- EAF Attractiveness*

The choice between an EAF or BOF production process resides in the consideration of the following aspects: 1) the implementation costs, 2) the quality required for the end product, and 3) scrap availability (4:6). How these aspects are scored for each of the processes determines the attractiveness of the production process. An additional aspect that can make EAF more attractive is the low impact on the environment, when environmental concerns are taken into account.

- *Implementation costs*

In terms of the implementation costs the EAF technology has an advantage over the BOF technology, as it requires lower capital costs, and it can produce steel at lower unit costs (15:5, 15:29). For the EAF plants, material input costs are the highest share of the total production costs (59.3%), while energy costs represent 19% (15:27). Both energy and materials are inputs for the production of steel. According to Reppelin-Hill (1999), the price of EAF input compared to BOF input has a negligible contribution to the decision of implementing EAF (15:36). In this way the rise in energy prices during the Energy Crisis did not have a significant effect on the adoption of EAF (15:28). This could be explained by the fact that the electricity grid is largely dependent on fossil fuels, and that the usage of EAF also entails high energy costs.

The consideration of the implementation costs is an important weighting factor for the introduction of a certain technology. Although the material and energy costs did not have an effect on the diffusion of EAF, the lower capital cost does increase the attractiveness of EAF technology (15:5), playing a role in the increase in the diffusion of EAF, especially from the 1980s onwards (Smil, 2016, p.104; see Appendix I). Capital costs need to be considered and accepted before building new EAF plants. In that way, implementation costs will not explicitly be included in the model, but instead embedded in the implementation of EAF plants.

- *Quality Requirements /Saturation of EAF technology*

The fact that the development of a country occurs in parallel with the increase in the requirement for quality, hinders the adoption of EAF technology. The quality of EAF steel is not as high as the quality of steel produced through the BOF technology (17:18). This means that the higher the *material quality requirement* of steel the lower the *implementation rate of EAF technology*. Furthermore, because the EAF technology has specialized in a narrow range of products (long products) that are useful mainly for the construction industry, the *demand for EAF* steel products becomes limited (15:33, 15:4). When the *EAF production activity* catches up with the *demand level for EAF products*, its diffusion levels off. This can explain the saturation of the market of EAF technology in developed countries (15:32). The causal relationships described here can be found in Table 12.

In this way, while EAF production keeps having a small scope, it will be hard to reach a higher diffusion rate that will allow replacing the integrated route. As of now, there have been already significant improvements in the EAF, that resulted in the expansion of the EAF products to new markets that can stimulate the adoption of EAF (4:9).

Demand for EAF products represents the requirement for products that are produced by using the EAF technology. An increase in demand for EAF products can be related to two factors, either an increase in the product scope (by producing a higher number of different types of products) or an expansion of the demand for existing products.

Table 12- Causal Relationships connected to the influence of quality requirements on the implementation of EAF technology.

GDP→ +Material Quality Requirement→- Demand EAF products →+ EAF implementation → New EAF plants→+ EAF plants→+ EAF production activity →- Demand for EAF products

- *Scrap Availability*

Scrap is a fundamental feedstock for the EAF technology, so the availability of scrap steel plays a role in the attractiveness of the EAF technology. As will be seen in the next section (III a- Scrap use– Resource availability delay) the availability of scrap is limited by the time that steel remains in use, and thus limited by the amount of available *end-of-use steel*. As such, the *implementation of EAF* is constrained by the lack of steel ready to recycle. The causal relationships related to this effect can be found in Table 13.

For countries like China, where steel in-use is relatively new, it will take some time before it reaches its end of life and for enough scrap to be generated. This ultimately constrains the implementation of the secondary route (1:13).

Furthermore, the availability of the resources required for each production process also matters for the attractiveness of EAF. For example, in Mexico, due to the access to an abundance of natural gas, there was a fast adoption of EAF technology (12:34, 8:7).

Table 13 - Causal Relationship connected to the influence of scrap availability on the implementation of EAF technology.

Production activity EAF →+ Production output→ + End-of-use steel →+ EAF implementation

- *II Model: Representation of causal relationships*

The model (Figure 10) shows the factors that influence the transition to disruptive technology. The higher amount of EAF plants the lower the GHG emission intensity. The model presents two feedback loops, one balancing (B1) and one reinforcing feedback loop (R1). The balancing feedback loop represents the saturation of EAF technology, and the reinforcing feedback loop shows how the higher amount of production activity of EAF plants increases the amount of end-of-use steel, and as a consequence stimulates its own implementation, there is however a delay embedded. The effect of approaching the efficiency limit on the implementation of EAF plants, is also represented in the model below.

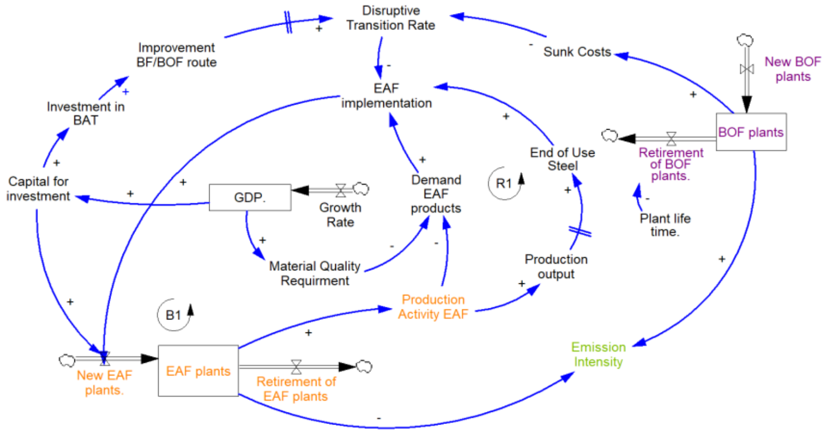


Figure 10 - Model retrieved from joining the causal relationships from the technology effect, in terms of the factors that affect the implementation of disruptive improvements.

III- Type of feedstock used

- *III a- Scrap use– Resource availability delay*

The type of feedstock used has an influence on the GHG emission intensity (17:17). According to Kim & Worrel (2002), feedstock differences have a larger effect on the amount of energy used than the product type (12:16). Using Scrap as input is less emission intensive than using iron ore.

The fact that the *lifetime of steel* is sought after to become higher, delays the amount of *available scrap* (9:28). As such, the use of Scrap is constrained by scrap availability. According to Strezov et.al (2013), 'the fraction of available scrap is less than 1% of the total iron ore reserves' (16:10). As the amount of scrap is not sufficient to respond to the demand for steel, it caused a perpetuation of the dependency on iron ores (04:07). The availability of scrap is determined by the amount of available of *end-of-use of steel*. As long as it is in-use, it is not available for recycling (9:19). Additionally, the scrap usage also depends on the end-of-use steel recovery capabilities, which is ultimately linked to the demolition techniques available and the state of end-of-use steel (19:08, 9:34). There is an offset between countries that have available steel and countries that demand steel, establishing an extra barrier to easily recycle (4:10). These are however external causes that will not be represented in the model, as they only depend on the development and application of techniques that enable the increase of the recovery rate.

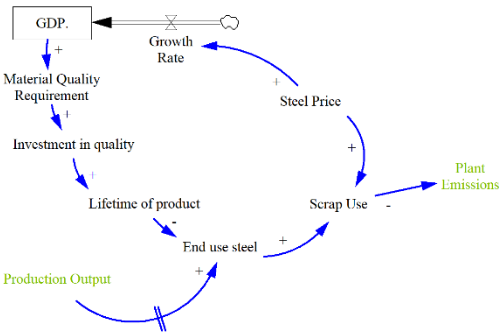
The availability of scrap sets the ground for the possibility to recycle steel, but the actual usage of scrap depends on other factors such as the price of steel or the circular economy mindset of a particular country. When the *price of steel* is low, the incentive to recycle becomes low, because buying new steel becomes more appealing (11:57). The other way around also holds:

the higher the willingness of a country to adhere to a circular economy, the higher the stimulus to recycle (11:58). The causal relationships that translate influence of recycling rate on the type of feedstock used can be found in Table 14.

Table 14- Causal Relationships connected to the influence of the recycling rate on the type of feedstock used.

Production output →+ (delay) End-of-use steel
Lifetime steel →+ End-of-use steel →- Scrap use→- Plant emissions
GDP→ + Material quality requirement→ + Investment in quality→ - Lifetime steel

- *III Model: Representation of causal relationships*



This structure (Figure 11) does not show any feedback loops but is relevant to have in the final model. This is because it explores factors that influence the *use of scrap*, an important driver of the GHG emission intensity behavior.

Figure 11 - Model retrieved from joining the causal relationships from the technology effect, in terms of the factors that affect the scrap use.

4.2.3 Composition effects

Composition effects induce a change in technological progress. It shows the effect of external factors on the implementation of green technology. These are namely the country's development level, the degree of government environmental regulation, and the research and development stage of green technology. These will be explored in the following section.

I- Investments in green technology

- *I a- Country Development Rate and Trade*

Countries in the world are not developing at the same pace. The phase-out of the development rate causes different scenarios and decision opportunities to switch to a cleaner industry. In industrialized countries the transition to a different production structure is slower due to the involvement of sunk costs and inherent resistance (15:15). Countries that have not yet built the infrastructure to produce steel have open opportunities to choose for the most advanced and fit technology (12:2, 15:34). Thus, countries can be categorized in terms of their development stage, developing countries and industrialized countries. Developing countries are investing more into new capacity (12:30). Industrialized countries have a higher economic level that enables investing in clean technology, however, the return benefits become less significant the higher the economic level (15:10, 15:35, 15:11). This makes the implementation of EAF less attractive for industrialized countries.

The technology adoption rates of different countries are phased out due to the consequence of their economic stage. The burst in the Chinese economy led to the exponential increase in the total amount of *BF/BOF plants*. In 1955, Japan was an early adopter of the Best Available Technology. This is coupled to the developing stage it was in back then when it started to grow economically. Mexico started to develop at a later time and has a higher EAF adoption rate (12:37). The motivation for the implementation of clean technology is in line with having lower sunk costs and starting to develop at a time when EAF had a higher share in the market (lower risk associated). Furthermore, according to Reppelin-Hill (1999, p.283), 'EAF technology diffused much faster in low – and lower-middle income countries' (15:22). For instance, Korea increased its share of EAF between 1981 to 1998 from 20% to 40%, showing that a developed country has a high EAF adoption rate, in line with higher *capital for investment* (12:36).

Phase out between countries gives rise to discrepancies in labor and production costs. Steel production companies are often independent of governments, and globalization has made it easier to allocate resources elsewhere. This means that developing countries that are still focused on economic goals are less committed to environmental concerns, but at the same time very attractive due to low labor and production costs (1:3, 26:15).

In terms of causal relationships (Table 15), the *GDP* level influences the *capital available for investment*, but the attainment of a high GDP level is preceded by investment in *new plants*. In that way, a high GDP level implies a higher amount of plants and thus higher *sunk costs*. The model is constructed in such a way that it can be read at a country level. The higher the *GDP* of a country the higher the *capital for investment*. Depending on the moment in time that each country started its economic development, different decisions were made regarding the type of *new plant* to be built. The choice between *BF/BOF plants* (Purple route – Figure 12) or *EAF plants* (Purple route – Figure 12) is thus time and context bounded.

Table 15 Causal Relationships connected to the influence of the country's development rate on the implementation of green technology.

GDP→+ Capital for investment → +New plants →+ BF/BOF plants + EAF plants

- <u>*I b- Government regulation - Environmental urgency*</u>

Governments and Institutions can change the structure of the steel industry by investing in *subsidies* that stimulate the choice of green technologies and by imposing *taxes* to control the GHG emission (2:11, 19:10). In this way the higher the *government intervention* the higher the *capital for investment* is made available through the former measure and the higher the production costs through the latter measure. Higher production costs give an incentive to invest in the *implementation of EAF* technology. Both government measures can be used stimulate the implementation of green technology (15:02).

The higher the country's development, the higher the GDP, and at the same time the higher the environmental strictness (19:12, 15:02, 15:14). This translates into higher *government intervention* measures. At the same time, the higher the increase in frequency of *extreme weather* events due to the GHG emission concentration in the atmosphere, the higher the urgency to act, and the higher the *government intervention* measures (15:02). The causal relationships that reflect the influence of government regulation on the investments in green technology are found in Table 16.

Table 16 Causal Relationships connected to the influence of the government intervention on the investment in green technology.

Extreme weather events→+ Government intervention→+ Subsidies→+ Capital for investment→+ New plants→+ EAF plants
Extreme weather events→+ Government intervention→ + Taxes→ + EAF implementation→+ EAF plants→- GHG emission intensity
Extreme weather events→+ Government intervention→ + Taxes→ + Retirement BOF→- BF/BOF plants→+ GHG emission intensity
GDP→+ Government intervention

II- Readiness of green technology

- *II a- Research and Development*

Research and Development (R&D) defines the progress of the industry and thus determines the technology that is available for implementation (14:33). Around the 1950s the world went through a scientific-technical revolution, where the development of continuously more efficient and productive technology occurred (14:06). This was due to the contribution of research and science. This behavior led to the gradual adoption of sophisticated technology in multiple industries, becoming the basis of the decrease in emission intensity reduction (14:06). Without the progress of science, no opportunities would arise.

However, research requires a lot of funding to be held properly. This means that it is deeply intertwined with the development of the global economy. Low-income countries are also unable to invest much in research. The U.S, for example, has spent about 16 billion dollars in twenty years starting from the 1980s (14:34).

The readiness for implementation of new technologies is dependent on the *stage of Research, Development and Deployment (RD&D)* that these technologies find themselves in (Buchner et. al, 2019). In this way, the *stage of RD&D* is closely related to what in literature is called Technology Readiness Level (TRL). TRL is a scale that is used to assess the stage that technology before entering the market. There are nine levels of technology readiness (Appendix XI). The deployment stage is only reached when technology becomes economically attractive.

The higher the investment in research, the more focus there is to dive into ways to make green solutions more attractive to the market. In this way, the higher the *GDP*, the higher the *capital for investments*, and the higher the *R&D stage*, the closer the system gets to the implementation of *Clean energy sources*, *EAF plants*, *Carbon substitutes*, and to the improvement of steel recovery capabilities, which stimulate *scrap use*. The causal relationships that reflect the influence of RD&D stage on the implementation of green technology are found in Table 17.

Table 17 Causal Relationships connected to the influence of the research and development stage on the implementation of green technology.

GDP→+ Capital to invest→+ *RD&D* stage→+ Clean energy source + EAF implementation + Carbon substitutes + Scrap use

Composition effects Model: Representation of causal relationships

The model presented in Figure 12, represents how composition effects influence the GHG emission intensity of the steel industry, including the relationships of sections I and II. It shows how the urge to act influences government intervention and how different growth rates have influenced the increase in BF/BOF plants. The model retrieved 5 balancing loops, that show the balancing of the GHG emission intensity when Taxes are imposed, and research is done to implement green technology.

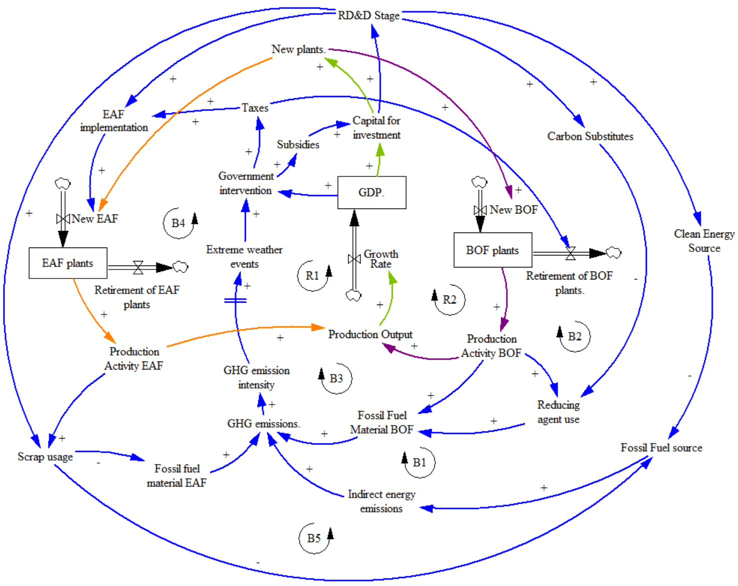


Figure 12- Model retrieved from joining the causal relationships from the composition effect.

4.2.4- Overall Final model

Joining all the sub-models together the final model was made (Figure 13), to have a clearer view see Appendix XII.

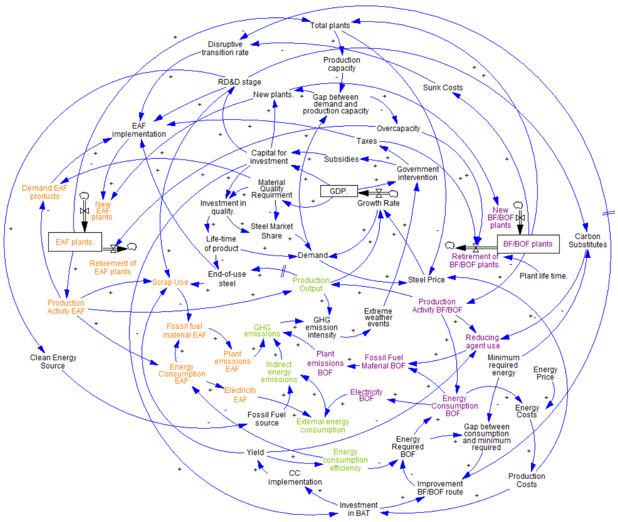


Figure 13 Final model.

