Iron and Steel industry

Evolution of energy efficiency and CO_2 emissions

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Abstract

The iron and steel industry has been having a hard time reducing its energy consumption and emissions in the last 20 to 25 years, despite a decrease of nearly 50 per cent in both energy and CO_2 intensity between 1970 and late 1990's. The recent increase in production in emerging countries with high energy and CO_2 intensity has counterbalanced the improvements made in developed countries, raising concerns regarding the industry's ability to achieve the climate goals set.

This work looks into the development of steel production to find the factors that were decisive to the evolution of its efficiency and emissions registered until the end of the 20^{th} century and investigates the causes of the recent stagnation, using the main findings to forecast long-term scenarios that test several emission reduction strategies and assess the likelihood of reaching the IPCC net zero emission goals.

The analysis of the evolution of steel production concluded that the efficiency improvements in each steelmaking route and the structural changes in steel production were equally responsible for the reduction of the industry's energy and CO_2 intensity between 1970 and the late 1990's. Results show that with a combination of an increase in the share of EAF, changes in electricity generation and implementation of the BAT and breakthrough technologies, the industry's energy and CO_2 intensity could be reduced by nearly 50 per cent but that it would not be enough to reach net zero emissions by 2050 nor put it in track to do it by 2070.

Keywords: Iron and steel industry; Energy intensity; CO_2 intensity; Emission reduction strategies; Long-term scenarios.

Resumo

A indústria do ferro e do aço tem tido dificuldade em reduzir o seu consumo energético a as suas emissões nos últimos 20 a 25 anos, ainda que tanto a intensidade energética como de CO_2 tenham sido reduzidas em cerca de 50 por cento entre 1970 e o final dos anos 90. O recente aumento de produção em países emergentes grande intensidade energética e carbónica anulou os avanços ocorridos em países desenvolvidos, comprometendo o cumprimento das metas ambientais definidas.

Este trabalho analisa o desenvolvimento da produção do aço para identificar os fatores que determinaram a evolução ocorrida até ao fim do século passado e as causas da recente estagnação, usando-os depois para projetar cenários a longo prazo que testam várias estratégias de redução de emissões e verificam a probabilidade de as metas de neutralidade carbónica do IPCC serem cumpridas.

A análise da evolução da produção do aço concluiu que as melhorias na eficiência de cada rota e as alterações das suas quotas de produção foram igualmente responsáveis pela redução da sua intensidade energética e de CO_2 entre 1970 e o final dos anos 90. Os resultados mostram que com a ocorrência em simultâneo de um aumento do uso das EAF, alterações na produção de eletricidade e aplicação da melhor tecnologia disponível e algumas inovações tecnológicas, seria possível reduzir a intensidade energética e de CO_2 em 50 por cento, mas mesmo assim isso não seria suficiente para atingir a neutralidade carbónica em 2050 nem levaria a indústria a fazê-lo em 2070.

Palavras-chave: Indústria do ferro e do aço; Intensidade energética; Intensidade de CO_2; Estratégias de redução de emissões; Cenários a longo prazo.

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Abbreviations

BAT – Best available technology;

BF – Blast furnace;

BOF – Basic oxygen furnace;

CIS – Commonwealth of Independent States;

CCU – Carbon capture and utilisation;

CCS – Carbon capture and storage;

CDQ – Coke dry quenching;

COURSE 50 - CO_2 ultimate reduction in steelmaking process by innovative technology for cool Earth 50;

DRI – Direct reduced iron;

EAF – Electric arc furnace;

EIA – United States Energy Information Administration;

EU – European Union;

HBI – Hot Briquetted Iron;

IEA – International Energy Agency;

IPCC – Intergovernmental Panel for Climate Change;

NAFTA - North American Free Trade Agreement;

OECD – Organization for economic cooperation and development;

OHF – Open-hearth furnace;

TGR-OBF – Top gas recycling in oxygen blast furnace;

TRTs – Top-pressure recovery turbines;

ULCOS – Ultra-low CO_2 steelmaking;

US – United States of America;

1. Introduction

1.1. Motivation and objectives

The exponential increase of steel production over the last decades and the dependence on energy intensive process and fossil fuels turned the steel industry into the number one in CO_2 emissions and number two in energy consumption amongst heavy industries (International Energy Agency., 2020a). Its annual CO_2 emissions correspond to almost 5 per cent of the world's total emissions (World Steel Association, n.d.-b) and 8 per cent of the world's energy-related emissions (International Energy Agency., 2019), which is mainly due to it using nearly one third of all the coal produced worldwide (International Energy Agency., 2020b), whereas its energy consumption accounts for 10 per cent of the industrial sector energy consumption in the OECD countries and 18 per cent in the non- OECD countries (U.S. Energy Administration, 2016). Such scenario contrasts with the industry's ambitions to reduce carbon emissions and be more energy efficient, making clear that changes have to be made and the much-desired industry's "green path" requires double efforts from all those involved.

Despite its heavy contribution to the world's CO_2 emissions and energy consumption, steel industry has undergone profound changes over time, adopting more environmentally friendly processes and being able to reduce crude steel's energy intensity by nearly 50 per cent between 1970 and 2000 (World Steel Association, 2019). However, there has not been much improvement in the last 20 years as the industry's processes got closer to the current technology's limits and the ever-growing steel demand has hindered the chances of a completely recycling-based production.

The aim of this work is then to analyse both the current and past states of the iron and steel sector and use this information to predict where it is headed and whether achieving the emission goals set is feasible. This analysis looks into its evolution since 1970, focusing on the demand, energy efficiency and CO_2 emissions. Unlike most studies previously done this one extends the analysis to the finished steel products, thus including the rolling and finishing processes the others neglect. The results obtained regarding the industry's energy efficiency and CO_2 emissions are compared to reference results that have been calculated by other authors and those that coherent are then used to break down its evolution and analyse the reasons behind its recent stagnation. The main takeaways of this analysis are utilised to project an energy and CO_2 intensity scenario for 2050. This scenario takes into account the major factors affecting the industry's efficiency and emissions evolution that have been highlighted along the way, with the final results being compared to the climate change goals that have been set.

1.2. Structure

This dissertation is divided in five chapters, complying with the following structure:

1) **Introduction:** contextualization of this work and summary of the topics it aims to address. There is also a description of its structure, with a clarification of how it is divided and of the contents encompassed on each chapter.

2) **Bibliographic review:** summary of the history of steel industry, reviewing how and why steel demand has changed and characterizing the steelmaking processes and their energy efficiency and CO_2 emissions. Discussion of previous works done on these topics that will be later used as reference values. Presentation of trends and demand forecasts that will later help to draw scenarios regarding energy intensity and CO_2 emissions.

3) **Methodology:** presentation of the data used and extensive explanation of its processing. Emphasis is given to the methods used to calculate the primary energy intensity from the IEA World Energy Balance and the boundaries used, as it required a rather complex approach and use of additional data to ensure energy consumption calculations were as accurate as possible. Disclosure of the calculation of CO_2 emissions, of the references used to validate the results and off the correction values that had to be applied to respect the boundaries set. Explanation of each step of the project scenarios form 2050.

4) **Results:** the results are presented and analysed. It starts with a review of their reliability, with a comparison between them and reference data being drawn to assess it. Eventual discrepancies are carefully looked into and suggestions are made to justify them. The results that are found to be within the expected values are then further analysed, as links are explored between different data sets and their implications on the current and future state of steel industry are discussed. A long-term scenario regarding energy and CO_2 intensity is projected using worthy findings from beforehand, with its results being compared to the climate goals set.

5) **Discussion and conclusions:** brief recapitulation of the iron and steel industry's efficiency and emissions problem, presentation of the solutions tested and the impact each had on the scenarios projected, analysis of those scenarios and discussion about what they mean for the industry's future. Final considerations on the main challenges faced during this work and on what would be interesting to focus on in future works.

2. Bibliographic review

2.1. Steel in society

2.1.1. Uses of Steel

According to the "World Steel in Figures" report from 2020 by the World Steel Association (World Steel Association, 2020a) the end-use of steel in today's world has the distribution displayed in Figure 1.

Buildings and infrastructure dominate the end-use of steel using 52 per cent of the annual steel production, as its mechanical properties, low cost and recycling potential make it a go-to material in most construction scenarios. According to the World Steel Association (World Steel Association,

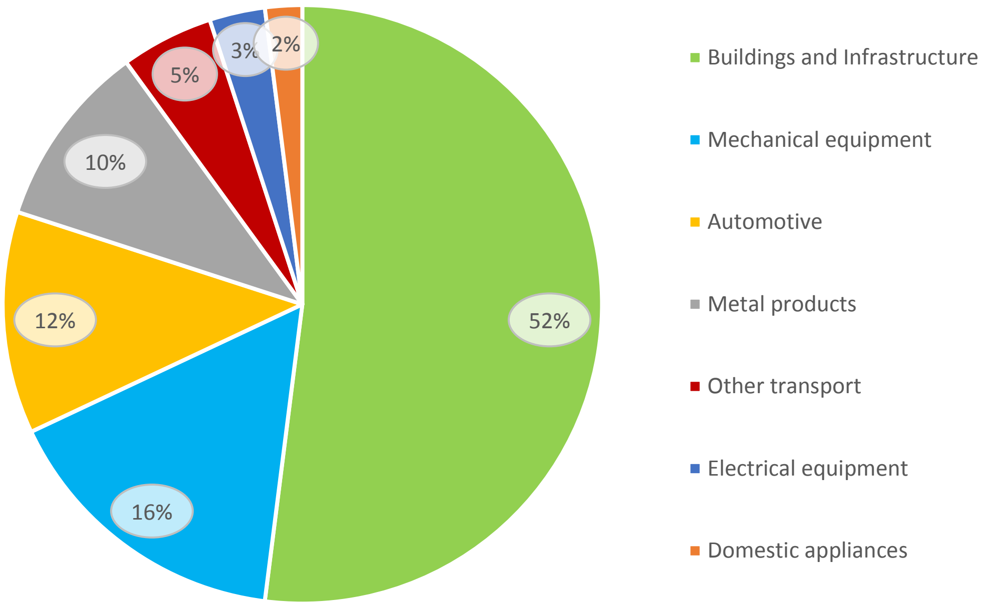


Figure 1 – Steel end-use distribution (modified from World Steel Association, 2020).

n.d.-d) 25 per cent of the steel destined to buildings is used in structural section, 44 per cent is in reinforcing bars and 31 per cent is in sheets products like ceilings and insulating panels for exterior walls, to which steel's stiffness, tensile strength and ability to bind with concrete are a must. Its use in infrastructures has a similar distribution and these properties – and others such as resistance to fatigue and corrosion – make it suitable for bridges, tunnels train rails and pipelines.

Steel's durability also comes in handy when producing **mechanical equipment**, which accounts for 16 per cent of today's steel end-use. Most tools and machinery used across all industries and activities are made from it due to its hardness and resistance to corrosion and heat. This includes equipment that can go from workshop tools to large factory-based machines (Allwood & Cullen, 2012).

Around 17 per cent of steel goes to **transport**, with automotive consuming 12 per cent on its own. The World Steel Association (World Steel Association, n.d.-c) states that on average 900 kg of steel are used per vehicle, with its structure, drive train and suspension taking 40 per cent, 23 per cent and 12 per cent respectively. The remaining part is divided between the wheels, tyres, braking system, steering and fuel tank. Other transports such as ships, trains and aeroplanes are responsible for the 5 per cent there are left.

The next biggest steel consumer are other **metal products**, with 10 per cent of the annual steel production. These cover a wide range of products that goes from baths and chair to filling cabinets and barbed wire (Allwood & Cullen, 2012).

Most the remaining 5 per cent are divided between **electrical equipment** and **domestic appliances**. A significant part of the steel used that goes to electrical equipment is electrical steel, which is a soft magnetic material that is widely used in transformers, generators and motors due to the high content of silicon and its thin lamination minimizes core losses (Collocott, 2016). This can also be found in the motors of domestic appliances, even though most of the steel used there is for panelling.

2.1.2. Evolution of annual crude steel production

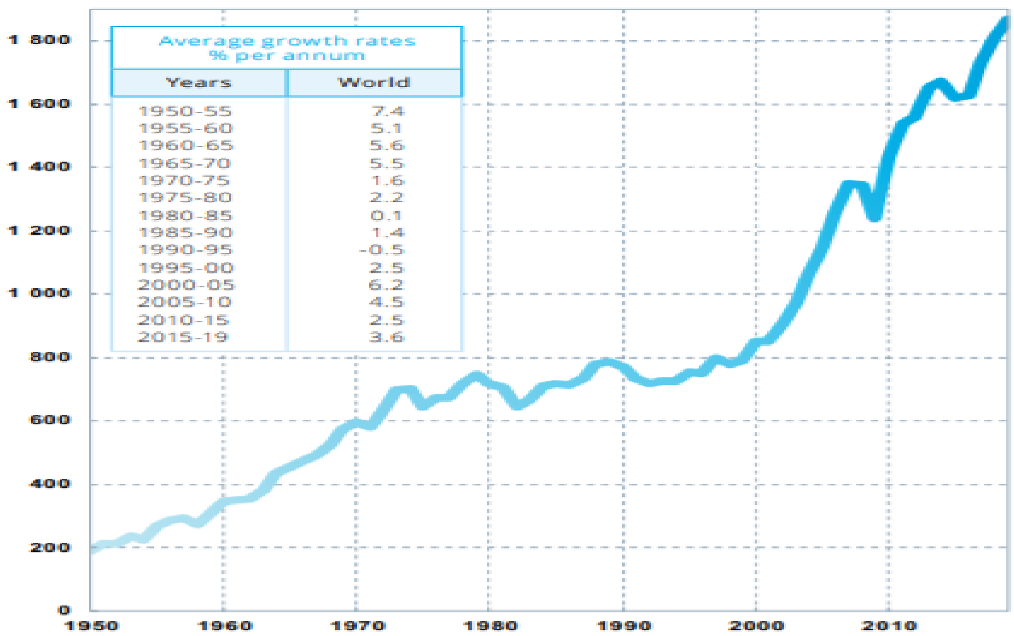


Figure 2 – World crude steel production in millions of tonnes (World Steel Association, 2020).