4.3- Stagnation Factors

The following section will explore the different types of reasons found in literature for the GHG emission intensity stagnation phenomena. Then the factors will be pinpointed in the model (Figure 14) and their consequences will be assessed by looking at the final model.

I- Efficiency stagnation - Research and Development Stage

According to several papers (Cullen et.al, 2012; Friedmann et.al, 2019; Lyakishev & Nikolaev, 2003; Wang et.al, 2021), one of the reasons for not having a further decrease in GHG emissions is that the mitigation technologies currently available all have limitations or are not ready for deployment. This is due to several reasons: the technology efficiency is reaching its threshold, and the existing mitigation technologies are not attractive/viable enough to be implemented.

There are mitigation opportunities inside steel producing plants, such as making technology more efficient, using substitutes for fossil fuel material (e.g., hydrogen, biomass combustion), using recycled steel, or capturing and storing GHG emissions (1:35). And also, opportunities outside steel plants, by decarbonizing the grid (e.g., creating nuclear plants) (7:20). All face challenges and limitations for the large scale use in the steel industry, these will be explored next.

There is a minimum energy requirement that sets a threshold of minimum plant emissions for the production of steel when using fossil fuels as a source. The energy efficiency saving potential keeps decreasing each time a new energy-saving technology is implemented. Cullen et. al (2012) states that even if there was an implementation of all the BAT in all the steel plants, it would not suffice to achieve a 50% cut in emissions (9:10). The gradual decrease of energy saving potential implies that implementation of new technology has continuously lower return in investment, as savings are lower.

Solutions like hydrogen as a coal substitute, and biomass combustion, face implementation barriers because none of them exceed fossil fuel in its cost-performance level (26:35). Limitations in scrap usage were described in the previous section.

CCUS is an example of technology that is already in a mature RD&D stage but has not yet reached the conditions for scale deployment (Kearns et.al, 2021). As mentioned in Bui et.al (2018), the implementation of CCS has reached a bottleneck at TRL7. According to the same paper, 'the progression of a technology beyond TRL 7 needs significant financial investment and/or commercial interest' (Bui et.al, 2018; p.1064).

Nuclear power plants, for example, are a solution to decarbonize the electricity grid, as they provide large amounts of energy compared to other renewable sources, however, the risks and costs of implementation are high.

The availability of viable alternatives is dependent on technology readiness (26:3). Mitigation technology it is not reaching the deployment stage (when it starts entering market at a large scale), either because it is not fully developed, or because it is not financially attractive, or even both. One way to make mitigation technologies more attractive and more affordable is to impose taxes and provide subsidies (this is discussed in the next section regarding government intervention). This reveals that the progress of innovation and economic viability of technology are determinant factors in the decrease in the GHG emission intensity (14:33). Investing in R&D and government incentives are crucial in pushing technology into the deployment stage (26:37, 14:32).

- *Hypotheses I: Analysis through the model*

As seen previously, the RD&D stage determines the readiness for the implementation of technology. When the technology does not reach the deployment stage, the technology does not become economically attractive to be implemented on large scale in the steel production plants (26:35,14:32). This generates a blockage to the change in GHG emission intensity. As can be seen in the model (Figure 14- in pink) when the *RD&D stage* remains low it affects the implementation of *clean energy sources*, the *implementation of carbon substitutes*, and the *EAF* *implementation rate*. Moreover, the reduction in the *improvements of BF/BOF* process efficiency, can either increase the *disruptive transition rate* or lead to withholding investments.

II- Scrap availability and saturation of the EAF market

Wide implementation of the secondary production route production process would lead to a lowering of the GHG emissions intensity. The combination of EAF technology and scrap use makes the secondary route score low on the dependency on fossil fuels.

However, the secondary production process faces a few challenges, such as the availability of scrap and the demand for EAF products in the market. Regarding the former, the average lifetime of a steel product is about 70 years and as such the scrap available today was produced decades ago, and the available scrap does not meet the current demand for it (11:59, 1:12). Moreover, when the availability of scrap becomes significantly higher (expected to rise 3.5-fold by 2050), the biggest constraint for a higher recycling rate, will be to have high-quality scrap (i.e. removing impurities) (4:7, 1:52, 17:20). Regarding the latter the demand for EAF products is dependent on the improvements of technology implemented. Research can play a role in improving the quality of EAF steel products and the initial scrap input; and even in broadening the scope of products produced. However, the focus on improving the recycling rate depends on other factors such as the degree of government incentive and the social perspective (1:50).

The existence of these two constraints leads to a balancing-off of the implementation of the secondary route. As such, it poses a barrier to the decrease of the GHG emission intensity of the steel industry.

- <u>*Hypotheses II: Analysis through the model*</u>

The availability of *end-of-use steel* is constraining *scrap usage*. As seen in Figure 14 (in red) this is caused by a delay that is induced by the *lifetime of steel products*. Scrap only becomes available at the end of its lifetime. In that way, the current amount of *end-of-use steel* available equals the amount produced at the initial stages of the growth of the industry. This amount is much smaller than the current demand for scrap. Moreover, it will take decades for end-of-use steel to reach the required demand. This prospect together with the current scrap shortage and the *material quality* constraints of *EAF products*, affects the further *implementation of EAF* plants, as these become less attractive, and as a consequence perpetuates the usage of *BF/BOF plants*.

III- Country development phase out and inefficient production fleet

The possibility to implement technology depends on the country's development level (15:10). Countries with a higher GDP have more capital available to invest in green technology. Nevertheless, the regions that have a higher development rate (e.g., the U.S and Europe), face a situation of overcapacity, taking away the need for new steel producing plants (2:5).

Overall, the steel demand has been rising in the world, with the increase in population and the economic growth of developing countries (1:1). In developing countries, such as Brazil, Ukraine, India, and Russia, steel demand has been increasing, mainly to be used to build infrastructure (18:6). This provides the opportunity to create new plants and to choose to implement a novel green fleet. This choice, however, is still bounded by the viability and attractiveness considerations that, as seen in the previous sections, might decrease the chance of taking place.

While developed countries have more resources to focus on innovation (e.g. Europe and the U.S), it is the developing countries with lower economic possibilities (e.g. India), who are emerging in the steel market (1:47). This creates a phase-out between countries that can afford mitigating technology but relatively low demand, and countries that have low investment possibilities but increasing demand. An opportunity lies here in stimulating emerging economies to adopt green technologies.

Moreover, according to Swalec and Shearer (2021) currently, 60% of existing steel production plants use the integrated (BF/BOF) route which is the most carbon-intensive route (2:2). This is most difficult to decarbonize, due to the high costs involved to make the process less carbon-intensive. The fact that the majority of the technology is composed of inefficient plants is aggravated by the fact that it is a young production fleet with an average age of 12 years (2:7). The estimated operation time of such a fleet is usually about 40 years (2:7). This delays the opportunity of replacement of inefficient active plants and does not stimulate the decrease of the GHG emission intensity.

- *Hypotheses III: Analysis through the model*

The Scale effect section (I – Development of Industry Scale and Consequences of Global Scale), mentioned how the economic growth expansion in the 1970's, also led to the increase of the industrial scale. As such, Figure 14 (in green) shows that an increase in *growth rate* stimulated an increase in *demand* for steel. Moreover, an increase in *demand* led to an increase in the *gap between demand and production capacity*, which in turn stimulated the generation of *new production plants*. Countries that were in a low development stage (*GDP*) in that period (e.g., Europe, U.S.) chose for the mainstream technology (BF/BOF fleet). This increased the *BF/BOF plants* stock, and also stimulated further industry *growth*. At a certain point the *Gap between demand and production capacity* became negative, and *overcapacity* took place. This led to the opportunity to *retire BF/BOF plants*.

Later, EAF entered the market and the developing countries at that time (e.g. Mexico), had the opportunity to choose between two types of plants. When the EAF is not considered beneficial, due to the product range and scrap availability, it decreases the EAF implementation, and the choice becomes more inclined to implement the BF/BOF plants. As a consequence, a higher number of BF/BOF plants are added to the total existent production fleet, and the sunk costs for replacement become high, perpetuating the use of carbon intensive plants.

Furthermore, a higher available *capital for investment* only comes with a higher *GDP* level, this, in turn, blocks the possibility of *investment in R&D* and delays the implementation of green technology.

IV- Government intervention

As discussed above (section I b- Government regulation - Environmental urgency), a higher country's development level is positively related to government pressure to implement green technologies (15:14). This is good for the environment, as high environmental taxes and subsidies, stimulate the search for green alternatives (15:17, 13:27, 26:4, 2:10). For the steel production companies, higher taxation translates in higher production costs, and higher development levels translates higher labor costs. The consequence is that companies seek to settle in countries that alleviate the production costs and have lower emission standards (26:40). The transition of steel production plants to regions that do not invest in green practices and often provide tax exemptions phenomenon, leads to what is described as 'carbon leakage' (2:15). Carbon leakage occurs when emissions decrease in one place and as a consequence increase in another location, causing the problem to continue or even to aggravate. This adds to the problem of emission intensity stagnation (2:15).

- *Hypotheses IV: Analysis through the model*

The higher the *government intervention* the higher the *taxes* and *capital for investment*, this stimulates the *EAF implementation* (Figure 14- in yellow). It also shows that when government intervention is low the attractiveness of EAF plants will be lower, ultimately leading to an increase in the *BF/BOF plants* to cope with demand. The effect of shifting to a country with lower government incentives is not explicitly modeled, however, if the overall *government intervention* increases the investment in green technologies also increases. As long as government intervention remains low in the majority of the steel producing countries, the transition to a state where the stagnation is lifted will be delayed.

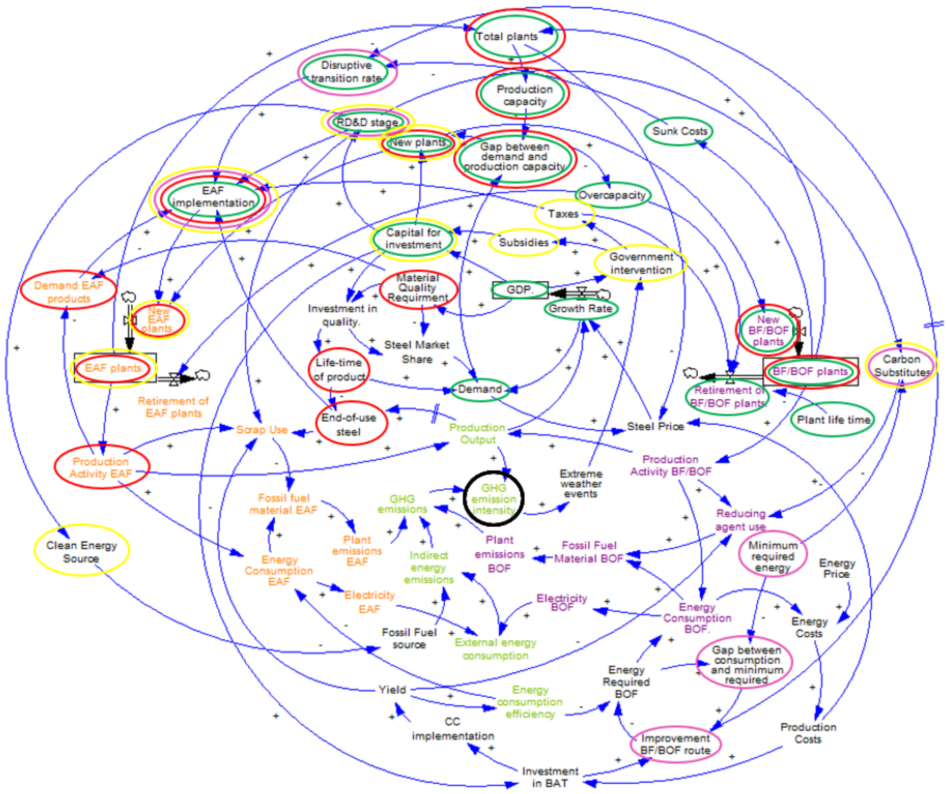


Figure 14- Representation in the model of the effect of the hypothesis on the GHG emission intensity behavior. In pink: hypotheses I, in red: hypothesis II, in green: hypotheses III, and in yellow: hypotheses IV.

5- Conclusion

<u>5.1- Outcomes of the research project</u>

An initial objective of this study was to identify the drivers of GHG emission intensity. To be able to understand what drives the GHG emission intensity behavior 4 distinct components were identified. The first is the understanding of the *origins of the GHG emission intensity*, i.e., what are the elements of the steel industry that are responsible for the change in the GHG emission intensity during the period between 1960 and 2015. These are the proportion of EAF and BF/BOF plants and the amount of fossil fuel material used in each plant, that in turn depend on the amount of energy and raw materials used.

Second, the *scale effect* allows an understanding of the drivers that were responsible for a change in the scale of the industry and that provided opportunities to change the proportion of

EAF and BF/BOF plants, and thus alter the GHG emission intensity behavior. These were the initial industry growth, the Chinese economic burst, and the consequences of overcapacity. Besides this, the ongoing development of the industry brings the need for materials of increasing quality, which in turn slows down its own growth.

Third, the *technology effects* allowed understanding the drivers that led to the occurrence of changes in technology, namely continuous and disruptive adaptations. Continuous process efficiency adjustments were stimulated by the energy crisis in the 1970s. The disruptive transition from BOF and EAF plants occurred gradually, and was affected by several considerations, such as the sunk costs, scrap availability, and quality requirements.

The fourth component, *composition effects,* surfaced the drivers that influenced the proportion of EAF and BF/BF plants in the steel industry. The growth rate of different countries influenced the choice for EAF plants, and the degree of government intervention has stimulated the investment in research and the implementation of green technology.

A second objective of the study was to synthesize the drivers into a system dynamics model to have an overview of the interactions between all the previously mentioned effects. The synthesis of the drivers resulted in a complex model, that explores the numerous aspects that change GHG emission intensity.

Finally, the goal was to find factors that determine the stagnation of the steel industry. The results for this part need to be interpreted with caution. In literature several reasons were found that explained the lowering of the decrease rate of GHG emission intensity. These can be seen as constraints that have stopped the GHG emissions intensity from further decreasing. When looking at the effect of each of these constraints through the relationships explored in the model, it might lead to the thought that stagnation can be removed by waiting for time to pass. This is because factors such as the availability of end-of-use steel, technology readiness, and the retirement of inefficient plants are dependent on time to stop constraining the decrease in GHG emission intensity. Even government intervention could be postponed until the urge to act becomes higher, as extreme weather events become more frequent. However, this is the exact opposite of what is trying to be achieved, with for e.g., through the Paris Agreement in 2004. There is an urgency to react now, therefore letting the system unblock by itself is not going to be a solution.

5.2- Limitations of the Research

This project is subject to several limitations. Firstly, the model itself is always a representation of a system, which by definition is bounded by the scope of the projects and the accurate functioning of its internal structure (Vennix, 1996). This means that approximations and assumption were made in the formulation of the model (see Appendix X). Secondly, due to time constraints, the literature review is done with a selective group of articles. Therefore, if the model does not replicate the observed behavior, it will not be entirely certain that there is a gap in the understanding of the phenomenon. Thirdly, the model is generated including drivers that have shaped the global industry which might not resemble interactions that occur at a regional level, and thus the insights might not be as useful applied to individual production sites. Lastly, the construct of environmental quality used in literature to describe economic growth might lead the project towards more economic drivers instead of social and political drivers.

The research was kept qualitative, because of the scope of the project, as the number of variables involved was too large (about 55 variables) to be able to quantify each of them properly within the timeframe of the project.

- *Reliability and Validity Considerations*

Models are always a select representation of reality, and as such, to check the validity and reliability of the results the model should be thoroughly tested. This was done briefly (Appendix IX), however, it can further be improved by attempting to simulate the model and check if the result is empirically verifiable or by making a qualitative test. The latter can be done by performing a disconfirmatory interview, or by generating a model with a second coder. All the above-mentioned possibilities fall outside of the reach of this project. In this way, the model is reliable to the extent that it is generated out of existing literature and there has been caution in backing up each relationship by multiple sources.

It would have been good to check *apriori* if there was any categorization available for factors that influence the environmental quality or GHG emission intensity to have a more guided search through literature. This might have led to the fact that certain relevant aspects might have gone unnoticed and could have an effect on the reliability of the research. On the other hand, at the beginning it was decided deliberately to go for an open coding process to avoid being biased toward any type of pre-established categories, this contributes to a more valid result.

Also, there are several aspects inherent to the structure of the industry that makes it hard to get a high accuracy for the model. As the steel production routes have many types of combinations, the representation needs to be simplified. The simplification requires approximations that make it difficult to establish reliable comparisons in implementation costs, energy required, and emissions produced. For example, direct reduced iron is sometimes used as input for the EAF, and scrap is also used in combination with the BOF, and as such the different types of possible combinations can change the contributions of the GHG emission of the existent plants. The only way to increase the reliability would be to take a local approach to decrease the degrees of freedom and increase the specificity of the information.

5.3- Further Research

Further research possibilities lie in finishing the steps required to perform a complete phenomenon driven explanation research strategy, i.e, the quantification of the model. The aim would be to reproduce the reference mode of behavior, in this case, the observed GHG emission intensity pattern. This would be done by introducing numerical data into the variables and modeling the equations that reflect the interaction between variables. It would test more accurately if the structure of the model explains the observed behavior. It would provide a more complete tool where the effect of policies can be tested, and more informed decisions can be extracted. The definition of the variables (Appendix VII) can be used to find values that describe their behavior, only the weight of each cause and the mathematical equation would have to be thought through in more detail. Additionally, it would be interesting to investigate more specific cases like one particular country or even a particular company.