The evolution of annual crude steel production since 1950 is illustrated in Figure 2. Its irregularity prompted the World Steel Association to distinguish 3 different eras in the "Global steel industry: outlook, challenges and opportunities" report from 2017 (World Steel Association, 2017). The first one goes from 1950 to the early to mid-1970's. During these years steel demand kept increasing as the world was rebuilding from World War II, thus causing the annual crude steel production to go from 189 million tonnes in 1950 to 644 million tonnes in 1975. This represented an average growth of 5 per cent year.

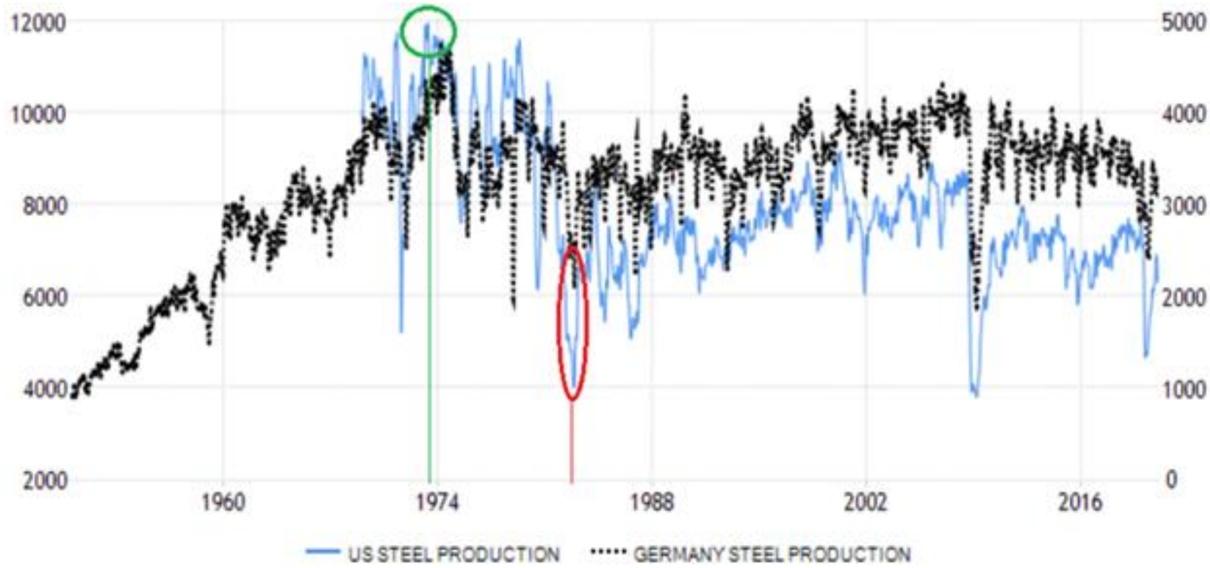


Figure 3 - Evolution of steel production in Germany and in the United States in thousands of tonnes. Left scale corresponds to the US and the one on the right to Germany. (modified from TRADING ECONOMICS, n.d.).

The post-World War II economic expansion came to an end with the 1973-1975 recession and steel production in most industrialized countries reached its peak by then (World Steel Association, 2017). Figure 3 shows the evolution of steel production in Germany and the United States, two of those who saw their steel production decrease during the recession. After reaching the peak in 1973 (highlighted in green) and decreasing until 1975, steel production in the industrialized countries bounced back and by 1980 reached the levels of 1973 (Tarr, 1988). However, a new oil crisis came in 1978 and steel demand decreased once again, hitting rock bottom on 1982-1983. It would then increase but this instability – mainly in western countries – prevented any serious growth during this period. Between 1975 and 2000 world crude steel production grew on average only 1.1 per cent per year, reaching the 850 million tonnes in 2000.

The new century brought a new scenario as China, already the biggest steel producer in the 1990's, went on to dominate the world's steel production. This boom is illustrated in figure 4, which shows how the share of crude steel production has changed in the last 20 years. In just 10 years, from 1999 to 2009, China's share of the world's crude steel production went from 15.7 to 46.6 per cent. This growth, however, slowed down in the last decade with China reaching 53.3 per cent in 2019. Such numbers are even more impressive if it is taken into account that during the last 20 years the total world production more than doubled, having gone from 850 to 1869 million tonnes. Despite an annual average growth of 4.2 per cent, the steel industry took big hits with the economic crisis of 2008 and China's stock market crash in 2015 (Babucea & Irina, 2015; de Carvalho, 2016).

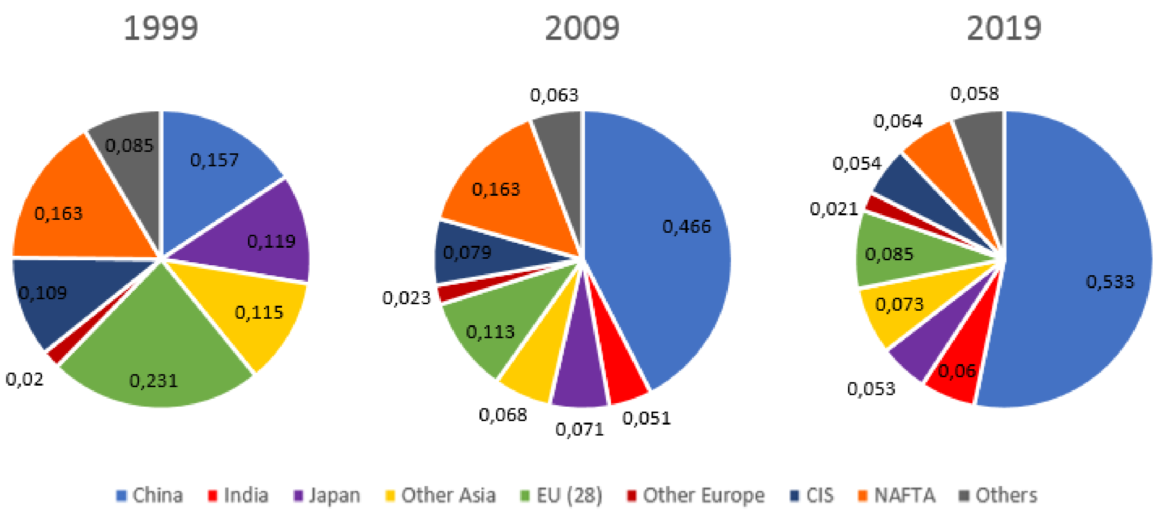


Figure 4 - Evolution of the geographical distribution of steel production (modified from World Steel Association, 2020 and World Steel Association, 2010).

2.1.3. Drivers and trends

With steel production playing a big factor in energy consumption and CO_2 emissions its rapid increase in the last 20 years can harm the ever-growing efforts to build a more sustainable worlds, particularly reaching carbon neutrality. This growth gets more worrying as it is mostly caused by a borderline out of control increase of steel consumption in developing countries like China and India, where steel production is usually less energy efficient (Phylipsen, Blok, & Bode, 2002) and there are lower environmental standards. Understanding the evolution of steel consumption is then crucial to forecast its future production.

The presentation of the evolution of steel production in section 2.1.2. showed that throughout the history of steel demand there were trends that stand out and can seem to be linked to very specific events. One of the obvious cases was the impact of the economic conditions. As it was pointed, economic recessions have had a negative impact on steel demand and, on the other hand, economic expansions have worked in its favour. If we add the fact that most of today's steel is used in construction, transport and mechanical equipment, it is reasonable to believe that its consumption might be related to **economic development**, as it is clearly affected by a country's **urbanization**, **motorization** and **industrialization**.

With this in mind, there will be a review of previous work exploring the relation between steel consumption and economic development (measured in GDP per capita).

2.1.3.1. GDP per capita

In the early 1970's the World Steel Association (at that time named International Iron and Steel Association) came up with the "intensity of use hypothesis" to try to explain the relation between steel consumption and economic development. This hypothesis, popularized by Wilfried Malenbaum, states that steel consumption is influenced by the GDP per capita. It claims that the

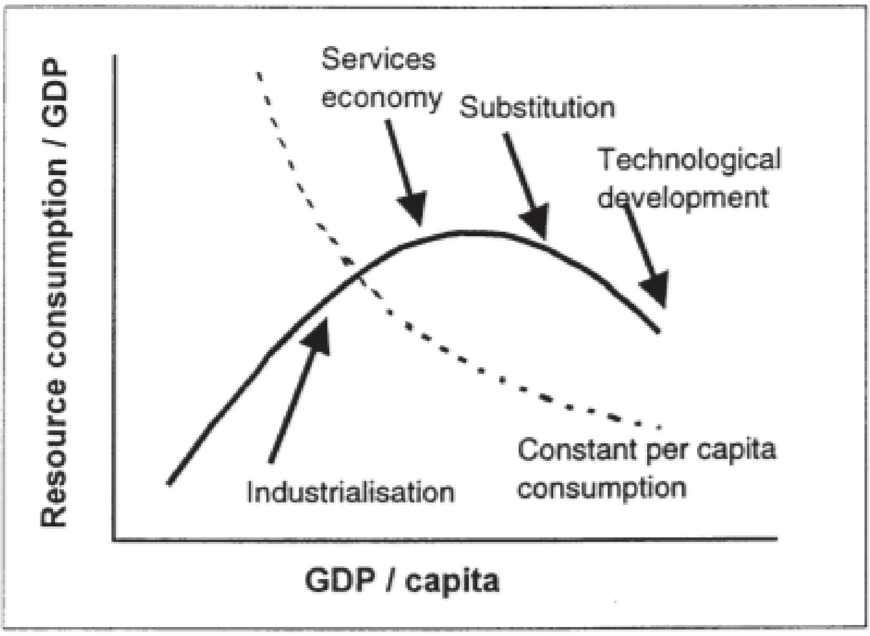


Figure 5 – "Intensity of use hypothesis" (Van Vuuren et al., 1999).

increase in GDP per capita initially pushes steel consumption up, but after a certain point this growth slows down and, for even greater GDP per capita levels, steel consumption starts to decrease (Ignacio Guzmán et al., 2005; Wårell, 2014). This behaviour corresponds to an inverted U-shaped curve like the one in figure 5.

Van Vuuren et al (1999) highlighted three trends to justify this relationship:

- Steel demand changes during the development cycle of an economy. As countries develop the investment in infrastructures increases and there is greater spending in goods that require high amounts of steel, pushing steel consumption up. However, this surge peaks at certain GDP per capita as society's focus shifts towards services - which are less steel intensive – and steel consumption drops. This trend is accentuated by the reallocation of steel intensive industries to developing countries where production cost is lower. Since the imports and exports of steel embodied in final products are not considered in trade statistics, the steel required to produce those goods will increase the steel consumption in the developing countries where the factories are based and decrease it in the developed countries where the final products are actually used (Xin Zhou & Ambiyah, 2011).

- Saturation of the market with steel can lead to the emergence of advantageous materials that replace it. Van Vuuren et al (1999) state that its substitution can be so drastic that not only it slows down its consumption growth but can even lead to its decrease.
- Technological developments allow for greater efficiency in production processes, minimizing their steel requirements. However, the benefits of such innovations are not equally distributed worldwide, as the least developed countries lack the investment in science and development and the funding to import foreign state-of-the-art technologies, among other difficulties ('Utoikamanu, n.d.).

The simplicity is one of the biggest upsides of the "intensity of use hypothesis" and it makes this hypothesis very useful to forecast future demand. However, this comes at a cost, as the importance of income per capita in the occurrence of some of the trends mentioned is far from undeniable. Although influenced by GDP per capita, both the substitution of materials and technological developments – as well as long-run price trends – are not primarily driven by it (Van Vuuren et al., 1999). According to Ignacio Guzmán et al (2005) they are correlated with time rather than per capita income and may just have the biggest impact in consumption. The occurrence of other disruption factors like energy crisis is also not possible to predict using this hypothesis (Van Vuuren et al., 1999).

These trends tend to shift the U-shaped curve downwards, especially for bigger GDP per capita values, but because they are linked with time instead of income the curve estimated considering income as the only driving factor will not truly represent the relation between steel consumption

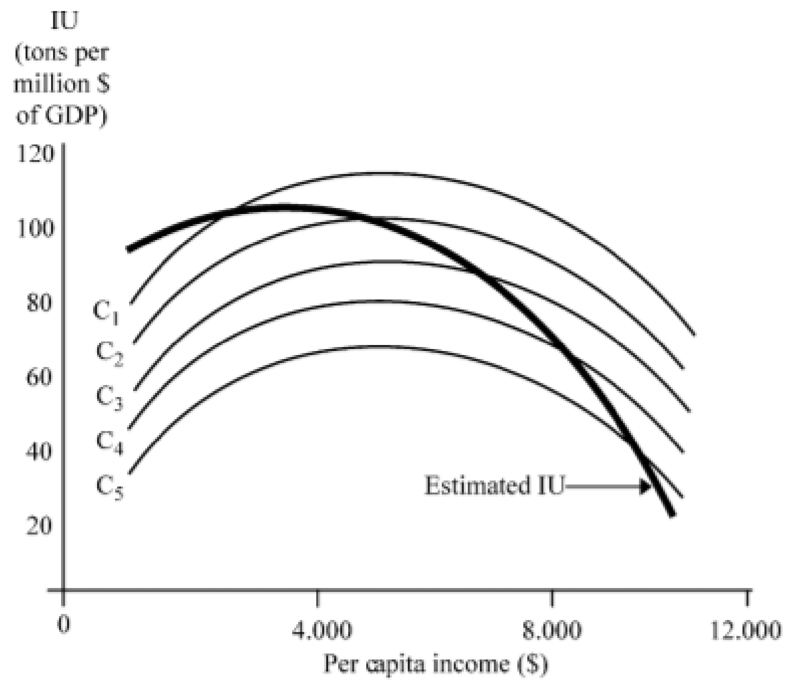


Figure 6 – True and estimated "intensity of use" curves (Ignacio Guzmán et al., 2005).

and GDP per capita. Figure 6 shows how the estimated curve of such studies (thicker line) is in fact a combination of different "intensity of use" curves and underestimates the GDP per capita that maximizes steel consumption, thus failing to approximate any of the real curves (Ignacio Guzmán et al., 2005). To avoid this issue the models must include a time variable, thus differentiating the effects of income per capita and time (Ignacio Guzmán et al., 2005; Wårell & Olsson, 2009).

The "intensity of use hypothesis" seems to be supported by the evolution of the world crude steel production and GDP over the last decades. Figure 7, which compares the variation of their indexed values, showns that both indicators have been varying in a very similar fashion.