Besides the emission of GHG, there are other problems that the industry faces (such as social health problems and water and soil pollution). The exploration and combination of the various problems the steel industry faces would be a worthwhile endeavor, particularly in how decision-making works in prioritizing solutions. Questions like, whether efforts should be focused first on the mitigation of GHG emissions or on solving social health problems, and how much is solving one problem delayed to be able to tackle the other.

6- Discussion

6.1- Interpretation of the results

This project set out the aim of finding an explanation for the goal-seeking behavior of the stagnation phenomena. This would mean that the model showing the GHG emission intensity behavior should be embedded in balancing loops. However, the model does not show any loops that directly involve the identified stagnation factors and the GHG emission intensity variable.

An interesting finding that stems from here is that more research needs to be done into what plays a role in human decision-making, in particular, what influences and accelerates government intervention, research and development, and the choice for green technology. As can be seen through this research, the current literature has only described a set of intertwined effects that influence the GHG emission intensity behavior. However, the reason why it has stagnated lies within the factors that are inhibiting the implementation of mitigation technology. These are the lack of available scrap, the narrow scope of EAF products, the lack of economic attractiveness of innovative technology, the phase-out of government strictness, and the sunk costs associated with the large number of inefficient plants. To get a full understanding of how the GHG emission stagnation came to be, the understanding of how decision opportunities are managed is needed first.

6.2- Comparison of stagnation results and situation of current industry

As is currently visible in the world, the prices of steel are increasing again, due to the war between Russia and Ukraine. An increase in prices stimulates countries to seek alternatives. This provides the opportunity to invest in green technology and stimulates the transition to clean energy. Furthermore, this opportunity could ignite a breakthrough necessary to restart decreasing the GHG emission intensity.

In the previous energy crisis, the solution that companies found to combat the high energy prices was to invest in BAT. Hence, as seen in the previous section (I- Efficiency stagnation - Research and Development Stage), the optimal energy efficiency has almost been reached. This means that investing in improvements to existing technology will not help to combat energy prices. Options nowadays are to find other energy sources that are feasible regionally and to invest in renewable energy. Since environmental concerns are playing a large role, the energy crisis presents a good opportunity for governments to transition towards a green energy grid.

6.3- Comparison of results between different types of documents.

During the literature review, there were no strong contractions between papers worth mentioning. The discrepancies found between information retrieved from the articles were mainly regarding the proportion of energy costs, the possible gain in energy efficiency of a particular technology, and the degree of increase in demand. These might be justified by the particular country, year, or specific technology it refers to. The fact that knowledge is constantly developing gives rise to discrepancies between papers.

6.4- Theoretical Implications

This project resulted in a compilation of the factors that influence the GHG emission intensity behavior. Besides the synthesis of the information from 19 literature pieces, the research has retrieved the causal relationships that reflected the drivers of GHG emission intensity. These causal relationships were connected into one final model, reflecting the dynamics that influence the GHG emission intensity. The model joins technical and non-technical aspects, as it explores the mechanical structure of the origin of GHG emission intensity, but also includes the impact of relevant events for the development of the industry on the behavior of GHG emission intensity. It provides an overview of the map of interactions between the factors that contribute to changing the behavior of the GHG emission intensity. The value of this work is the insight that the dynamic view provides into the GHG emission intensity, compared to the linear cause-effect explanations found in literature. It allows identifying intrinsic problematic patterns and intervention possibilities. Moreover, the multidisciplinary character of this project helps academics of different backgrounds to have a more holistic understanding of the GHG emission intensity. In the literature no work has yet been done that brought all these components together and generated a single visual representation translating the dynamic interactions.

6.5- Practical Implications

The knowledge about the drivers that have been responsible for changes in the GHG emission intensity behavior between 1960 and 2015 can be used by policymakers to create a set of mitigation policies that consider the GHG emission behavior dynamics. More specifically, policies can be implemented by taking into account factors that helped decrease GHG emission intensity in the past, or by looking at possible solutions to remove the current blockage.

As such, it is interesting for policymakers to note from this study, that several opportunities can be used to make the industry less emission intensive. These are for example: the closing of inefficient plants, the introduction of secondary plants in developing countries, and using the current political tension to stimulate the adoption of clean tech. Furthermore, the removal of the blockage can be accelerated, by increasing the funding of research in green technology and stimulating government intervention.

6.6- Reflection

Being a student that was not familiar with nor in contact at all with the steel industry context, I tried to capture and process the information with the highest possible accuracy. It is an advantage in the way that as a researcher I had a neutral perspective not biased by reading previous papers, but it is also a disadvantage, as the understanding of the information might be adjusted to my own perception and interpretation of the data. The latter might lead to an inadequate weighting of factors and might make my model less representative of reality. However, I did my best to be careful with possible assumptions and to be aware and alert in order to minimize this effect. The usage of complex systems made it hard to follow a structured and predetermined research process. This means the project was iterative and sometimes difficult to make it consistent and valid. Finally, the different levels involved in the structure of the steel industry, (namely global, country, and plant levels) made it difficult to develop one joint final model that included all the important effects.

6.7- Research Ethics

This project attempts to comply with research ethics at all times. The sources used are part of the public university domain, accessible to anyone who possesses such credentials. The quotations used for the literature are found in Appendix VI and are labeled with the source and the literal quotation. In the results chapter, information is labeled with numbers and not in the common APA style. Furthermore, as a researcher that is not in any way associated or familiar with the steel industry prior to this research project, the intention is to stay neutral, open, and avoid bias at all times.

7- Acknowledgements

In the first place, I would like to thank Floris Swennenhuis for all the constructive feedback, but also for the availability and patience during the whole Master Thesis. Vincent de Gooyert follows, for the valuable advice and for giving me the opportunity to take longer than expected.

Secondly, I would like to thank my new friends from the Master for all the motivation you gave me and of course the good company. It meant a lot. They have been sweating and working with me for many days in the Library of Science: Bram van de Peut and Jennifer Smith.

Thirdly, I would like to thank a long list of friends and family that have supported me all along, through the whole process. They gave me indispensable help and love. My mum, my dad, my 'grandparents' (Jan and Helen Dol), my niece (Puck de Haan), my work colleagues, my housemates (with a special thanks to Jesse van der Hoeven), and all my close friends in Portugal (with a special thanks to Sofia Lourenço, David Silva, Ricardo Peres, and Alexandre Falcão) and all my close friends in the Netherlands.

Finally, a special thanks to Ruud Verhagen, who was responsible for helping me recover from a difficult phase of my life and made me feel capable to perform this project.

It has been a long and difficult journey and therefore I want to highlight that I am extremely thankful to all the above-mentioned people. There are no words to describe my gratitude.

I want to dedicate this project to my mum (Ellen van de Brake), who has been the pillar of my life, and has always been there for me. Also, she insisted on creating the artistic cover of this project, and so deserves a special mention.

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Appendix I

Development of steelmaking technology

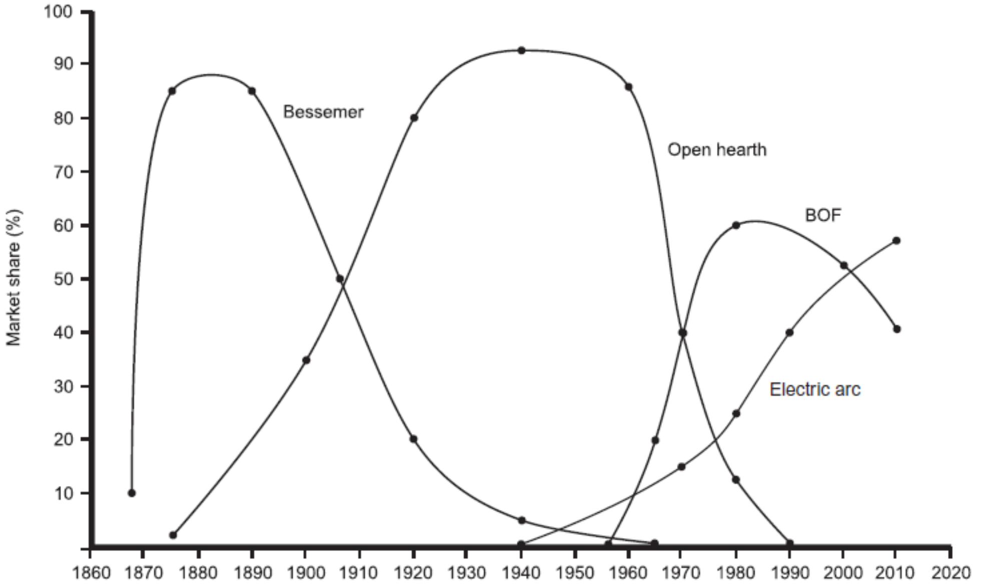


Figure 9.5 Transitions from Bessemer converters to open hearth furnaces to basic oxygen and electric arc furnaces. *Plotted from data in Campbell (1907), Temin (1964), and WSA (2014).*

Figure 15 Market share development of mainstream steel making technology between 1860 and 2020, retrieved from Smil (2016; p. 190)

Appendix II

Steel Production Material Flow

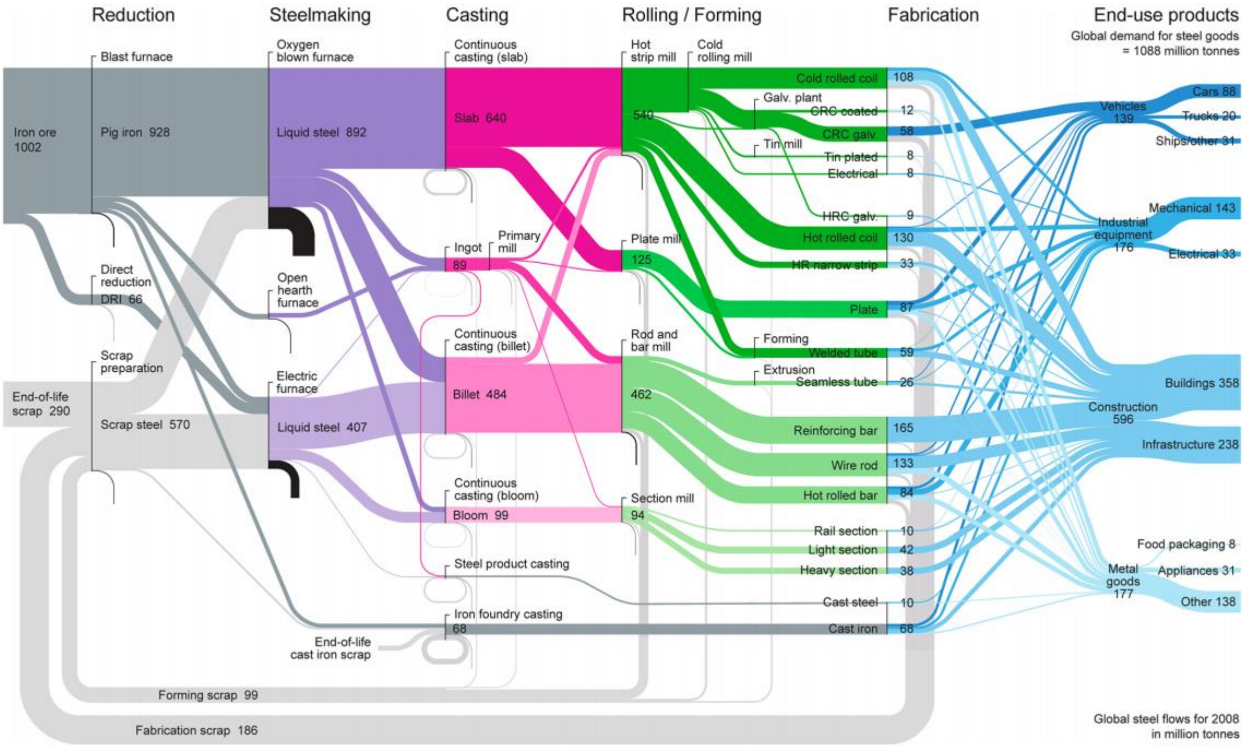


Figure 16 Steel Material Flow in 2008, retrieved from Cullen et. al (2012)

Appendix III

Elaboration on Research process

Open Coding and Axial Coding

The research process started with coding the selected papers. The program used for the coding process was Atlas.ti. First an open coding process was followed, to identify pieces of text that contained information about drivers that play a role in the industry's GHG emission intensity behavior. From each of the selected papers, the most relevant quotations have been extracted and entered in the following table (Table 18).

The structure of the table allows the visualization of the type of document, author and publication year, each piece of coded text belongs to. In the same table a column is there to describe the causal relationships that can be extracted from the information and the GHG emission drivers that it translates to.

Table 18- Outline of table to aid the coding of the steel industry's emission intensity drivers

Type of document	Author and Publication Year	Text Citation	Quotation Nr.	Causal Relationship / Information
Scientific Paper				
Report				
(…)				

In total the open coding step retrieved 564 quotations. Next followed a sorting step, where each of the quotations was assessed again to ensure that it effectively had a connection to the GHG emissions of the steel industry.

To finish the open coding process each coded script was labeled by a short code on the side (mainly in terms of the most important variables that related to the quote), and after the literature review the quotations where divided on the basis of short codes by different groups: economic drivers, environmental drivers, political drivers, social drivers, technological drivers, competitive landscape, cost and income, energy, final use of steel, internal industry drivers, material, processes, recycling procedure, Research and Development, solution, World trade. This step helped to get insights about the structure of the industry and served as an initial categorization, that was meant to aid the next step.

Next followed a sorting step, where each of the quotations was assessed again to ensure that it effectively had a connection to the GHG emissions of the steel industry. The filtered-out quotes where then divided into different themes through an axial coding process. The themes were found after reading all the articles and based on the most frequently mentioned aspect of the steel industry, namely energy, recycling, yield efficiency, demand drivers, technology diffusion, and trade dynamics (Table 19).

Table 19-Themes retrieved from axial coding process.

Energy	Recycling	Yield efficiency	Demand Driver	Trade	Technology diffusion
Carbon Dependency	Scrap availability and demand	Material Efficiency	Steel Dependency	Uncertainty factors present	Viability
Thermodynamic Constraint	Transition of BOF to EAF	Continuous casting	Alternative to steel	Overcapacity	Research and Development
Efficiency Transition costs	Scrap Iron ore Ratio	Improvement in Yield	Industry/Population Growth	Competitiveness	Technology Implementation
BOF energy saving	Perspective on recycling	energy efficient process	China demand Burst	Fragmentation of industry	Techno-economic Metrics
EAF efficiency gain	Quality steels Demand	Effect on Demand		Differences between countries	Barrier of implementation
OHF substitution					EAF Attractiveness
Cost of Energy					
Energy Crisis					
Fuel Source					
Renewable energy					
Energy Consumption					
Feedstock vs Product type					

<u>*Data Analysis and Selective coding*</u>

Dividing the relevant quotations into the previously mentioned themes helped in uncovering the most forthcoming emission related aspects in literature. These aspects started to indicate the main drivers of GHG emissions, (e.g, economic crisis with spiked energy prices and energy efficiency gains). In order to make drivers more concrete an iterative process started between seeking connection between separate quotes, creating generic models that sketched the interaction described in the quotes (Figure 18), and with perspectives provided by the models adjusting the drivers.

After a few iterations three overarching categories were found and connected to theoretical construct of environmental quality. According to Reppelin-Hill (1999), Environmental Quality is determined by the following effects: scale effect, technology effect and composition effect. For this study in particular these dimensions will be used to categorize the drivers that affect GHG emission intensity behavior. The reason for introducing this construct is because the Results section needed a guideline to present the main drivers and since all the drivers fitted one of the categories it seemed relevant to insert it in the project. Although this construct is deeply connected to theory regarding trade and economic growth, it can still be employed to introduce the drives of GHG in a logical sequence.

Elicitation of Causal Relationships and Model Building

After coupling the quotes to different categories, the causal relationships were determined from the different text segments (all quotations are in Appendix VI). From there, separate models where derived for each driver of each category and then joint together into one category model. In the end, variables needed to be reviewed in order to be sure that there was no repetition or overlap in the meaning of the variables. The final model provides a synthesis of the drivers in literature. The research process described above is summarized in Figure 17.

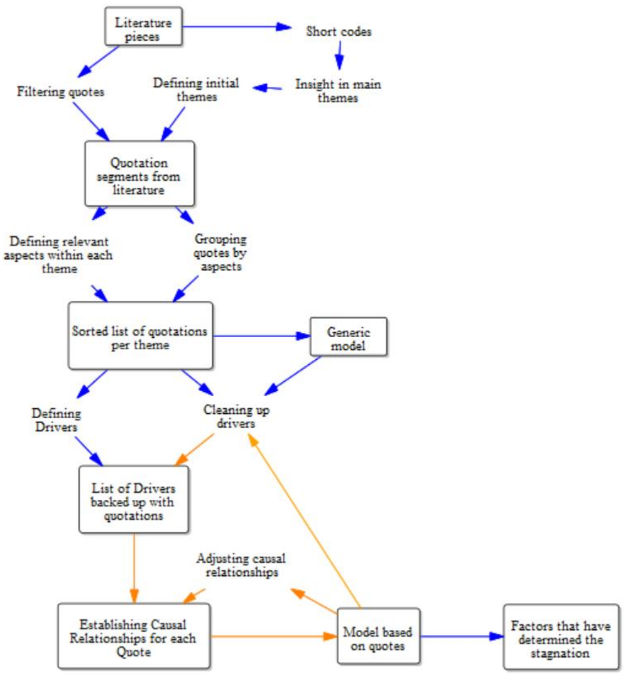


Figure 17- Visual representation of the research process. In orange is indicated the iterative cycle of the data analysis process.