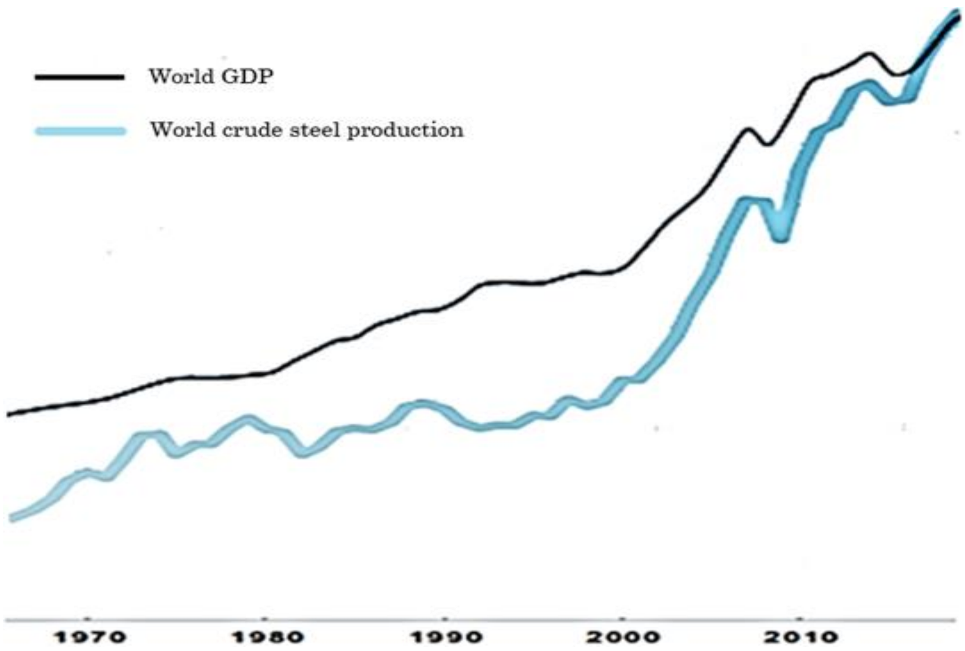


Figure 7 - Evolution of indexed world crude steel production and GDP (modified from TRADING ECONOMICS, n.d.-a and World Steel Association, 2020).

Understanding the economic trends behind the "intensity of use hypothesis" is fundamental to analyse the evolution of steel consumption and how it might respond to different stimulus. However, this knowledge is of little importance if it cannot be used to accurately forecast future steel demand. Then, the question to ask is when do countries' steel consumption peak? And does it occur at the same GDP per capita for every country?

To answer these questions researchers have been performing empirical analysis with data from large group of countries during an extensive period of time (Wårell & Olsson, 2009; Wårell, 2014; Döhrn & Krätschell, 2014).

The results obtained by (Wårell & Olsson, 2009) and Döhrn & Krätschell (2014) support the inverted U-shaped form suggested by the "intensity of use hypothesis" and predict that countries reach their maximum steel consumption at 28000 and 30000 US dollars, while in Wårell's study from 2014 this hypothesis only held for the middle income group – Wårell divided the countries in low, middle and high income – where the peak consumption was estimated to happen around 24000

US dollars. All these studies also showed that the “intensity of use hypothesis” only holds if time variable is included.

It is important to mention that these GDP per capita values should be analysed with caution. Firstly, they are the average turning points of the respective groups and can differ greatly from country to country due to one’s very own industry structure, urbanization and culture having a significant impact in steel consumption (Wårell & Olsson, 2009; Wårell, 2014). Secondly, and as Döhrn & Krätschell pointed out, the data used regarding steel consumption used (apparent steel consumption) does not account for the indirect trade of steel embodied in products, thus overestimating the consumption of countries that are large exporters of goods and underestimating consumption of those who import high shares of them. Their study, where the analysis was mostly done using GDP in purchasing power parities, also showed that the predicted turning point can also be affected by the base year chosen for the price adjustment. Lastly, panel unit root test performed by Wårell (2014) confirmed that steel consumption and GDP per capita are non-stationary variables for the middle income group – the only one where results corroborated the “intensity of use hypothesis” – and an adjusted model that accounted for these effects predicted a new turning point of 19000 US dollars, which is considerably lower than the 24000 US dollars estimated before.

2.1.4. Future scenarios

With China and India – the two emerging economies responsible for the recent boom in steel consumption – still far from the turning points presented in section 2.1.3.1 it seems the world crude steel consumption will continue to increase. Is it then safe to assume there is still a long way to go before world production peaks?

2.1.4.1. Long-term forecasts

In the Iron and Steel Technology Roadmap published last October, the IEA forecasts a steel demand scenario for 2050 based on the application of the expected effects existing and announced policies to its current trajectory (International Energy Agency., 2020a). It is named the Stated Policies Scenario (STEPS). In this scenario, shown in figure 8, the IEA expects crude steel production to grow from nearly 1900 in 2019 to over 2500 million tonnes in 2050., with India, not China, being the driving force of this growth. While China’s share of global production is set to decline from 53 to 35 per cent, India’s is projected to increase from 6 to 17 per cent (International Energy Agency., 2020a).

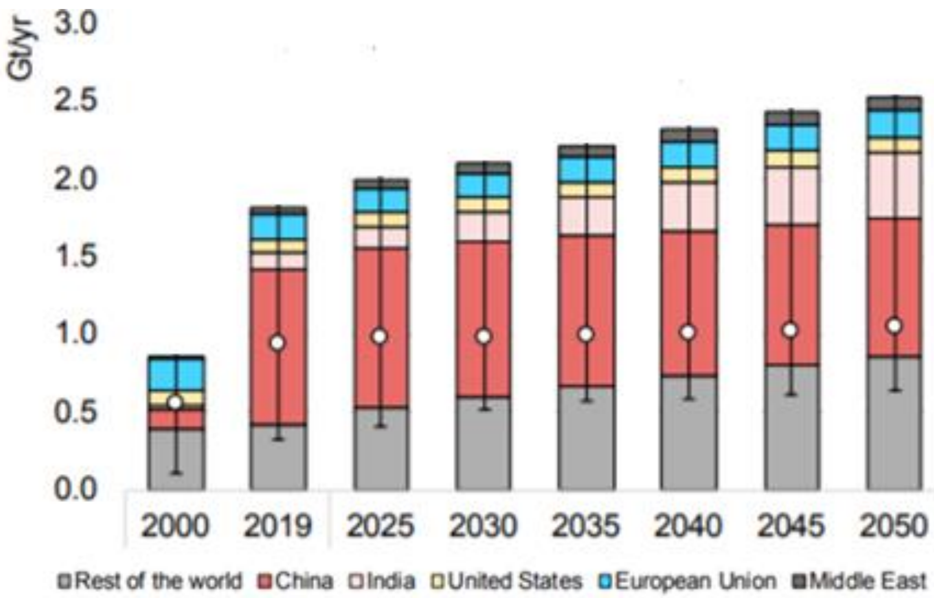


Figure 8 – Stated Policies Scenario (STEPS) crude steel production forecast for 2050 (modified from International Energy Agency., 2020).

India's expected steel production growth is largely fuelled by their population growth and economic development, as they are on track to be the world's most populous country before 2030 (United Nations, 2019) and move up to be the 5th largest economy in 2025 and, just 5 years later, the 3rd (Bloomberg, 2020). The combination of these two factors makes the Indian government believe that by 2030 they will solidify their position as the 2nd biggest steel producer with an annual crude steel production of 300 million tonnes (BEE, 2018), which represents an increase of almost threefold from their 2019 production of 111 million tonnes.

Headed the opposite is China, with an expected stagnation and, later on, decline of steel production. Unlike with India, China's unusually high steel consumption has not followed the growth of GDP (Wårell & Olsson, 2009). Incentive policies for public infrastructure and housing construction have played a major role in this increase (Holloway et al., 2010). This strategy caused a big surge of investment in real estate that led construction to be responsible for 70 per cent of steel consumption in China (Wårell & Olsson, 2009). However, and despite the economic stimulus to overcome the pandemic resulting in steel production increasing in 2020, the Chinese government has stated they intent to reduce steel production and focus on reducing carbon emissions (Reuters, 2021; Bloomberg, 2021).

As for the rest of the world, especially for developed countries such as the United States, Japan, South Kore and the European Union, it is expected that steel production will stall, reflecting the effects of a circular economy driven by economic and environmental concerns, steel substitution and a slower population growth (Accenture, 2017; World Steel Association, 2017). This stagnation will have them continue to lose ground to the emerging economies with rising consumptions that are expected to push world steel production up, even though they should keep a fairly similar absolute output in coming years. Their total share of steel production is expected to decrease from 25 per cent in 2019 to 20 per cent in 2050 (International Energy Agency., 2020a).

Unlike previous forecasts, most of which have been shown to be rather optimistic (Accenture, 2017; World Steel Association, 2017), this IEA report highlights that despite consumption reduction trends setting the tone in the developed countries, the overall world steel production is likely to continue to grow due to the demand increase in developing countries.

2.1.4.2. The impact of COVID-19

COVID-19 pandemic ended up having a less of an impact than initially expected (S&P Global, n.d.). In 2020 steel production only decreased by 0.9% compared to 2019. China's growth of 5.2 per cent made up for the decline in the European Union, the United States, Japan and India, all of which saw their crude steel production decrease more than 10 per cent (World Steel Association, 2021d).

The post-pandemic stimulus spending is set to keep steel demand high and help the industry recover in the next few years, as steel production is expected to resume its growth in 2021 and, in 2022, surpass pre-pandemic levels. However, this recovery – mostly driven by China and India – is not bound to happen at the same rate in every country, with most developed economies taking a few years to re-establish their 2019 steel demand levels (World Steel Association, 2021f).

2.2. Steel production

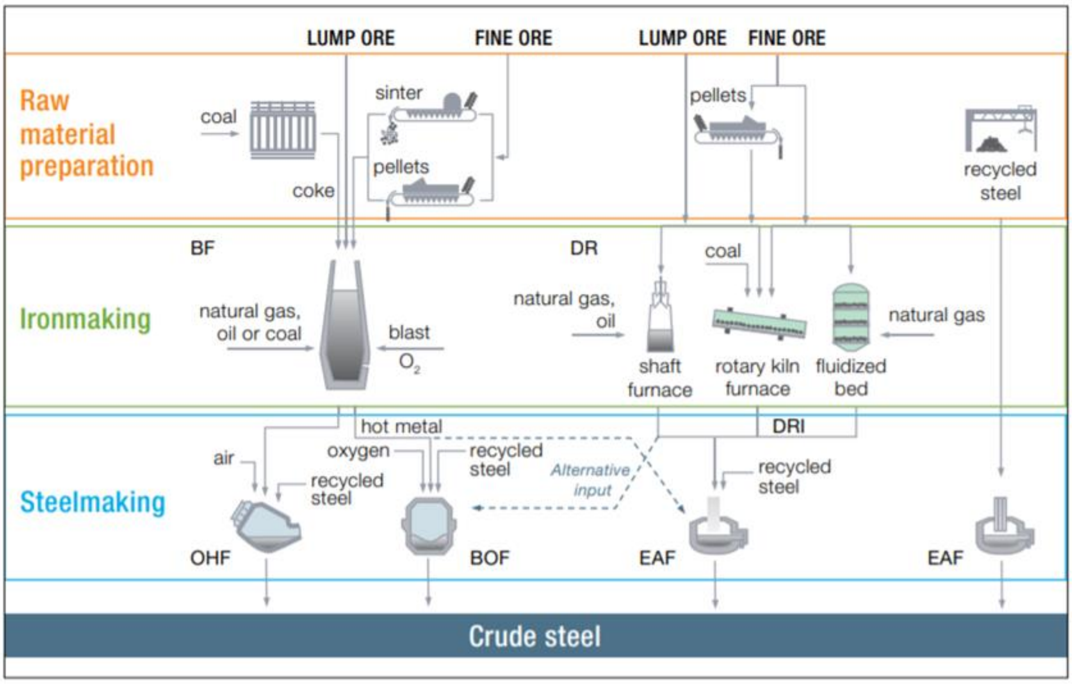


Figure 9 - Steelmaking routes (World Steel Association, 2019)

Steel can either be produced from iron or from scrap metal. The first process takes place at an integrated facility that includes coke production, ore preparation and later reduction, crude iron melting and steel shaping. The latter skips some of the previous stages as it recycles scrap steel, which results in a smaller energy consumption.

2.2.1. Steel production from iron ore

As shown in Figure 9 there are three main stages iron ore goes through in order to produce raw steel. Since raw steel still needs to be shaped into the final product, the production of steel from iron can be divided in four major steps:

1. **Raw material (ore) preparation:** iron ore goes though grinding and sintering or pelletizing processes so that it can be better used in the furnaces;
2. **Reduction (ironmaking):** CO obtained through the gasification of coke is used to reduce the iron oxides, producing molten crude iron;
3. **Refining (steelmaking):** removal of carbon and other impurities from the crude iron by melting it. It can be done using an open-hearth furnace, a basic-oxygen furnace (BOF) or an electric arc furnace (EAF);
4. **Shaping:** molten steel is casted and later shaped in the various finishing mills according to the requirements;

2.2.1.1. Ore preparation

Iron is extracted in the shape of iron ore, which consists in various minerals that contain high levels of iron oxides such as magnetite (Fe_3O_4) and hematite (Fe_2O_3). Iron ore usually contains up to 60-70 per cent of iron but the use of low-grade iron ore with around 30 per cent of iron like taconite has become more common due to the depletion of high-grade ores and improvements in mining and processing technology.

This trend has raised the need to utilise concentration processes to increase the iron levels and, consequently, use agglomeration processes to turn its product into a larger material that better fits the furnaces requirements and optimizes reduction.

Iron ore is first crushed into fine powder to allow the separation of different minerals and subsequent removal of gangue minerals (**beneficiation**), resulting in a more concentrated and powder-like iron ore. This is achieved through processes such as magnetic separation, gravimetric separation and flotation.

As furnaces do not work with fine ore due to permeability issues (Fernández-González et al., 2018) an **agglomeration** process is needed. There are five agglomeration processes: briquetting, nodulizing, extrusion, sintering and pelletizing. Sintering, that is responsible for about 70 per cent of the world's production (Harvey, 2010), and pelletizing are the main ones.