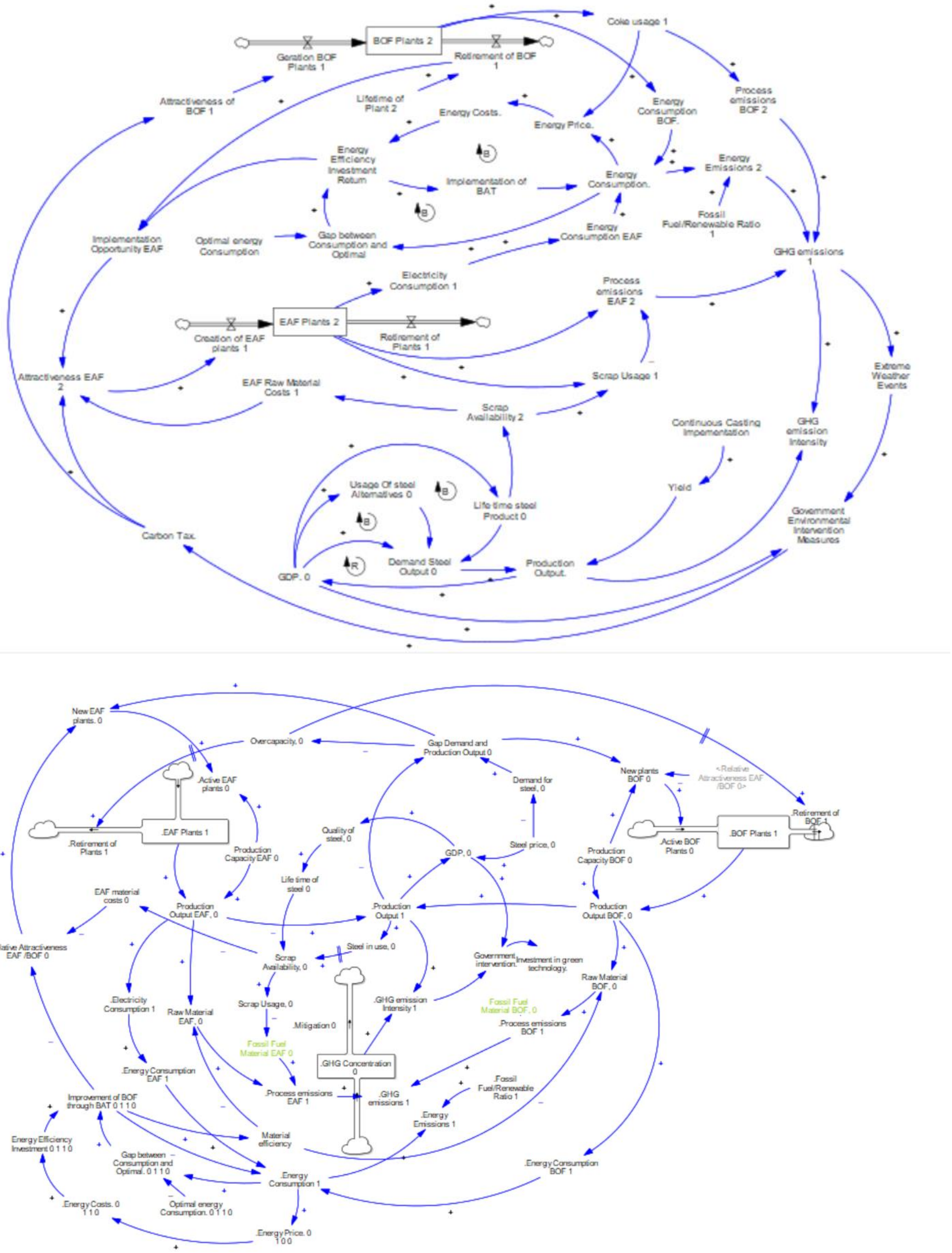


Figure 18 – Examples of Generic models before reaching the end drivers.

Appendix IV

Source Selection Procedure

A- Google search

The search for scientific papers for the literature review was done by joining several keywords to find relevant articles:

1- ‘GHG emission’ and ‘steel industry’ and ‘development’
2- ‘Emission drivers’ and ‘Steel Industry’
3- ‘Emissions' and ‘steel’ and ‘history’
4- ‘Sustainability’ and ‘steel production’
5- ‘systems approach’ and ‘steel industry’
6- ‘Environment’ and ‘steel industry’
7- ‘steel industry’ and ‘historical perspective’

The first three searches the initial 8 to 10 articles were assessed in terms of their connection to the project (relating to the global steel industry, to emissions and with an historical view). For the last 3 searches (4,5,6,7) only the first 5 Google Scholar results were assessed, as the terms cover the research topic are slightly less connected to the main topic. These were however performed to check if there where articles that fitted the current research and would possible be overlooked.

The terms: ‘Development’ and ‘history’ and ‘historical perspective’: reflect the longitudinal aspect of the project, including articles that cover the timeline of relevant events.

The terms ‘GHG emissions’ and ‘emissions’: Represent the fundamental unit of the study, searching for papers that elaborate on factors that determine GHG emissions. The term ‘emissions’ on its own was used to include relevant papers that would talk about the steel industry and factors that contributed to the GHG emission intensity but mentioned CO_2 (one of the gases that contributes the most for the GHG effect) emissions instead.

The term ‘steel industry’: certifies that paper included address the steel industry.

The term ‘system dynamics’: includes papers that have looked at the steel industry through a systems lens.

The terms ‘environment’ and ‘sustainability’: includes papers that address environmental issues and sustainability in the steel industry which might contain information about GHG emission drivers of the steel industry.

The results of the Google search can be found in the following table.

1.1- Google Scholar: 'GHG emission' and 'Steel Industry' and 'Development':	Sorted by relevance
Tian, Y., Zhu, Q., & Geng, Y. (2013). An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry. *Energy Policy*, *56*, 352-361. (China)	Country specific
Zeng, S., Lan, Y., & Huang, J. (2009). Mitigation paths for Chinese iron and steel industry to tackle global climate change. *International Journal of Greenhouse Gas Control*, *3*(6), 675-682.	Country specific
Gielen, D., & Moriguchi, Y. (2002). CO2 in the iron and steel industry: an analysis of Japanese emission reduction potentials. *Energy policy*, *30*(10), 849-863.	Country specific
Kim, Y., & Worrell, E. (2002). International comparison of CO2 emission trends in the iron and steel industry. *Energy policy*, *30*(10), 827-838.	Global industry + emissions + historical view
Rynikiewicz, C. (2008). The climate change challenge and transitions for radical changes in the European steel industry. *Journal of Cleaner Production*, *16*(7), 781-789.	Country specific
Burchart-Korol, D. (2011). Significance of environmental life cycle assessment (LCA) method in the iron and steel industry. *Metalurgija*, *50*(3), 205-208. (not readable)	LCA method
Pal, P., Gupta, H., & Kapur, D. (2016). Carbon mitigation potential of Indian steel industry. *Mitigation and adaptation strategies for global change*, *21*(3), 391-402. (India) (Springer)	Country specific
Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. *Metals*, *10*(9), 1117.	Global industry + emissions
Wang, K., Wang, C., Lu, X., & Chen, J. (2007). Scenario analysis on CO2 emissions reduction potential in China's iron and steel industry. *Energy Policy*, *35*(4), 2320-2335. (China) (Elsevier)	Country specific
1.2- Google Scholar: 'GHG emission' and 'Steel Industry' and 'Development':	**Sorted by relevance and since 2017**
Holappa, L. (2020). A general vision for reduction of energy consumption and CO2 emissions from the steel industry. *Metals*, *10*(9), 1117.	Global industry + emissions
Ahlström, J. M., Zetterholm, J., Pettersson, K., Harvey, S., & Wetterlund, E. (2020). Economic potential for substitution of fossil fuels with liquefied biomethane in Swedish iron and steel industry–Synergy and competition with other sectors. *Energy Conversion and Management*, *209*, 112641.	Country specific
Lv, W., Sun, Z., & Su, Z. (2019). Life cycle energy consumption and greenhouse gas emissions of iron pelletizing process in China, a case study. *Journal of Cleaner Production*, *233*, 1314-1321.	Country specific
Conejo, A. N., Birat, J. P., & Dutta, A. (2020). A review of the current environmental challenges of the steel industry and its value chain. *Journal of environmental management*, *259*, 109782.	Global industry + emissions + historical view
De Ras, K., Van de Vijver, R., Galvita, V. V., Marin, G. B., & Van Geem, K. M. (2019). Carbon capture and utilization in the steel industry: challenges and opportunities for chemical engineering. *Current Opinion in Chemical Engineering*, *26*, 81-87.	Solutions for GHG emission not drivers

Huang, B., Chen, Y., McDowall, W., Türkeli, S., Bleischwitz, R., & Geng, Y. (2019). Embodied GHG emissions of building materials in Shanghai. *Journal of Cleaner Production*, *210*, 777-785.	Building Materials
Haider, S., & Mishra, P. P. (2019). Benchmarking energy use of iron and steel industry: a data envelopment analysis. *Benchmarking: An International Journal*. (India)	Country specific
Dudin, M. N., Reshetov, K. Y., Mysachenko, V. I., Mironova, N. N., & Divnenko, O. V. (2017). " Green Technology" and Renewable Energy in the System of the Steel Industry in Europe. *International Journal of Energy Economics and Policy*, *7*(2), 310-315. (Europe)	Country specific
Eva, S. N., Sekiyama, T., & Yamamoto, M. (2021). Decomposing the Energy Impact of the Steel Industry in the Manufacturing Sector: Evidence from Japan and China. In *Growth Mechanisms and Sustainability* (pp. 147-174). Palgrave Macmillan, Singapore. (Japan and China)	Country specific
2- Google Scholar: 'emission drivers' and 'Steel Industry':	**Sorted by relevance**
Tian, Y., Zhu, Q., & Geng, Y. (2013). An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry. *Energy Policy*, *56*, 352-361. (China)	Country specific
Song, Y., Huang, J. B., & Feng, C. (2018). Decomposition of energy-related CO2 emissions in China's iron and steel industry: A comprehensive decomposition framework. *Resources Policy*, *59*, 103-116.	Country specific
Kim, Y., & Worrell, E. (2002). International comparison of CO2 emission trends in the iron and steel industry. *Energy policy*, *30*(10), 827-838.	Global industry + emissions + historical view
Xu, R., Xu, L., & Xu, B. (2017). Assessing CO2 emissions in China's iron and steel industry: evidence from quantile regression approach. *Journal of Cleaner Production*, *152*, 259-270.	Country specific
Zhang, B., Wang, Z., Yin, J., & Su, L. (2012). CO2 emission reduction within Chinese iron & steel industry: practices, determinants and performance. *Journal of Cleaner Production*, *33*, 167-178.	Country specific
Lutz, C., Meyer, B., Nathani, C., & Schleich, J. (2005). Endogenous technological change and emissions: the case of the German steel industry. *Energy policy*, *33*(9), 1143-1154.	Country specific
Xu, B., & Lin, B. (2016). Regional differences in the CO2 emissions of China's iron and steel industry: Regional heterogeneity. *Energy Policy*, *88*, 422-434.	Country specific
Xu, B., & Lin, B. (2016). Assessing CO2 emissions in China's iron and steel industry: A dynamic vector autoregression model. *Applied Energy*, *161*, 375-386.	Country specific
Lin, B., & Wang, X. (2015). Carbon emissions from energy intensive industry in China: evidence from the iron & steel industry. *Renewable and Sustainable Energy Reviews*, *47*, 746-754.	Country specific
Neelis, M. L., & Patel, M. K. (2006). Long-term production, energy use and CO2 emission scenarios for the worldwide iron and steel industry.	Global industry + emissions
3- Google Search: 'emissions' and 'steel' and 'history'	**Sorted by relevance**
Serrenho, A. C., Mourão, Z. S., Norman, J., Cullen, J. M., & Allwood, J. M. (2016). The influence of UK emissions reduction targets on the emissions of the global steel industry. *Resources, Conservation and Recycling*, *107*, 174-184. (UK)	Country specific

Cullen, J. M., Allwood, J. M., & Bambach, M. D. (2012). Mapping the global flow of steel: from steelmaking to end-use goods. *Environmental science & technology*, *46*(24), 13048-13055.	Global industry + emissions
Conejo, A. N., Birat, J. P., & Dutta, A. (2020). A review of the current environmental challenges of the steel industry and its value chain. *Journal of environmental management*, *259*, 109782.	Global industry + emissions + historical view
Wang, H. F., Zhang, C. X., Qie, J. M., Zhou, J. C., Liu, Y., Li, X. P., & Shangguan, F. Q. (2017). Development trends of environmental protection technologies for Chinese steel industry. *Journal of Iron and Steel Research International*, *24*(3), 235-242.	Country specific
Karakaya, E., Nuur, C., & Assbring, L. (2018). Potential transitions in the iron and steel industry in Sweden: towards a hydrogen-based future?. *Journal of cleaner production*, *195*, 651-663.	Country specific
4- Google Search: 'Sustainability' and 'steel production'	**Sorted by relevance**
Nidheesh, P. V., & Kumar, M. S. (2019). An overview of environmental sustainability in cement and steel production. *Journal of cleaner production*, *231*, 856-871.	Cement industry as well
Yellishetty, M., Ranjith, P. G., & Tharumarajah, A. (2010). Iron ore and steel production trends and material flows in the world: Is this really sustainable?. *Resources, conservation and recycling*, *54*(12), 1084-1094.	Global industry + emissions + historical view
Strezov, V., Evans, A., & Evans, T. (2013). Defining sustainability indicators of iron and steel production. *Journal of cleaner production*, *51*, 66-70.	Global industry + emissions
Holappa, L. E. K. (2017). Energy efficiency and sustainability in steel production. In *Applications of Process Engineering Principles in Materials Processing, Energy and Environmental Technologies* (pp. 401-410). Springer, Cham.	Focus on energy efficiency
Pan, H., Zhang, X., Wu, J., Zhang, Y., Lin, L., Yang, G., ... & Peng, H. (2016). Sustainability evaluation of a steel production system in China based on emergy. *Journal of cleaner production*, *112*, 1498-1509.	Country specific
5- Google Scholar search: 'systems approach' and 'steel industry':	**Sorted by relevance**
Kumar, S., Ghildayal, N., & Ostor, C. (2008). A systems approach in examining optimization opportunities and dynamics of the global steel industry. *Information Knowledge Systems Management*, *7*(4), 401-427.	Global industry + emissions + historical view
Sun, W., Wang, Q., Zhou, Y., & Wu, J. (2020). Material and energy flows of the iron and steel industry: Status quo, challenges and perspectives. *Applied Energy*, *268*, 114946.	Flow maps
Hafeez, K., Griffiths, M., Griffiths, J., & Naim, M. M. (1996). Systems design of a two-echelon steel industry supply chain. *International Journal of Production Economics*, *45*(1-3), 121-130.	Supply chain management study
Singh, R. K., Murty, H. R., & Gupta, S. K. (2007). An approach to develop sustainability management systems in the steel industry. *World Review of Entrepreneurship, Management and Sustainable Development*, *3*(1), 90-108.	About Decision Support systems
Duflou, J. R., Sutherland, J. W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., ... & Kellens, K. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP annals*, *61*(2), 587-609.	Efficient manufacturing

6- Google Scholar search: 'Environment' and 'steel industry':	Sorted by relevance
Reppelin-Hill, V. (1999). Trade and environment: An empirical analysis of the technology effect in the steel industry. *Journal of Environmental Economics and Management*, *38*(3), 283-301.	Global industry + historical view
Zhang, S., Yi, B. W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., ... & Varis, O. (2019). Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. *Journal of Cleaner Production*, *232*, 235-249.	Country specific
Proctor, D. M., Shay, E. C., Fehling, K. A., & Finley, B. L. (2002). Assessment of human health and ecological risks posed by the uses of steel-industry slags in the environment. *Human and ecological risk assessment*, *8*(4), 681-711.	Human Health issues not GHG emissions
Birat, J. P. (2020). Society, materials, and the environment: The case of steel. *Metals*, *10*(3), 331.	Global industry + emissions
Tatar, M., Sergienko, O., Kavun, S., & Guryanova, L. (2017). COMPLEX OF MANAGEMENT MODELS OF THE ENTERPRISE COMPETITIVENESS FOR STEEL INDUSTRY IN THE CURRENCY INSTABLE ENVIRONMENT. *Economic Studies*, *26*(5)	Not directed to GHG emissions
7- Google Scholar search: 'historical perspective' and 'steel industry':	**Sorted by relevance**
Stubbles, J. (2000). Energy use in the US steel industry: a historical perspective and future opportunities. Energetics, Inc., Columbia, MD (US).	Emissions + historical view
Carlsson, B. (1981). Structure and performance in the West European steel industry: A historical perspective. In *The structure of European industry* (pp. 125-157). Springer, Dordrecht.	Not related to emissions
Sharp, R. M., Cann, N. K., & McFadzean, D. (1990). NZ's Iron and Steel Industry-an Historical Perspective. *New Zealand Engineering*, *45*(4).	Not related to emissions
Olasky, M. N. (2013). *Corporate public relations: A new historical perspective*. Routledge.	Not related to emissions
Ge, S., Isac, M., & Guthrie, R. I. L. (2012). Progress of strip casting technology for steel; historical developments. ISIJ international, 52(12), 2109-2122.	Not accessible and Not related to emissions
Green- Literature sources chosen **Purple-** Literature relative to a specific country **Red-** Literature that did not match the study	

Selected Literature from Google search on 30 September 2021:

Selected articles (Authors + publication year)	Frequency in search
Birat, J. P. (2020)	1
Conejo, Birat, & Dutta, (2020)	3

Cullen, Allwood & Bambach, (2012)	1
Holappa, L. (2020)	2
Kim & Worrell (2002)	2
Kumar, et. al. (2008)	1
Strezov & Evans, (2013)	1
Reppelin-Hill (1999)	1
Yellishetty, et.al. (2010)	1
Neelis & Patel, (2006)	1
Stubbles (2000)	1

B- Supervisor suggestion

Literature suggested by supervisor:

Selected articles (Authors + publication year)
Wang et. al (2021)
IEA (2020)
Swalec & Shearer (2021).
Lyakishev & Nikolaev, (2003)

C- Snowballing

Literature from snowballing:

Selected articles (Authors + publication year)	Snowballed from:
Worrell, et.al (1997)	Cullen et.al, (2012)
Yellishetty, et.al (2011)	Lyakishev, & Nikolaev, (2003)
Friedmann et.al, (2019)	Wang et. al (2021)
Hasanbeigi, & Springer (2019)	Wang et. al (2021)

Appendix V

List of Sources

Table 20 - List of Sources

Document	Authors	Source ID number
Reference Paper	1- Wang et. al (2021)	1
Scientific Papers:	2- Birat (2020)	7
	3- Conejo et.al (2020)	8
	4- Cullen et.al (2012)	9
	5- Holappa (2020)	11
	6- Kim & Worrell (2002)	12
	7- Kumar et.al (2008)	13
	8- Lyakishev & Nikolaev (2003)	14
	9- Reppelin-Hill (1999)	15
	10- Strezov & Evans (2013)	16
	11- Worrell, et.al (1997)	17
	12- Yellishetty et.al (2010)	18
	13- Yellishetty et.al (2011)	19
Reports:	14- IEA (2020)	3
	15- Swalec & Shearer (2021)	2
	16- Neelis & Patel (2006)	4
	17- Friedmann et.al (2019)	26
	18- Hasanbeigi & Springer (2019)	6
	19- Stubbles (2000)	25

Appendix VI

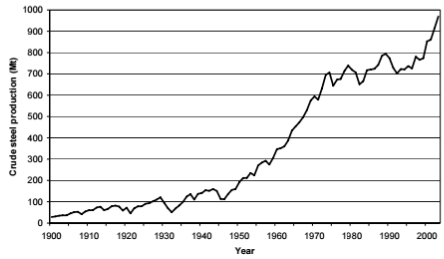
Overview of Quotations

The following Tables present literal citations from the literature pieces used for this study. Each citation is coupled to its source and numeration of the quotes result from the coding process in the Atlas.ti9 program.

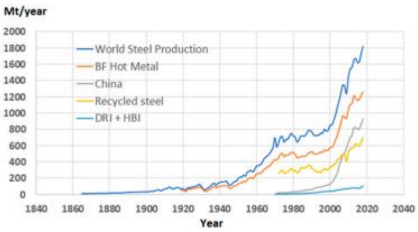
<u>4.2.1- Scale effect</u>

I – Development of Industry Scale and Consequences of Global scale

- *I a- Initial demand growth: Industry expansion*

Document	Type of Document	Quote	Nr.	Relationship
Holappa, (2020)	Scientific Paper	<u>Extensive investments</u> were made in the steel industry, with Japan, Soviet Union, United States, and South Korea in the vanguard. The annual steel production reached 700 Mt in the 1970s (record 749 Mt in 1979)	11:14	Demand$\rightarrow^{+}$New plants
Neelis & Patel (2006)	Report	 Figure 3-2 Apparent worldwide crude steel production, 1900-2003 (IISI, Various years)	4:20	Demand $\rightarrow^{+}$ Production capacity
Swalec & Shearer, (2021)	Report	The average age of the existing global fleet of BF and direct reduced iron (DRI) furnaces is 13 years and 14 years, respectively. Over half the world's global steel fleet is in China, where the average age for BFs is 12 years and DRIs is 8 years. BF and DRI furnaces are typically operated for around 40 years with investment cycles of 15–20 years for BFs and 20 or more years for DRI plants,3 though refurbishments may extend their overall lifetime by several decades	2:7	Average life-time of production fleet
Birat (2020)	Scientific Paper	This was organized with economic targets in mind, based on the rationale of economies of scale, as, indeed, the integrated steel mills grew in <u>size</u> accordingly while the <u>steel market</u> exploded: this was the first wave of globalization, before a second wave of globalization moved goods around the world, beyond raw materials.	7:4	Demand$\rightarrow^{+}$ Gap between Demand and production Capacity$\rightarrow^{+}$ New Plants$\rightarrow^{+}$ Total number of plants
Worrel et.al (1997)	Scientific paper	Primary steel is produced by two processes: open hearth furnace (OHF) and basic oxygen furnace (BOF). The OHF is still used in different configurations, mainly in Eastern Europe, China, India and other developing countries; of the countries examined in this paper, the OHF process share is high in Poland (29')0) and China (20%) [IISI, 1992]. While OHF uses more energy, this process can also use more scrap than the BOF process. However, the BOF process is rapidly replacing OHF worldwide because of its greater productivity and lower capital costs. In addition, this process needs no net input of energy and can even be a net energy exporter in the form of BOF-gas and steam. The process operates through the injection of oxygen, oxidizing the carbon in the hot metal. Several configurations exist depending on the way the oxygen is injected. The steel quality can be improved further by ladle refining processes used in the steel mill.	17:4	BOF plant diffusion
Yellishetty (2010).	T-Scientific papers	4.1.3. Open hearth furnace technology (OHF) is where excess carbon and other impurities are burnt out of the pig iron to produce steel. OHF was developed to overcome some of the difficulties faced in steel production until that time. However, most OHFs worldwide were closed by the early 1990s, because of their fuel inefficiency and resource intensity, and are being replaced by the BOF.	18:9	OHF retirement

- *I b- Demand and Economic Growth*

Document	Type of Document	Quote	Nr.	Relationship
IEA (2020)	Report	Among the most important are economic development, trade and competitiveness, all of which are interlinked. Steel is used in a number of sectors that are closely tied to overall economic activity – the steel industry is both a reflection of, and contributor to, global economic growth. When the global economy is buoyant, people buy houses and cars, governments build more infrastructure, and the private sector invests in commercial buildings and machinery. While the regional dynamics are more nuanced, the relationship between steel demand and economic activity at the global level are closely related.	3:28	Production output →+ Growth rate →+ Demand for steel →+ Production output
Holappa (2020)	Scientific Paper		11:13	China late production burst
Kim & Worrel, (2002)	Scientific Paper	Fig. 1 shows the steel production trends in the six analyzed countries. Steel production varied in the countries over the period. China shows a prominent growth (on average 6.5%/ year) and, after 1994 became the world's largest steel producing country. There is no clear trend for the US (average of 0.2%/year), however, the US is still the second largest steel producing country in the world. Korea (+8.9%/year) and India (+5.3%/year) also show a remarkable increase in production.	12:17	Growth Rate $\rightarrow^{+}$ Demand$\rightarrow^{+}$ Gap between Demand and production Capacity$\rightarrow^{+}$ New Plants$\rightarrow^{+}$production activity$\rightarrow^{+}$ GDP$\rightarrow^{+}$ development rate
IEA (2020)	Report	Steel will also be an integral ingredient for the energy transition, with solar panels, wind turbines, dams and electric vehicles all depending on it to varying degrees. Since 1970 global demand for steel has increased more than threefold and continues to rise as economies grow, urbanise, consume more goods and build up their infrastructure.	3:1	GDP→+ steel demand
Holappa, (2020)	Scientific Paper	This was the overture to the "boom" with China in the forefront. Since then, the world production has doubled and the record so far is 1,869 Mt, attained in 2019 [6]. China´s share is over 50%.	11:16	GDP$\rightarrow^{+}$ Demand$\rightarrow^{+}$ Gap Demand and production Output$\rightarrow^{+}$ New Plants
Kumar et.al (2008)	Scientific Paper	In 1997, the Chinese industry became the world's largest producer of crude steel.	13:42	Growth rate $\rightarrow^{+}$ Demand$\rightarrow^{+}$ Gap Demand and production Output$\rightarrow^{+}$ New Plants
Kumar et.al (2008)	Scientific Paper	Despite the rapid growth in Chinese steel production, it still could not keep up with its own booming demand. Thus, China has also become the most dominant importer in the world.	13:43	GDP→+Demand→+ Total Steel plants→+ Production activity→+ Steel from export
Kim & Worrel, (2002)	Scientific Paper	Seven major producing countries: Republic of Korea (South Korea), Mexico, Brazil, China, India, and United States (US). These six countries, except Mexico, have always been among the top 10 steel producing countries in the 1990s. Together, these countries produced over 40% of global steel production in 1999.	12:1	Country Production Output Production Rate
Wang et.al (20210	Scientific paper	Unfortunately, our analysis shows that these improvements have not kept up with the fast growth in steel consumption in recent decades as in-use stocks in emerging economies like China were too young (average age: 8.6 years in Fig. 3a) to generate enough old scrap, forcing regional steel production to rely heavily on iron ores.	1:13	Life-time of plants determines structure
Gordon et.al (2015)	Scientific papers	The traditional blast furnace integrated route will continue to be a major process technology in the global steel industry (since this is a mature technology with a long history of optimization). In addition, its performance can be improved with the incorporation of available energy savings and CO2 abatement technologies.	10:14	Mature process
Swalec & Shearer, (2021)	Report	Inefficient Plants: Over 60% of global steelmaking capacity in the GSPT uses the blast furnace-basic oxygen furnace (BF-BOF) pathway, the most carbon-intensive conventional method of producing steel with limited, difficult, and high-cost decarbonization options.	2:2	Plant inefficiency due to long life-time

- *I c- Decrease in demand: Overcapacity*

Document	Type of Document	Quote	Nr.	Relationship
Kumar et.al (2008)	Scientific Paper	In the early 1990's, the demand for steel fell dramatically in Europe. Steel prices peaked then fell 20 percent and profits fell 65 per cent from 1989 through the end of 1992. The EU Commission saw the oversupply on the European market mainly as a structural problem, so it suggested the use of binding contracts as a means of coordinating and enforcing reductions in capacity by 1993. The reason for the lack of incentive to cooperate was the result of allowing producers not financing the closures to profit from the increased market price resulting from the successful correction of oversupply, as well as those who were actively financing.	13:40	Demand$\rightarrow^{-}$Gap between Demand and production capacity$\rightarrow^{-}$Overcapacity Demand→- Steel Price
IEA (2020)	Report	The most recent five-year period can be characterized as one of low prices and low margins, in part explained by overcapacity. China accounts for around half of the world's steel production capacity. Despite China's efforts to close down outdated and inefficient iron and steelmaking capacity by tens of millions of tonnes in recent years, including the closure of dozens of illegal induction furnaces, new investments are still underway. Hence the world remains in a position whereby the potential output of the global production fleet outstrips demand by almost 25% (OECD Steel Committee, 2019a, 2019b).	3:29	Overcapacity→- Steel price
IEA (2020)	Report	The industry has faced a number of economic headwinds in recent years, including overcapacity, trade tensions and low margins for producers.	3:4	Overcapacity + Low margins +Trade tension $\rightarrow^{-}$Opportunity to invest
Swalec & Shearer, (2021)	Report	Excess capacity: Current global steelmaking capacity is about 25% higher than global steelmaking production, meaning many older and polluting steel plants can be closed without disrupting global supply. Countries with the most overcapacity as a percentage of total production in 2020 were EU27+UK with 26.6%, Japan 23.7%, US 20.0%, and China with between 13.5% and 20.0%.	2:5	Overcapacity$\rightarrow^{+}$ Retirements of plants $\rightarrow^{-}$Total number of plants$\rightarrow^{+}$ Emissions
Swalec & Shearer, (2021)	Report	Steel overcapacity causes a host of problems in the steel industry and global markets. Overcapacity serves as a longtime source of tension in trade between various countries, leading to international "trade wars" and disputes. Overcapacity also constrains the profitability of steelmakers, creating challenging and volatile market conditions.	2:12	Overcapacity →+ Trade tension→- Steel Profit margin
Swalec & Shearer, (2021)	Report	Overcapacity represents a particular challenge in China, which is estimated to have around 350 mtpa of operating capacity in excess of the capacity control target in 2020, meaning that if Chinese capacity control targets were actualized, global overcapacity would be cut in half (52% reduction).	2:14	Retirement of plants$\rightarrow^{-}$Total number of plants $\rightarrow^{+}$Emissions
Swalec & Shearer, (2021)	Report	Addressing overcapacity requires reducing capacity to meet demand. Given that demand could drop 20% by 2050 under the effects of material efficiency gains, significant capacity reductions are in order. Overcapacity presents an opportunity to shift the status of the global steel plant fleet by creating strategic reductions in capacity by retiring or permanently downscaling plants with higher emissions intensities, primarily blast furnace-basic oxygen furnace (BF-BOF) capacity and ensuring that new projects use only the cleanest steelmaking technologies.	2:13	Overcapacity$\rightarrow^{+}$ Retirement of Plants Customer material saving$\rightarrow^{-}$ Demand for steel

- *I d- Global scale: Fragmentation of the steel industry*

Document	Type of Document	Quote	Nr.	Relationship
IEA (2020)	Report	Steel is a highly traded commodity and is often in the spotlight of trade negotiations. The People's Republic of China accounts for more than half of global steel production today and – despite high domestic demand – it is also the largest exporter, followed by Korea, Japan and the Russian Federation. The steel industry is highly competitive and fragmented. The top 10 producers account for just 25% of global production, which is low compared with other sectors, such as aluminum.	3:8	Fragmentation of industry→ Steel Profit Margin.
IEA (2020)	Report	The degree of consolidation in a given marketplace cannot be seen as the only measure of competitiveness, but it is an important indicator. In 2019 the World Steel Association recorded 104 steel producers with an output of more than 3 Mt per year (0.2% of global production). The top 10 companies account for just over a quarter of global output, with the top 25 and top 50 accounting for 42% and 56% respectively. This reflects a highly competitive marketplace, especially given the extent to which steel is traded. While the degree of consolidation in the industry has not changed much over the past half-century, gone are the days when a regional producer can expect to have unfettered access to a regional marketplace – contracts with international players can be signed in minutes.	3:30	Fragmentation industry+ global market = high Total number of plants →+Competitiveness→- Steel Price
IEA (2020)	Report	In part because of the global market for steel, and the great extent to which it is traded, the steel industry is highly competitive (Box 1.2). As with many bulk commodity businesses, in the absence of monopolies, margins tend to be low. Net pre-tax margins tend to be in the range of 5-10% in good years, and negative in bad ones. The most recent five-year period can be characterized as one of low prices and low margins, in part explained by overcapacity.	3:29	Global market = high Total number of plants →- Steel price

Friedmann et.al, (2019)	Report	This is accentuated by the fact that the margins for many of these industries are very thin—sometimes even negative. As such, a central business priority in industrial production is to maintain very low-cost supply chains, including operating facilities in locations with low energy costs, labor costs, and sometimes minimal burdens for environmental protections.	26:15	Steel Price→- GDP→- Capital to invest
Kumar et.al (2008)	Scientific Paper	– Steel is now an international commodity. The competition in the commodity grade products is fierce.	13:03	Global market→+ Competitiveness

II- Factors that induce a change in the scale of the industry

- *II a- Requirement for Quality Materials*

Document	Type of Document	Quote	Nr.	Relationship
IEA (2020)	Report	A number of macroeconomic factors influence the global and regional dynamics of steel production. Among the most important are economic development, trade and competitiveness, all of which are interlinked. Steel is used in a number of sectors that are closely tied to overall economic activity – the steel industry is both a reflection of, and contributor to, global economic growth. When the global economy is buoyant, people buy houses and cars, governments build more infrastructure, and the private sector invests in commercial buildings and machinery. While the regional dynamics are more nuanced, the relationship between steel demand and economic activity at the global level are closely related.	3:28	Production output →+ GDP →+ Demand for steel →+ Production Output
IEA (2020)	Report	since the middle of the 20th century, has led to the displacement of steel used in the packaging sector, and plastics are increasingly substituting steel in certain components of buildings (e.g. pipes and fittings) and cars (e.g. bumpers and external body panels). Because plastic can be extruded and moulded into complex geometries, a smaller amount can be used for certain applications, and it is highly resistant to corrosion and degradation. Composites, such as glass and carbon fibre- reinforced resins, are increasingly the materials of choice where weight reductions are critical, and ductility and cost are less of a concern. Aluminium has long been the material of choice for aircraft – and increasingly many high-performance vehicles – for the same reasons. Timber, for low-rise buildings especially, continues to be the material of choice in many regions where it is available at low cost and local environmental conditions permit, whereas steel and concrete are dominant in high- rise and commercial buildings.	3:25	Steel market share→- Steel Demand
Lyakishev and Nikolaev (2003)	Scientific Paper	Although steel still occupies the leading position in the market (90% based on weight and 70% based on volume), it is losing ground to aluminum, plastics, and polymers (the production of composites and ceramics is still in early growth stage).	14:14	Steel market Share→- Steel demand
Lyakishev and Nikolaev (2003)	Scientific Paper	The use of steel in the U.S declined 15% during the period 1971-1991, while the consumption of products made of aluminum and plastics increased 55% and almost 300%, respectively.	14:16	Steel market Share→- Steel demand
Lyakishev and Nikolaev (2003)	Scientific Paper	A similar situation unfolded in Japan, Germany, and other countries, and it has forced steel producers to focus even more attention on the quality of their product.	14:17	Steel Market share→+ Demand for steel→+ GDP→+Investment in quality →+Quality of Steel→- Steel Market share
Stubbles (2000)	Report	Despite competition from materials such as plastics, aluminum, sintered powdered metals, composites, and even wood, steel has remained dominant on both a low cost and high-tonnage basis. Basic industries such as transportation, construction, machine building, mining, and others concerned with energy production and transmission depend upon the unique properties of steel. Steel is also central to the fastener industry: nuts, bolts, screws, nails, staples, and even paperclips are all everyday steel products.	25:2	Steel Demand → - Steel market share
Neelis & Patel, (2006)	Report	The second argument used in the explanation of the inverse U shape is more related to the material composition of product and explains the observed inverse-U shape by suggesting that the material demand experience phases in which old, lower quality materials linked to mature industries undergo replacement by higher quality or technologically more advanced materials (Labys, 2004). For individual materials, this lead to phases of expanding use (the new material substitutes existing materials), stabilising use (demand for the main end-use of the material saturates) and declining use (the material is increasingly being substituted by other materials).	4:19	GDP→+Steel alternative usage Requirement for Quality materials→+ Investment in Quality →+ Steel market Share
Cullen et. al, (2012)	Scientific Paper	Both longer-life products and reducing final demand for end-use steel products shrink the steel flows at right-hand end of the global steel map (Figure 1). Doubling the lifespan of a product leads to a halving of product demand and will halve the lifecycle steel demand and energy input required to produce the product. Designing long-life products requires	9:35	Quality→+Life-time→- Demand→

		introducing resilience and adaptability into the product to allow for the changing needs and desires of the future.		
Cullen et. al 2012	Scientific papers	longer life products: the lifespan of end-use goods could be doubled with only minor design changes to the product, which in the long term would halve the projected annual demand for new products and halve steel demand.	9:28	Lifetime consequence