- **Sintering** is a thermal process that turns iron fines around 8mm into larger agglomerates usually between 5 and 50mm with physical and metallurgical properties that optimize reduction (L Lu & Ishiyama, 2015). The process can be divided in three

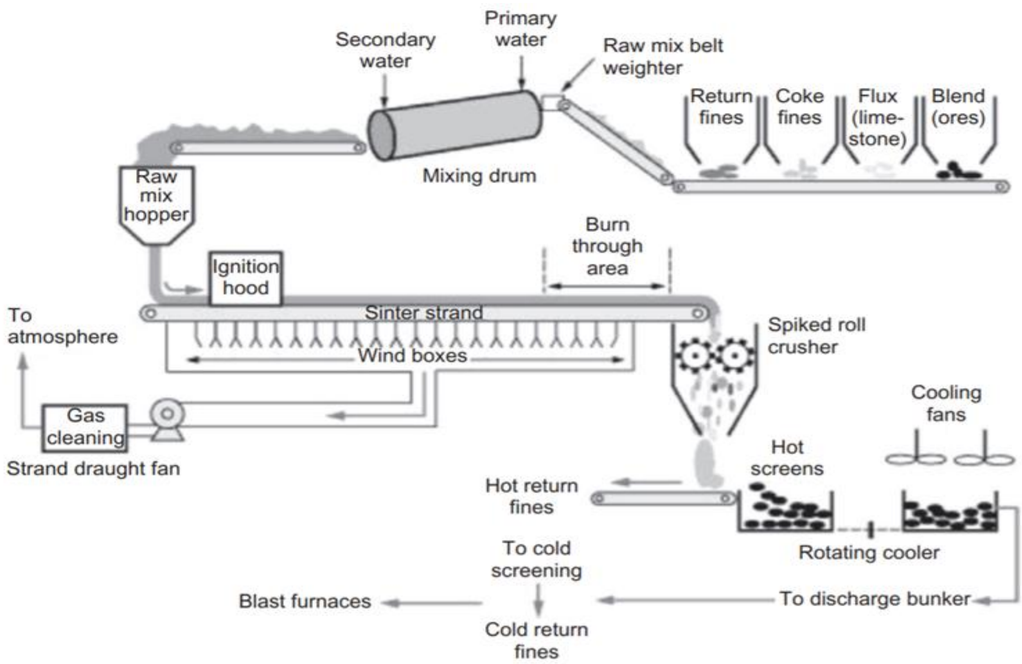


Figure 10 - Sintering process (L Lu & Ishiyama, 2015).

main stages: granulation, firing and cooling. A homogeneous mixture of iron ore fines, solid fuel (coke or anthracite), fluxes and return fines is granulated in a mixing drum with the addition of moisture to form a properly sized sinter mixture. After being screened, this mixture is fed to the sinter strand and a hearth layer is placed at the bottom to prevent the sinter mixture from over-heating. A series of gas burners ignite the fuel at the bed furnace and the high temperatures allow the fusion and blending of the mixture as it moves forward. Suction fans below the strand and the fresh air that is continuously supplied to the top of the mixture force the front flame to move downward and, eventually, reach the bottom of the sintering bed (burn through point). By then the mixture is ready to be discharged into a breaker where it will be crushed prior to being cooled in a rotary cooler. A second screening and crushing unit ensures sinter ore meets the size requirements and returns the particles that do not. These will be later used as return fines and loaded into the new sinter mixture.

- **Pelletizing** differs from other agglomeration techniques in that the powdered ore is first formed into a "green" pellet that is later dried and hardened in a separate step, usually by heating (Zhu et al., 2015). The process starts with the fine ore being mixed with

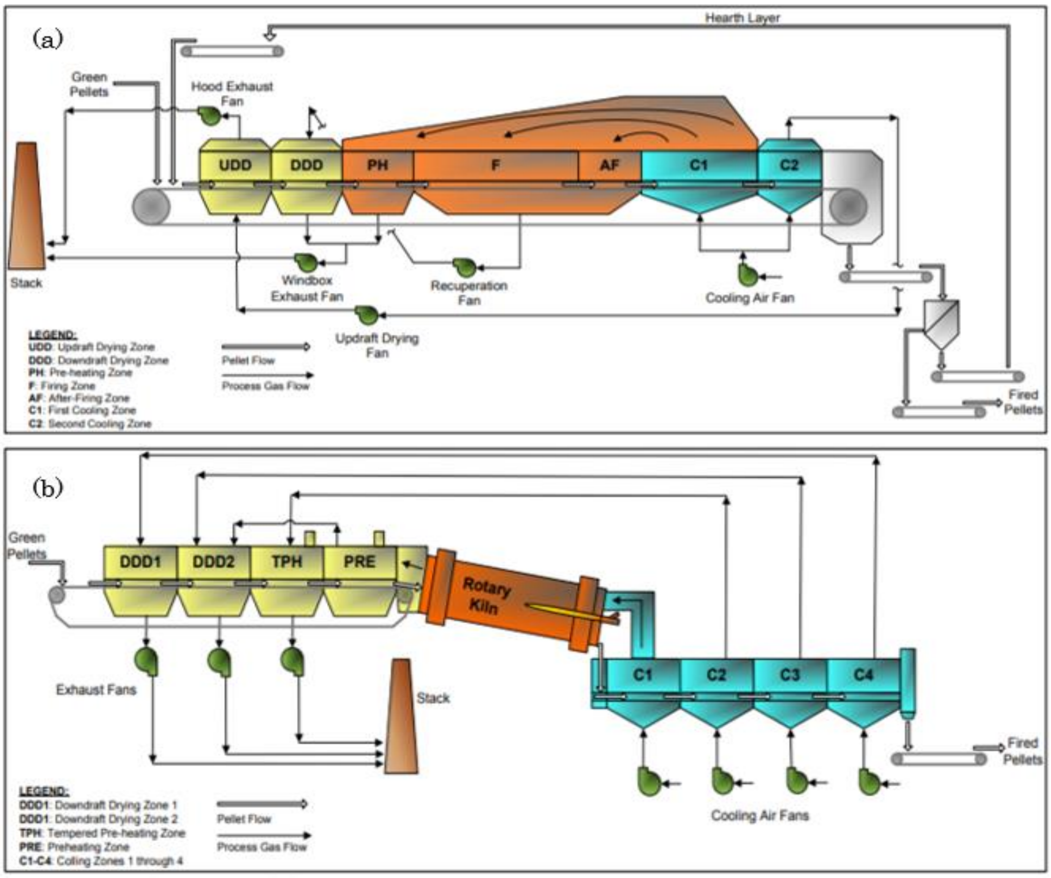


Figure 11 - Schematic of different induration processes: (a) straight grate, (b) grate-kiln (modified from Mourao & Researcher, 2020 and Huerta et al., 2013).

binders (often bentonite), water and lime. Then, the mixture goes through a balling process that can either using rotating drums or discs. The "green" pellets are screened and those within the size requirements are subjected to an induration process. There are three main types of induration furnaces: the shaft furnace, the grate-kiln and the straight-grate, of which the last two have become dominant (Yang et al., 2014). These two technologies differ in the disposal of the different zones as shown in Figure 11. Unlike the straight grate where the drying, preheating, indurating and cooling zones are all in the same unit, the grate-kiln has separated in the grate-kiln the "green pellets" are dried in a traveling grate and indurated in a rotary kiln, from which the fired pellets produced are cooled in a subsequent annular cooler. In both cases the pellets experience temperatures close to 1400ºC (Huerta et al., 2013) that will harden them up enough that they can be transported further away without compromising its quality when compared to sinter. Pellets can be classified based on the type of furnace they are destined for as this plays a major part in their physical and chemical properties. Direct reduction pellets usually have higher iron content and less gangue minerals than those produced for blast furnaces (Mourao & Researcher, 2020).