4.2.2- Technology effects

- Implementation of Continuous technology - Process efficiency
    - *I a- Reinforcing factor: Energy Crisis -R1*

Document	Type of Document	Quote	Nr.	Relationship
Friedmann et.al, (2019)	Report	Energy costs represent a substantial fraction of steel production costs (20 to about 40 percent) depending on fuel type, fuel price, and the full operational technology suite. Although the blast furnace consumes most of the input energy and emits most of the CO2, fractional costs on blast furnaces' energy input alone is much smaller than for cement production.	26:33	Energy Costs
Birat (2020)	Scientific Paper	Energy conservation in the steel sector was driven by the fact that energy costs account for roughly 20% of operating costs and therefore needed to be minimized for sound management.	7:14	Energy Costs Operating cost
Wang et.al, (2021)	Scientific paper	With spiked energy prices, the production costs for steel producers increased drastically, stimulating the quest for energy efficiency improvement to maintain total costs.	1:25	Energy Consumption+ Energy Prices$\rightarrow^{+}$Energy Costs$\rightarrow^{+}$Production Costs $\rightarrow^{+}$Investment $\rightarrow^{+}$Energy Efficiency
Lyakishev and Nikolaev (2003)	Scientific paper	The growth of world industry was accompanied by a substantial increase in energy consumption. This led to an energy crisis in the 1970s – a crisis that continues on a more muted scale even today. In light of this, the industrially advanced countries have devoted a considerably amount of effort to reducing the energy content of the GDP.	14:8	Growth of industry$\rightarrow^{+}$Energy consumption$\rightarrow^{+}$Investment in energy efficiency
Birat (2020)	Scientific paper	Steel therefore was one of the first industries to react to high energy prices, ever since the first energy crisis of 1974.	7:34	Growth of industry$\rightarrow^{+}$Energy consumption$\rightarrow^{+}$ Energy Costs
Wang et.al (2021)	Scientific papers	After the 1940s, the largest drop in emissions intensity occurred between 1970 and 1995 (from ~4.5 to 2.6 t CO2-eq/t steel), due to the improvement in energy efficiency through technological advances, such as the use of pelletizing in lieu of sintering for ore preparation and increased use of BOF instead of open-hearth furnace.	1:16	Energy efficiency$\rightarrow^{-}$Energy required BOF $\rightarrow^{+}$ Plant emissions
Kim & Worrel, (2002)	Scientific Paper	Steelmaking is followed by casting and shaping. Ingot casting is the classical process and is rapidly replaced by more energy efficient, continuous casting process (Worrell et al., 1997). The degree of penetration of continuous casting process is also used as the main explanatory indicator of changes in energy efficiency.	12:14	CC Implementation $\rightarrow^{+}$ Yield $\rightarrow^{+}$ + Energy Efficiency
Kim & Worrel, (2002)	Scientific Paper	The energy efficiency improvements found in all countries are explained by the decreasing share of OHF and increasing share of continuous casting. The share of OHF has declined sharply over the years for all of the countries analyzed (Fig. 4)	12:29	CC implementation$\rightarrow^{+}$Yield Improvement$\rightarrow^{+}$Energy efficiency

- *Implementation of BAT – R2*

Document	Type of Document	Quote	Nr.	Relationship
Wang et.al, (2021)	Scientific Paper	Thus, process efficiency was significantly improved in these periods (Fig. 4a, c, e), mainly in primary production through the adoption of emerging, more efficient technologies as previously mentioned at the steelmaking stage and through the promotion of energy-saving practices in the Blast Furnace.	1:26	Investment$\rightarrow^{+}$ BOF improvement through BAT$\rightarrow^{-}$ Energy consumption
Wang et.al, (2021)	Scientific paper	In parallel, the energy crises also lowered total steel demand, which slowed the growth of steel production. In short, total GHG emissions were reduced as a result of changes on both production and consumption sides.	1:27	Energy consumption $\rightarrow^{-}$ energy emission Energy costs$\rightarrow^{+}$ Steel price$\rightarrow^{-}$Demand
Gordon et.al, (2015)	Scientific Paper	The traditional blast furnace integrated route will continue to be a major process technology in the global steel industry (since this is a mature technology with a long	10:14	Optimization$\rightarrow^{+}$ Mature process$\rightarrow^{-}$ EAF adoption

		history of optimization). In addition, its performance can be improved with the incorporation of available energy savings and CO2 abatement technologies.		

- *Implementation of Continuous Casting technology*

Document	Type of Document	Quote	Nr.	Relationship
Cullen et. al, (2012)	Scientific Paper	Industry efforts to improve yield for example the world steel report, Yield Improvement in the Steel Industry have focused on reducing scrap from forming and casting, the upstream steelmaking processes where large, concentrated flows allow for simpler implementation. For example, a significant improvement in casting yield has been achieved with the introduction of continuous casting machines for slab, blooms, and billets since the 1970s.	9:20	Yield→-Scrap availability
Lyakishev and Nikolaev (2003)	Scientific Paper	The continuous casting of steel – originally developed in the USSR – later became widespread as well. Continuous casting made it possible to increase output 15% while improving the quality of the steel. However, only 50% of steel is cast by this method at Russian factories, whereas the corresponding figure abroad is more than 90%.	14:05	CC Implementation→+ Quality of steel
Cullen et. al, (2012)	Scientific Paper	Improving the material yield of the steel supply chain not only saves money by reducing scrap losses, but also reduces the energy and CO2 emissions linked to melting scrap steel at high temperatures.	9:30	Yield→$^{-}$ (scrap use + reducing agent) Yield→$^{-}$ energy consumption efficiency
Worrel et.al (1997)	Scientific Paper	Casting and shaping are the next steps in steel production. Casting can be a batch (ingots) or a continuous process (slabs, blooms, billets). Ingot casting is the classical process and is rapidly being replaced by continuous casting machines (CCM). In 1990 nearly 60% of global crude steel production was cast continuously (IISI, 1992). The ratio of CCM varies among the countries analyzed in this study, between a low of 8% in Poland, and a high of 94% in France and Japan (IISI, 1992). The casted material can be sold as ingots or slabs to steel manufacturing industries. However, most of the steel is rolled by the steel industry to sheets, plates, tubes, profiles, or wire. Generally, the steel is first treated in a hot rolling mill.	17:8	Casting /Ingot Ratio
Kim & Worrel, (2002)	Scientific Paper	Korea, US and Mexico show a high level of penetration of efficient continuous casting technology. The ratio of continuous casting is still relatively low in India and China.	12:22	US Korea and Mexico CC implementation compared to India and china

- *I d- Constraint: Efficiency saturation -B1*

Document	Type of Document	Quote	Nr.	Relationship
IEA (2020)	Report	Energy performance improvements to existing equipment are important, but by themselves not sufficient for a long-term transition. The energy intensity of state-of- the-art blast furnaces is already approaching the practical minimum energy requirement.	3:7	Energy Consumption→$^{+}$Gap between optimal and actual consumption-← Minimum required energy
Holappa, (2020)	Scientific Paper	steel industry, energy consumption can still be reduced by 10–15% on average to meet the BAT values by applying best available technologies [15,16]. Even bigger deduction of CO2 emissions is possible by transfer to low-carbon energy sources.	11:24	Low carbon energy sources
Cullen et. al, (2012)	Scientific Paper	Significant opportunities remain for improving energy efficiency, mainly related to improving the average plant performance to Best Available Technology. However even a perfect pursuit of all process efficiency options will not be sufficient to achieve an absolute 50% cut in CO2 emissions for the sector	9:10	Gap between optimal and actual consumption→+ Improvement BAT→$^{-}$ Disruptive transition rate

II- Disruptive technology implementation

- *II a- Constraint: Sunk Costs and Retirement Rate*

Document	Type of Document	Quote	Nr.	Relationship
Reppelin-Hill, (1999)	Scientific Paper	Most importantly for our purposes, electric arc furnaces also have an advantage over integrated plants in that they tend to have less impact on the environment.	15:6	Environmental impact of EAF implementation

Lyakishev and Nikolaev (2003)	Scientific Paper	It is no secret that a significant reduction in the emission of carbon dioxide can be achieved only by replacing old, traditional technologies by fundamentally new ones – a process that will require enormous capital investments. For example, the cost of the modernization that needs to be done in the U.S. to reduce CO2 emissions to 20% below the 1990 level might total 3.6 trillion dollars [2]	14:11	BF/BOF plants→+ Sunk costs→- Disruptive transition rate→+ EAF Implementation
Kim & Worrel, (2002)	Scientific Paper	In the United States, restructuring of the steel industry has led to closing of older inefficient mills, while more recently a trend towards low-cost electric steel production has further re-shaped the industry. This has led to substantial reductions in energy intensity, although the energy savings have partially been offset by increased production of cold rolled steel products	12:38	Plant life-time→+ BF/BOF plants→+ Sunk Costs→- Disruptive Transition Rate→+ EAF implementation
IEA (2020)	Report	This rapid growth has resulted in a young global blast furnace fleet of around 13 years of age on average, which is less than a third of the typical lifetime of these plants	3:5	Plant lifetime →- Retirement of plants
Swalec & Shearer, (2021)	Report	The average age of the existing global fleet of BF and direct reduced iron (DRI) furnaces is 13 years and 14 years, respectively. Over half the world's global steel fleet is in China, where the average age for BFs is 12 years and DRIs is 8 years. BF and DRI furnaces are typically operated for around 40 years with investment cycles of 15–20 years for BFs and 20 or more years for DRI plants,3 though refurbishments may extend their overall lifetime by several decades	2:7	Production fleet age
Swalec & Shearer, (2021)	Report	Stranded asset risk: If innovative low-emissions technologies reach commercial scale at the projected pace, the steel industry faces 47–70 billion USD in stranded asset risk for carbon-intensive steel plants currently under development.	2:4	BF/BOF plants→+ Sunk costs→- Mitigation technology implementation

- *II b- Reinforcing factors: EAF Attractiveness*

Document	Type of Document	Quote	Nr.	Comment
Neelis & Patel, (2006)	Report	The choice for a certain steel production technology (EAF or BOF) and the choice of the iron sources used in the steel production technology (primary iron or scrap) is influenced by many things such as • The required investment (EAF requires less investment than integrated steel plant). • The quality requirements for the various steel products. • The availability of scrap of sufficient quality of produce certain steel qualities.	4:6	3 attractiveness factors

- *Implementation costs*

Document	Type of Document	Quote	Nr.	Relationship
Reppelin-Hill, (1999)	Scientific Paper	Minimills appear to have an advantage over integrated plants in that they can produce at lower unit costs than integrated plants [3]	15:5	Lower Relative unit costs BOF/EAF→+ EAF implementation
Reppelin-Hill, (1999)	Scientific Paper	A few important features of the cost structure in electric arc furnaces should be noted, however. In the case of the EAF but not the conventional basic oxygen furnace, material costs account for a much larger share (59.3%) of total costs than do energy costs (19%) (see [23])	15:27	Material costs→- EAF implementation
Reppelin-Hill, (1999)	Scientific Paper	Apparently even the energy price shocks of the 1970s had little influence on the adoption decision. This is most likely due to the fact that while electricity prices increased substantially over that period, so did coking coal prices, which presumably limited the impact on the EAF diffusion decision	15:28	Energy costs (no effect) →Relative attractiveness EAF/BOF
Reppelin-Hill (1999)	Scientific Paper	The long-run effects of input prices on the speed of EAF diffusion also appear to be negligible, with average coefficients across all model specifications ranging from 0.0006 for the COAL variable to -0.86 for the ELEC variable.	15:36	No effect
Reppelin-Hill, (1999)	Scientific Paper	In fact, in terms of relative costs, the cost advantage of EAF production resides primarily in lower capital costs (11.6% of total costs for EAF versus 24.7% for BOF), an aspect that is not captured in the current model.	15:29	Relative unit costs BOF/EAF→+ EAF implementation

- *Quality Requirements /Saturation of EAF technology*

Document	Type of Document	Quote	Nr.	Relationship
Reppelin-Hill, (1999)	Scientific Paper	the results may simply indicate that high-income countries have reached a saturation point with respect to electric arc furnace production. Because the EAF technology seems to have specialized in a narrower range of products than have	15:32	EAF Implementation →+ EAF plants →+ Production activity →- Demand EAF

		integrated steel mills, it is unlikely that EAF will completely replace integrated production, and thus one would expect EAF production to level off after a certain production share threshold.		Products →+ EAF implementation (Saturation)
Reppelin-Hill, (1999)	Scientific Paper	The product composition of steel production does seem to play a role in the decision to produce with the EAF technology. The results point to a positive and statistically significant correlation between the proportion of EAF production and the ratio of long products in total steel production.	15:33	Demand EAF Products →+ EAF implementation
Reppelin-Hill, (1999)	Scientific Paper	However, widespread production of steel using this process has occurred only more recently, in the mid-1970s, with the development of the minimill - a combination of electric arc furnace and continuous casting technology. These minimills primarily produce long products (e.g., railway track material; angles, shapes, and sections; and bars and rods), which are mostly used in the construction industry.	15:4	Increased Demand EAF products in the 1970
Neelis & Patel, (2006)	Report	The first factor is that the scrap market and the way prices are established is mainly fixed by the growing demand of EAFs and mini mills and the growing supply of obsolete scrap... The second factor is that in the past the market for scrap, mainly EAFs in mini mills, was different from the market for iron ore or the primary metals from iron ore, practically only pig iron... Iron ore and pig iron were used in integrated iron and steel plants; mini mills were accounting for a growing proportion of long products while the integrated plants were concentrating on flat products... Now, the mini mills are 'invading' all types of product sectors, especially in the US and the competition is growing between collected scrap and the primary metals produced from iron ores, i.e. pig iron and DRI/HBI including iron carbide (UN, 1999, pp. 73).	4.9	Demand EAF+ Scrap availability →- Scrap price Demand EAF Products →+ EAF implementation
Worrel et.al (1997)	Scientific Paper	The production of primary steel consumes more energy but produces a higher quality steel. In the BOF-process the amount of scrap used is different for each plant.	17:18	Material quality Requirement →- Demand EAF products →+ EAF implementation

- *Scrap Availability*

Document	Type of Document	Quote	Nr.	Relationship
Conejo et.al (2020)	Scientific paper	The source of energy in the integrated plant is primarily chemical energy and, in the EAF route, electrical energy. The energy consumption in the integrated route BF-BOF is 13–14 GJ/ton (Fruehan, 2009). Energy consumption in the EAF depends on the metallic charge. For the DRI-EAF route, the production of DRI consumes 8.3-10 GJ/ton DRI of natural gas and 0.21–0.29 GJ/ton DRI of electricity (Garza, 2006). In the EAF, if the charge is 100% DRI the energy consumed, depending on the metallization of DRI, varies from 2.1–2.5 GJ/ton, therefore a total of about 10.6–13.8 GJ/ton for the DRI-EAF route. The energy consumption using 100% cold scrap ranges from 1.2–1.6 GJ/ton. Thus EAF steelmaking exhibits the smallest values of energy consumption when operating with close to 100% of recycled scrap although pig iron has been used at the level of 10% of the charge with scrap in Europe for a normal operation. The higher consumption of energy in China is due primarily to the high share of steel production through the blast furnace route (91.9% in 2017 based on www.worldsteel.org). Mexico is one example of low energy intensity in the steel industry as EAF steelmaking there has about a 75% share (Rojas et al., 2017).	8:7	Mexico high amount of EAF
Wang et.al, (2021)	Scientific Paper	Unfortunately, our analysis shows that these improvements have not kept up with the fast growth in steel consumption in recent decades as in-use stocks in emerging economies like China were too young (average age: 8.6 years in Fig. 3a) to generate enough old scrap, forcing regional steel production to rely heavily on iron ores.	1:13	In use steel* Life-time steel → Scrap Availability
Kim & Worrel, (2002)	Scientific Paper	In Mexico, in addition to the closure of the OHF capacity and an increase of continuous casting ratio, an increase in the utilization of blast furnace gas for electricity generation also led to an increase in energy efficiency (Ozawa et al., 1999). Mexican steel industries have been very active in technology development. The Mexican producer Hylsa is one of the world leaders in development of DRI technology as well as EAF technology. The availability of low-cost natural gas has contributed to the position of Hylsa. The use of natural gas has also contributed to the relative low CO2 intensity of the Mexican steel industry.	12:34	Resource availability advantage

III- Type of feedstock used

- *III a- Scrap use– Resource availability delay*

Document	Type of Document	Quote	Nr.	Relationship
Worrel et.al (1997)	Scientific Paper	The most important input-factor influencing energy consumption in the iron and steel industry is the feedstock: iron ore and scrap for primary steel, or scrap only for secondary steel.	17:17	Scrap use →⁻ Energy Consumption

Holappa, (2020)	Scientific Paper	When steel became a mass product, its price fell and remanufacturing almost disappeared. However, collection of scrap and delivery to steel plants has been duly organized for long in industrialized countries. The recycling rate is moderate, and nowadays vigorously increasing e.g., by recovering rebar steel from concrete of demolished buildings.	11:57	Steel Price→+Incentive to recycle→+Recovery Rate→+ Scrap Availability →+Scrap usage
Holappa, (2020)	Scientific Paper	The principle of "circular economy" has recently gained ground. Intensified scrap usage is a self-evident goal.	11:58	Consumism perspective→ Scrap usage
Strezov et.al, (2013)	Scientific Paper	Both iron ore and scrap steel have limited reserves, as shown in Fig. 2. While iron ore reserves are limited to the natural distribution and quality of available iron oxides, the availability of scrap used in EAFs is limited to the end-of-life capacity of various steel products and replacement rates. Iron ore reserves were previously modelled by Yellishetty et al. (2011), while the availability of scrap is estimated based on the 65-year trend supplied by Terörde (2006). It is apparent that the fraction of available scrap is less than 1% of the total reserves of iron ore, hence, despite the opposing trend of availability of both resources, iron ore will remain to be the major source for steel production in the next 20 years.	16:10	End use steel→+Scrap availability
Neelis & Patel, (2006)	Report	The scrap availability is insufficient to meet the still growing demand for steel and the global recycling rate is near the maximum. In the future, the demand for steel is likely to grow at a slower rate and may even stabilize in the long term. Then, the insufficient availability of good quality scrap, required for prime quality steel, will become the main constraint for attaining a much higher recycling rate (Daniels, 2002, pp. 14).	04:07	Life-time + End Use steel→ Scrap use
Neelis & Patel, (2006)	Report	The areas where recycled scrap is processed tend to be those areas where steelmaking is not growing, and the areas where steelmaking is growing tend to be the areas that are not self-sufficient in scrap generation – so we have a physical problem.	04:10	Regional Scrap availability→- steel production
Cullen et. al, (2012)	Scientific Paper	The low fraction of end-of-life scrap in the recycling stream results from the historical growth in steel demand. The end-of-life scrap collected today is related not to the steel goods being produced today, but to the demand for steel at the time when today's discarded goods were first produced.	9:19	Delay
Yellishetty (2011)	Scientific Paper	Nevertheless, the ability to recover metals economically after use is largely a function of how they are used initially in the economy and their chemical reactivity. Therefore, the success of secondary metals markets depends on the cost of retrieving and processing metals embedded in abandoned structures, discarded products, and other waste streams and its relation to primary metal prices.	19:8	Usability of end use steel→−Recovery costs (economic feasibility) →+ Recovery Rate
Kim & Worrel, (2002)	Scientific Paper	Important structural (process mix) indicators in iron and steel industry are feedstock (iron and scrap) and product type (iron and steel, slabs, hot rolled and cold rolled product, wire rods). The feedstock differences have a larger effect on energy use than differences in product mix.	12:16	Iron Ore/scrap ratio→+ Energy consumption (large effect)
Cullen et. al, (2012)	Scientific Paper	Large steel components, such as beams in construction, are rarely damaged in use and show great potential for reuse, but to be viable, require the development of nondestructive demolition techniques and procedures for recertifying used beams	9:34	Demolition techniques→+ Steel Recovery Rate
Cullen et. al 2012	Scientific papers	longer life products: the lifespan of end-use goods could be doubled with only minor design changes to the product, which in the long term would halve the projected annual demand for new products and halve steel demand.	9:28	Lifetime consequence

4.2.3 Composition effects

I- Investments in green technology

- *I a- Country Development Rate and Trade*

Document	Type of Document	Quote	Nr.	Relationship
Kim & Worrel, (2002)	Scientific Paper	The selection of countries reflects different development pattern, e.g. growth in developing countries (e.g. Brazil, China, and India), strong growth using modern equipment in the newly industrialized countries (i.e. Mexico and South Korea) and a more stationary situation in the industrialized world (i.e. United States). The countries also reflect differences in economic and energy infrastructure.	12:2	Growth rate
Reppelin-Hill, (1999)	Scientific Paper	The ratio of production via open hearth furnaces per year to the total production of integrated steelworks, i.e., open hearth plus basic oxygen furnaces, is used as a measure of capital obsolescence (OBSOLETE). For poor countries just beginning to develop their steel industries, the likelihood of using EAF may be greater, since these countries do not have large sunk costs invested in integrated plants. In such instances the spread of EAF is expected to be negatively correlated with OBSOLETE. On the other hand, for wealthier countries that have more developed steel industries, the spread of EAF is expected to be positively correlated with OBSOLETE, as an obsolete integrated	15:15	Sunk Costs→- EAF implementation Retirement Rate→+ EAF implementation

		capital stock will eventually need to be replaced, and the likelihood of EAF technology adoption is high in this case.		
Reppelin-Hill, (1999)	Scientific Paper	The negative correlation may indicate that poor countries that are just beginning to develop their steel industries (and hence have no integrated stock) may be more likely to adopt EAF, since they do not have large sunk costs in OH or BOF.	15:34	Sunk Costs→- EAF implementation
Kim & Worrel, (2002)	Scientific Paper	An important difference between the steel industry in developing countries and that in industrialized countries is the fast growth of production volumes. Investments in new capacity are being made in developing countries. This construction has also led to increased energy efficiency in Korea, China, Brazil, Mexico and India, demonstrating the role of stock turnover as an important driver for change in capital- intensive industries.	12:30	GDP→$^+$Capital for investment→$^+$ New plants + Energy efficiency
Reppelin-Hill, (1999)	Scientific Paper	Per capita income is included as a proxy for presumed ability and willingness to absorb the new technology. Wealthier countries are more likely to be able to afford the cleaner technology.	15:10	GDP→+ Capital for investment→+Transition opportunity
Wang et.al 2021	Scientific papers	Third, the long-lived facilities in their production may further hinder the required mitigation progress due to the carbon lock-in effect	1:3	Old production sites-> carbon lock-in
Reppelin-Hill, (1999)	Scientific Paper	Across the various income groups, the EAF technology was diffused much faster in low- and lower-middle income countries (Fig. 2)	15:22	EAF diffusion on lower income countries
Kim & Worrel, (2002)	Scientific Paper	There was an upward trend in the share of EAF in Korea from 1981 to 1998, increasing from 23.3% to 40.3%, changing to a less CO2-intensive structure.	12:36	Increase in EAF 1981-1998
Reppelin-Hill, (1999)	Scientific Paper	As for the relationship between trade openness and the speed of EAF diffusion, the empirical evidence confirms the main hypothesis that the diffusion of EAF production is faster in countries with more open trade regimes.	15:35	Open Trade Regime→+ EAF Implementation
Reppelin-Hill, (1999)	Scientific Paper	However, one may suspect that as a country grows richer, a marginal rise in income may become less important in adopting the cleaner EAF technology.	15:11	GDP→ +Investment opportunity→- Price margin change→-EAF Implementation
Kim & Worrel, (2002)	Scientific Paper	Mexico has a relatively high share of EAF of about 60% of production in recent years, however, using a relative high input of DRI. In Mexico DRI is made in natural gas-based processes resulting in relative low CO2 emissions. There was also a downward trend in the share of cold rolled steel in Mexico (see Figs. 6 and 7).	12:37	Lower sunk costs and later development stage
Friedmann et.al, (2019)	Report	This is accentuated by the fact that the margins for many of these industries are very thin—sometimes even negative.16 As such, a central business priority in industrial production is to maintain very low-cost supply chains, including operating facilities in locations with low energy costs, labor costs, and sometimes minimal burdens for environmental protections.	26:15	Low labor costs and low supply chains focus

- *I b- Government regulation - Environmental urgency*

Document	Type of Document	Quote	Nr.	Relationship
Swalec & Shearer, (2021)	Report	Governments and financial institutions will play a key role in guiding investment decisions to avoid creating stranded assets. Examples of policy and finance levers that may be used to manage investments in new plants and retrofits of existing assets include: ■ Carbon pricing ■ Emissions schemes ■ Technology sunsetting (i.e. phasing out BF-BOF steelmaking) ■ Efficiency policies ■ Climate-related financial risk assessment frameworks ■ Credit ratings that account for the cost of carbon emissions ■ Green steel demand decreation through public procurement policies	2:11	Governments Measures→ Carbon Tax + Subsidies Carbon taxes→+ production costs→+ Mitigation Options attarctiveness
Yellishetty (2011)	Scientific Paper	These programmes to enhance metals recovery rates could be adopted by other countries to enhance their metal recovery rates. In developing and underdeveloped economies, fewer policies seem to exist that are aimed at enhancing recycling activities. According to Medina (2008), in these countries almost 1–2% of the population makes their living by salvaging recyclables from the waste	19:12	Government intervention→ subsidies→+Incentive to recycle→+ Scrap Recovery Rate
Yellishetty (2011)	Scientific Paper	These legislative measures complement the existing popular tools that lawmakers frequently use to sustain and promote recycling, such as tax credits, incentives and disincentives. By and large, these regulations, undoubtedly, force product recovery schemes to play a greater role in post-use management, regardless of costs involved.	19:10	Government intervention→ Subsidies and taxes→ Mitigation options attractiveness→+Incentive to recycle→+ Scrap Recovery rate
Reppelin-Hill, (1999)	Scientific Paper	As increased importance is assigned to environmental quality with increases in income (generated through trade as opposed to an autarchic equilibrium), markets for green technologies may develop and grow.	15:2	GDP→+Government intervention→ Mitigation technology implementation

Reppelin-Hill, (1999)	Scientific Paper	In the literature, it is argued that at sufficiently high levels of development, pressures for a cleaner environment eventually come to dominate the scale effect, and hence environmental degradation decreases.	15:14	GDP →Government intervention

II- Readiness of green technology

- *II a- Research and Development*

Document	Type of Document	Quote	Nr.	Relationship
Lyakishev and Nikolaev (2003)	Scientific Paper	An important factor that will in part determine the fate of the industry is the progress of innovation.	14:33	RD&D stage +→Mitigation Opportunities
Lyakishev and Nikolaev (2003)	Scientific Paper	In the second half of the Twentieth Century, the machine-based technological revolution was replaced by a scientific-technical revolution (STR) characterized by greater use of increasingly sophisticated technologies.	14:6	RD&D stage → + mitigation opportunities→ + energy efficiency
Lyakishev and Nikolaev (2003)	Scientific Paper	In the U.S., over the last 20 years in the materials-producing sectors (metallurgy, the chemicals industry, etc.) expenditures on scientific research and experimental-design work have increased nearly fivefold and now stand at 16 billion dollars. The total expenditures on research and development in the U.S. amount to roughly 160 billion dollars. In Russia, the investments made in science as a whole have declined sharply during the last decade and are now no greater than 2 billion dollars [18]	14:34	Capital investment→ + RD&D stage

4.3- Stagnation Factors

I- Efficiency stagnation - Research and Development Stage

Document	Type of Document	Quote	Nr.	Relationship
Lyakishev and Nikolaev (2003)	Scientific Paper	utilize unconventional energy resources and raw materials, and alleviate pollution, they are still either in the developmental stage or have been introduced commercially relatively recently. The successful development of environmentally clean and energy-efficient technologies will depend on capital investment in the creation and commercial testing of methods developed with the use of the latest advances in science.	14:32	Delay in R&D stage
Lyakishev and Nikolaev (2003)	Scientific Paper	An important factor that will in part determine the fate of the industry is the progress of innovation.	14:33	Importance of R&D
Friedmann et.al, (2019)	Report	All approaches have substantial limitations or challenges to commercial deployment. Some processes (e.g., steelmaking) will likely have difficulty accepting options for substitution. All options would substantially increase the production cost and wholesale price of industrial products. For many options (e.g., biomass or electrification), the life-cycle carbon footprint or efficiency of heat deposition are highly uncertain and cannot be resolved simply. This complicates crafting sound policy and assessing technical options and viability.	26:3	Limitations and barriers
Friedmann et.al, (2019)	Report	Finding 2: Few options exist today to reasonably substitute low-carbon heat sources. Unlike the power sector and light-duty vehicles, the operational requirements of temperature, quality, flux, and high-capacity place stringent constraints on viable options. These are further narrowed by geographic limits of natural resources and infrastructure. The true viability, cost, and carbon footprint of options remain poorly understood.	26:35	Option to decarbonize
Cullen et. al, (2012)	Scientific Paper	Significant opportunities remain for improving energy efficiency, mainly related to improving the average plant performance to Best Available Technology. However even a perfect pursuit of all process efficiency options will not be sufficient to achieve an absolute 50% cut in CO2 emissions for the sector	9:10	BAT→ Energy Efficiency
Friedmann et.al, (2019)	Report	• Conclusion 2: More options and better options are needed. Given the urgency for deep decarbonization globally, options for substitution are essential. Given the paucity of good industrial heat-related emissions options, the current set is hard to deploy even with substantial subsidies. Researchers, governments, industrial leaders, and investors must add greatly to existing efforts to develop new and better solutions or to improve existing ones dramatically.	26:37	Research and development Subsidies
Wang et.al (2021)	Scientific paper	(a) Hydrogen-based options, (b) Electrolysis-based options, (c) CCUS with direct/smelting reduction, (d) Biomass-based options, (e) Blast furnace-improvement, (f) Carbon-free EAF and (g) Low-carbon rolling technologies.	1:35	Decarbonizing options

Birat (2020)	Scientific paper	5 Mt/y steel mill based on ore electrolysis would require a 1200 MW nuclear power plant or 240 recent wind turbines. This might require new investments in power generation [16]. On the other hand, this would open up opportunities in terms of demand-side management of	7:20	Nuclear plants

II- Scrap availability and saturation of EAF market

Document	Type of Document	Quote	Nr.	Relationship
Holappa, (2020)	Scientific Paper	As for scrap dynamics, the "age of scrap" or lifetime from production and usage to recycling varies from a few years to decades, or in some constructions, even centuries—as a rule, resulting in 30–40 years [92–94]. Consequently, the amount of scrap should strongly increase from 2020 to 2050 [6,95,96].	11:59	Scrap Availability Steel recycling rate
Wang et.al (2021)	Scientific Paper	Given that the average lifetime of steel products is ~70 years, a rapid increase in old scrap generation can be foreseen in these countries over the next 30–50 years.	1:12	End-of-life Scrap Scrap Input Steel recycling rate
Wang et.al (2021)	Scientific paper	Moreover, the scrap quality from contaminated scrap mix remains a great challenge for producing high-quality steel that is comparable to the primary route. Thus, closing the steel cycle requires more attention to the development of smart and low-carbon sorting, separation and refnery production, etc. as well as measures for improving source separation of steel scrap to improve the overall quality of secondary steel production.	1:52	Higher quality scrap, Improvement in refinery techniques
Wang et.al (2021)	Scientific paper	However, in practice, the success of scrap recycling is dependent on other factors, such as social behaviour, governmental regulation, product design, and existing facility inertia.	1:50	Other factor affecting recycling rate
Worrel et.al (1997)	Scientific paper	The quality of the steel might be influenced by impurities in the scrap, although the introduction of ladle refining technologies improves quality control of the product. Scrap prices have increased due to the increasing share of EAF production in steelmaking worldwide, making pig iron relatively less expensive.	17:20	Impurities in scrap reduce scrap quality

III- Country development phase out and inefficient production fleet

Document	Type of Document	Quote	Nr.	Relationship
Wang et.al, (2021)	Scientific Paper	First, their global demands are projected to increase to support a growing and increasingly affluent population	1:1	Demand Population
IEA (2020)	Report	steel in several applications, its high strength, recyclability and durability, the ease with which it can be used to manufacture goods, and its relatively low cost make its wholesale substitution unlikely in the foreseeable future.	3:12	Steel properties will not decrease demand
Swalec & Shearer, (2021)	Report	Inefficient Plants: Over 60% of global steelmaking capacity in the GSPT uses the blast furnace-basic oxygen furnace (BF-BOF) pathway, the most carbon-intensive conventional method of producing steel with limited, difficult, and high-cost decarbonization options.	2:2	Blast Furnace Inefficient plants Production structure
Swalec & Shearer, (2021)	Report	The average age of the existing global fleet of BF and direct reduced iron (DRI) furnaces is 13 years and 14 years, respectively. Over half the world's global steel fleet is in China, where the average age for BFs is 12 years and DRIs is 8 years. BF and DRI furnaces are typically operated for around 40 years with investment cycles of 15–20 years for BFs and 20 or more years for DRI plants,3 though refurbishments may extend their overall lifetime by several decades	2:7	Production fleet age
Wang et.al (2021)	Scientific paper	Moreover, there is a regional mismatch of technology innovation and implementation. At present, the EU is pioneering innovation and testing of low-carbon technologies. Hence, it is recommended to focus on and incentivise technology sharing among regions to facilitate penetration of emerging low-carbon technologies (from Tier 1 regions) in emerging steel markets (e.g., Tier 3 regions).	1:47	Resources for innovarion
Swelec & Shearer (2021)	Report	Excess capacity: Current global steelmaking capacity is about 25% higher than global steelmaking production, meaning many older and polluting steel plants can be closed without disrupting global supply. Countries with the most overcapacity as a percentage of total production in 2020 were EU27+UK with 26.6%, Japan 23.7%, US 20.0%, and China with between 13.5% and 20.0%.	2:5	Overcapacity

IV- Government intervention

Document	Type of Document	Quote	Nr.	Relationship
Reppelin-Hill, (1999)	Scientific Paper	more restricted policy regimes tend to be associated with a slower EAF diffusion. For example, Europe, which would probably be categorized as one of the least open regions over our sample period, is also the region that experienced some of the slowest diffusion of EAF technology. 'Within Europe itself, there were important differences, with the French and Italian governments being more interventionist, and the German governments being much more liberal. These differences also seem consistent with the empirical result.	15:17	Country diffusion Implementation Rate/Diffusion Rate Regulatory strictness
Kumar et.al (2008)	Scientific Paper	In the European Union the policies and strategies are mixed, but there has been, generally, a much more activist government policy to ease the transition to a restructured industry. Funds, for example, have been available for retraining, relocation and unemployment	13:27	Employees Europe
Friedmann et.al, (2019)	Report	Unlike power markets, where all product generated is consumed within the balancing authority of regional markets, industrial markets span the globe—steel, fuel, and chemicals are globally traded commodities. For this reason, a risk facing industrial decarbonization is carbon leakage, wherein industrial production is displaced from one nation to another (along with and attendant environmental emission or impact).	26:40	Carbon leakage
Swalec & Shearer, (2021)	Report	The free allocations have been provided under the argument that increasing emission costs will lead producers or buyers to source production from countries with lower emissions standards, resulting in little to no carbon reductions at the global level— an effect known as “carbon leakage”.	2:15	Carbon leakage
Friedmann et.al, (2019)	Report	New policies specific to heavy industry heat and decarbonization are required to stimulate market adoption. Policies must address concerns about leakage and global commodity trade effects as well as the environmental consequences. These policies could include sets of incentives (e.g., government procurement mandates, tax credits, feed-in tariffs) large enough to overcome the trade and cost concerns. Alternatively, policies like border adjustment tariffs would help protect against leakage or trade impacts. Because all options suffer from multiple challenges or deficiencies, innovation policy (including programs that both create additional options and improve existing options) is essential to deliver rapid progress in industrial heat decarbonization and requires new programs and funding. As a complement to innovation policy and governance, more work is needed to gather and share fundamental technical and economic data around industrial heat sources, efficiency, use, and footprint.	26:4	Border adjustment tariffs Carbon leakage Policies
Swelec & Shearer (2021)	Report	Steel plants could become unnecessary or inoperable in a number of situations. For example, if the cost of carbon is realized through carbon pricing (i.e. taxes) or emission standards a conventional steel plant may be unable to price competitively with low carbon steelmaking plants. Conventional steel plants could also become stranded assets due to changes in the steel market including decreases in steel demand from material efficiency (see section Material efficiency) or overcapacity (see section An opportunity in overcapacity), or shifts in steel demand as a result of product differentiation (green steel vs. conventional steel).	2:10	Imposing taxes and emission standards to decrease GHG emission intensity

Appendix VII

Definition of variables and units

Variables	Definition	Unit
Total Plants	Total number of active steel producing plants	plants
Gap between demand and production capacity	Difference between the total steel capacity and the demand required	ton
Yield	Amount of raw material (input) needed for each ton of steel output	ton/ton
EAF plants	Total number of active EAF plants	plants
New EAF plants	New EAF plants built, i.e. new plants ready for production each year	plants/year
Retirement of EAF plants	EAF Plants that are shut down or not used each year	plants/year
BF/BOF plants	Total number of active BF/BOF plants	plants
New BF/BOF plants	New BF/BOF plants built, new plants ready for production each year	plants/year
Retirement BF/BOF plants	BF/BOF Plants that are shut down or not used each year	plants/year
Production Capacity EAF	Average amount of steel produced in a EAF steel plant	ton/plant
Production Capacity BF/BOF	Average amount of steel produced in a BF/BOF steel plant	ton/plant
Production Activity EAF	Total amount steel produced from EAF plants each year	ton/year
Production Activity BF/BOF	Total amount steel produced from BF/BOF plants each year	ton/year
Scrap Use	Scrap used as input for the production of steel	ton/year
Reducing agent BF/BOF	Amount of fossil fuel material used functioning as reducing agent in the production of steel	ton/year
Energy Consumption efficiency	Amount of energy improvement per ton of steel produced each year	J/ton/year
Energy Consumption EAF	Amount of energy consumed each year for the production of steel in all EAF plants	J/year
Energy Consumption BF/BOF	Amount of energy consumed each year for the production of steel in all BF/BOF plants	J/year
Fossil fuel Material EAF	Amount of fossil fuel material used the production of steel through EAF production.	ton/year
Fossil fuel Material BF/BOF	Amount of fossil fuel material used functioning as reducing agent and energy source in the BF/BOF production of steel.	ton/year
Plant emissions EAF	Cumulative emissions from inside the EAF plants each year	CO_2 equiv/year
Plant Emissions BF/BOF	Cumulative emissions from inside the BF/BOF plants each year	CO_2 equiv/year
Electricity EAF	Energy consumed from the electricity grid to produce steel in EAF plants each year	J/year
Electricity BF/BOF	Energy consumed from the electricity grid to produce steel in BF/BOF plants each year	J/year

External energy consumption	Total energy consumed from the electricity grid to produce steel each year	J/year
Fossil Fuel source	Amount of emissions per unit of energy from fossil fuel sources each year	CO_2 equiv/J
Indirect energy emissions	Total amount of emissions caused by generating fossil fuel-based energy outside the plants each year	CO_2 equiv/year
GHG emissions	Total GHG emitted each year from the production of steel	CO_2 equiv/year
GHG emission intensity	GHG emission produced per unit of steel produced each year by the global industry	CO_2 equiv/ton/year
Total plants	Total number of plants producing steel each year	plants/year
New plants	Total number of new plants built, i.e., new plants ready for production each year	plants/year
Plant Retirement	Total number of plants that are shut down or not used each year	plants/year
Overcapacity	Negative difference between demand and available production capacity	ton
Steel price	Selling price of unit steel	dollar
GDP	Gross Domestic Product of a steel producing country or cumulative GDP of all steel producing countries.	dollar
Growth Rate	Adding amount of GDP, from steel production each year.	dollar/year
Demand	Amount of steel products required each year	dollar
Capital for investment	Amount of capital available for investments	dollar/year
Investment in Quality	Amount of investments with focus on quality of end products	dollar/year
Lifetime of steel products	Amount of years that steel products are in use	year
Material Quality requirement	Amount of steel product that has high quality requirements	ton
Steel Market share	Percentage of steel market share	dmsn
Energy price	Price of energy for steel production	dollar
Energy costs	Cost of energy consumption necessary for the production of steel	dollar/year
Production costs	Cost involved in the production of steel	dollar/year
Investment in BAT	Money invested in best available technology	dollar/year
CC implementation	Yield improvement by the implementation of CC technology	ton/unit/year
Gap between consumption and minimum required	Difference between the energy that is consumed at a certain moment and the lowest possible energy requirement	J/ton
Minimum required energy	Threshold of energy necessary to produce steel	J/ton
Improvement BF/BOF	Gain in energy efficiency by implementing BAT, i.e. the amount of decrease in energy necessary to produce steel	J/ton
Disruptive transition rate	Amount of BF/BOF plants that become EAF plants.	plants/ year
Demand EAF products	Amount of EAF product requested	ton
End of use steel	Amount of steel that is at the end of its lifetime/use	ton

Plant lifetime	Amount of expected years of utilization	year
Sunk costs	Cost involved in the substitution of technology before the end of their lifetime	dollar
EAF implementation	Amount of EAF plants created due to favored aspects, i,e reflects the degree of attractiveness of EAF plants, including the attractiveness of lower capital costs, increasing scrap availability…	plants/ year
Extreme weather events	Natural disasters that are consequence of high GHG emission concentration in the atmosphere, e.g. floods, fires, drought	amount of events/ year
Research and development stage	Level of technological readiness of mitigating technology	dmsl
Government intervention	Degree of government intervention in terms of mitigation measures	measures or dollars/ year
Taxes	Fee for the emission of GHG	dollar
Subsidies	Monetary value destined to implement clean technology	dollar
Clean energy source	Sources of energy that do not cause the emission of GHG into the atmosphere, e.g. nuclear power, solar, wind…	CO_2 equiv/ J
Carbon substitutes	Amount of fossil fuel material that is replaced by using substitutes to carbon-based material, for eg. Hydrogen.	ton/year

Appendix VIII

Additional Model Assumptions

Next, are clarifications about some approximations made during the modeling process:

- In the final model the total amount of plants stock is split into two separate stocks EAF plants and BOF plants, this is done because the two types of plants have different contributions to the GHG emission intensity and different characteristics (input, production chain, energy consumption). As such, the number of 'total plants' accounts for the sum of the total active 'EAF plants' and 'BF/BOF plants'; the 'new plants' will connect positively with 'new EAF plants' and 'new BF/BOF plants'; and 'overcapacity' will positively relate to 'Retirement of BF/BOF plants' and 'Retirement of EAF plants'. It is important to note that during the study period, as the BF/BOF have always been the most dominant technology, the influence of 'overcapacity' is stronger on the 'retirement of BF/BOF plants'.
- Removed from the final model the variable 'production capacity EAF' and 'production capacity BF/BOF' (that can be found in the model of the origins of GHG emission intensity behavior), because the variables did not reveal a relevant contribution to the understanding of the GHG emission intensity behavior.
- In the model of origins of GHG emissions the variable 'yield' connects to 'production activity' and in the final model the impact of 'yield' is connected to 3 distinct variables, 'energy consumption efficiency', 'scrap use' and 'reducing agent use'. These are two ways of representing equivalent effects. This is because 'energy consumption efficiency' directly influences 'energy consumption' of EAF and BF/BOF plants, which in turn, together with 'scrap use' and 'reducing agent use' are the variables directly influenced by 'production activity' of EAF and BF/BOF plants.
- Although literature revealed that an increase in carbon 'taxes' directly translates into an increase in production costs, this is only the case for the 'BF/BOF plants', that are highly emission intensive. In the model the variable 'production costs', stands for the average unit costs of steel products, calculated for the overall output for both types of steel plants. In this way the relationship between carbon 'taxes' and higher BF/BOF production costs is not directly represented in the model, but instead embedded in the relationship between 'taxes' and the 'retirement of EAF plants'.
- 'Energy consumption efficiency' (J/ ton) influences the 'energy consumption' as it decreases the 'required energy consumption' in joule for the same amount of steel activity. In the full model, the 'energy required' is measured in J/ ton, and energy consumption is a measured in Joule. When representing the energy crisis effect, 'energy required for BOF' is placed in

between ‘energy consumption efficiency’ and ‘energy consumption BOF’, this is to make sure that the structure introduced would fit the units.

- Although there is a relationship between a higher ‘product lifetime’ and a higher ‘steel price’, this is not significant to understand the GHG emission behavior. It only justifies an increase in ‘growth rate’ due to steel price fluctuations. Although the ‘growth rate’ increase by itself if relevant as a stimulator for more production, the drivers of Growth rate are out of the scope of the project.

Appendix IX

Validity Tests

To assure the validity and reliability of the model, several tests were made. These are followed as described in Sterman (2000; p. 859). The tests performed were de boundary adequacy test, structure assessment and dimensional consistency (see below).

1- **Boundary adequacy tests:** 'assess the appropriateness of the model boundary for the purpose at hand' (Sterman, 2000; p.861)

The boundaries of the model were defined to incorporate the most prominent drivers of GHG emission intensity. The focus was on driving forces of the behavior itself, i.e., in terms of factors that change the GHG emission intensity. In this way the model does not focus on representing dynamically the possible explanation for stagnation. The final model was achieved after a series of iterations in order to increase the reliability of the contents and assure the boundary adequacy. Moreover, the validity of the model is assured by Appendix VIas it shows how the literature quotations translate into causal relationships. The aim was to stay close to the literature and that was iteratively assured, by continuous adjustments in the interpretation of the quotes and the creation of numerous generic models that can be seen in Figure 18.

2- **Structure Assessment:** 'asks whether the model is consistent with knowledge of the real system relevant to the purpose' (Sterman, 2000; p.863).

There are a few limitations in the model structure:

- The model does not show clearly that the subsidies stimulate the usage of EAF plants.
- Model fails to show evidently how a decrease in EAF attractiveness represented by 'EAF implementation' causes a decrease in EAF plants and a perpetuation of BF/BOF usage instead.

3- **Dimensional consistency:** Checks the unit of measurement consistency

Not all the relationships in model are consistent in terms of dimensions, adding variables that would assure the consistency would make the model more chaotic. However, all the variables have a unit attached, and when the model is to be quantified, these variables that assure unit consistency can be added a posteriori.

Appendix X

Additional Model Assumptions

Next, are clarifications about some approximations made during the modeling process:

- In the final model the total amount of plants stock is split into two separate stocks EAF plants and BOF plants, this is done because the two types of plants have different contributions to the GHG emission intensity and different characteristics (input, production chain, energy consumption). As such, the number of 'total plants' accounts for the sum of the total active 'EAF plants' and 'BF/BOF plants'; the 'new plants' will connect positively with 'new EAF plants' and 'new BF/BOF plants'; and 'overcapacity' will positively relate to 'Retirement of BF/BOF plants' and 'Retirement of EAF plants'. It is important to note that during the study period, as the BF/BOF have always been the most dominant technology, the influence of 'overcapacity' is stronger on the 'retirement of BF/BOF plants'.
- Removed from the final model the variable 'production capacity EAF' and 'production capacity BF/BOF' (that can be found in the model of the origins of GHG emission intensity behavior), because the variables did not reveal a relevant contribution to the understanding of the GHG emission intensity behavior.
- In the model of origins of GHG emissions the variable 'yield' connects to 'production activity' and in the final model the impact of 'yield' is connected to 3 distinct variables, 'energy consumption efficiency', 'scrap use' and 'reducing agent use'. These are two ways of representing equivalent effects. This is because 'energy consumption efficiency' directly influences 'energy consumption' of EAF and BF/BOF plants, which in turn, together with 'scrap use' and 'reducing agent use' are the variables directly influenced by 'production activity' of EAF and BF/BOF plants.
- Although literature revealed that an increase in carbon 'taxes' directly translates into an increase in production costs, this is only the case for the 'BF/BOF plants', that are highly emission intensive. In the model the variable 'production costs', stands for the average unit costs of steel products, calculated for the overall output for both types of steel plants. In this way the relationship between carbon 'taxes' and higher BF/BOF production costs is not directly represented in the model, but instead embedded in the relationship between 'taxes' and the 'retirement of EAF plants'.

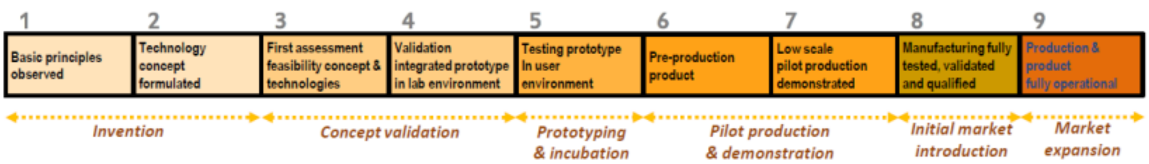
- 'Energy consumption efficiency' (J/ton) influences the 'energy consumption' as it decreases the 'required energy consumption' in joule for the same amount of steel activity. In the full model, the 'energy required' is measured in J/ ton, and energy consumption is a measured in Joule. When representing the energy crisis effect, 'energy required for BOF' is placed in between 'energy consumption efficiency' and 'energy consumption BOF', this is to make sure that the structure introduced would fit the units.
- Although there is a relationship between a higher 'product lifetime' and a higher 'steel price', this is not significant to understand the GHG emission behavior. It only justifies an increase in 'growth rate' due to steel price fluctuations. Although the 'growth rate' increase by itself if relevant as a stimulator for more production, the drivers of Growth rate are out of the scope of the project.

Appendix XI

Technology Readiness Level

The first figure shows what each TRL entails, and the second figure shows the subdivision of each TRL level in different stages.

Figure 5: EARTO reading on the TRL scales, incorporating manufacturability and including non-technological aspects in a multi-technology adaptation.



Source: European Association of Research and Technology Organizations (EARTO). TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations; 2014

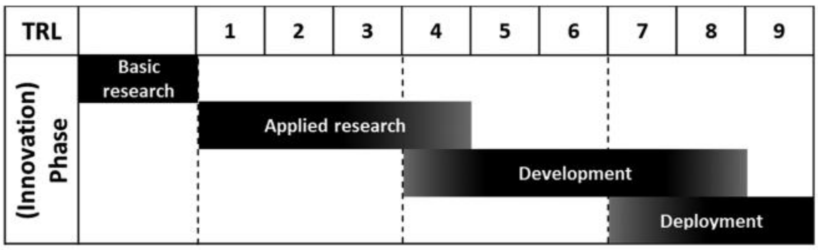


Figure 3. TRLs attributed to (innovation) phases "basic research", "applied research", "development", and "deployment".

Source: Buchner, G. A., Stepputat, K. J., Zimmermann, A. W., & Schomäcker, R. (2019). Specifying technology readiness levels for the chemical industry. *Industrial & Engineering Chemistry Research*, *58*(17), 6957-6969.

Appendix XII

Final Model (large)