2.2.1.2. Reduction

The reduction of iron oxides is the last step of ironmaking and it turns the iron ore into molten crude iron that will then go through the steelmaking phase. The blast furnace (BF) process has dominated ironmaking over the last two centuries and as of today it is still the most common method being responsible for about 93 per cent of the world iron ore reduction (Yang et al., 2014). Nonetheless, alternative methods such as direct reduction (DR) and smelting reduction have taken off-gas they allow some energy and material savings (Harvey, 2010) and can be less damaging to the environment (Sohn & Sridhar, 2005).

- **Blast furnaces** are shaft-furnaces where the carbon monoxide resultant from coke gasification is used to reduce the iron oxides in a counter-current principle (Yang et al., 2014). Such process, where hydrogen can be also used as a reducing agent, is often referred to as indirect reduction. From the top the furnace is charged with coke, limestone (and other slag formers) and an iron burden consisting of pellets, sinter and/or lump ore. Coke is used both to obtain the reducing agent and to provide energy. Pulverised coal and pre-heated air are blown into the furnace from the bottom and react with the coke, producing carbon monoxide that moves up and reduces the iron oxides coming down. Part of the resultant carbon dioxide will react with the coal at the bottom and produce more carbon monoxide, as shown in Figure 12. The now reduced iron continues to move down and ends up melting as the ever-growing temperature approaches 2000°C at the bottom (Ghosh & Chatterjee, 2008) and surpasses its melting

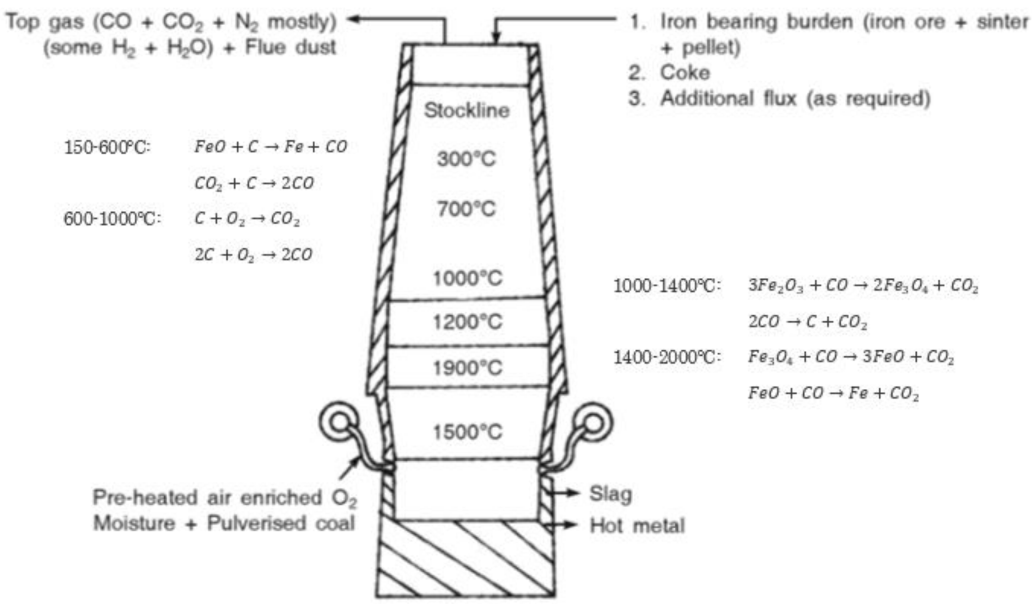
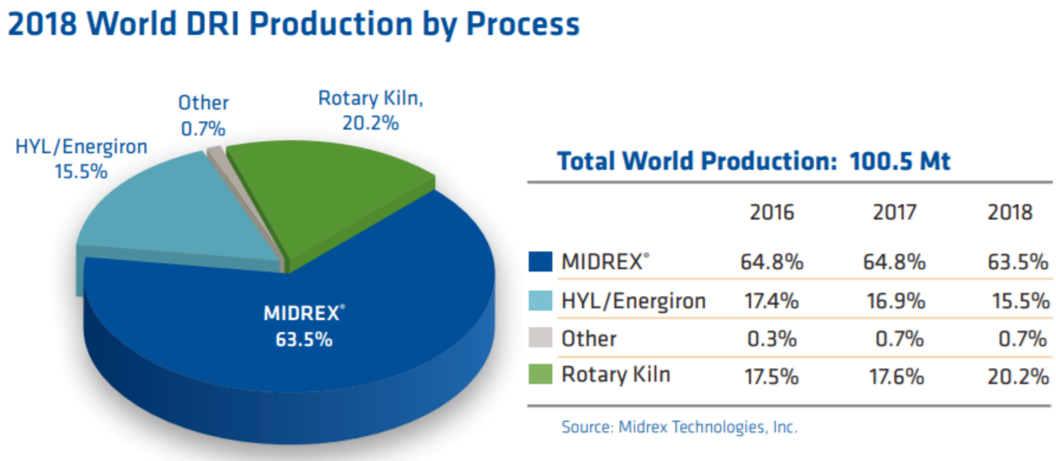


Figure 12 - Blast furnace reactions and material balance (modified from Ghosh & Chatterjee, 2008).

point (1535ºC). The molten metal is then collected through a tap hole, together with the slag that floats on top of it.

- **Direct reduction** processes turn iron oxides into solid pig iron (also known as sponge iron) through coke-free reactions without any of the materials being melted. These are two advantages when comparing DR and BF processes as they allow to reduce energy consumption and pollution. On the other hand, the absence of melting makes the removal of any impurities extremely difficult, which forces the pellets destined to direct reduction to present a lower content of gangue minerals than those used in blast furnaces (Battle et al., 2014). Lump ore and fines can also be used as iron-bearing materials. Due to its porosity the direct reduced iron (DRI) has an undesirable tendency to re-oxidize that makes it not ideal for long transports. This prompted the development of hot briquetted iron (HBI) (Tanaka, 2015), which is a compacted version of DRI. DR processes can be divided according to the reducing agent in gas and coal/oil-based, meaning the reactions will either be solid-gas or solid-solid. The former typically uses a shaft-furnace where a reformed mixture of natural gas and off-gas rich in hydrogen and carbon monoxide reduces the iron oxides in a counter-current principle. As of 2013 gas-based processes produced close to 80 per cent of world's direct reduced iron (DRI), with MIDREX® being the biggest contributor and HYL coming second (Liming Lu et al., 2015). Such dominance has continued over the years as illustrated in Figure 13.



	2016	2017	2018
MIDREX®	64.8%	64.8%	63.5%
HYL/Energiron	17.4%	16.9%	15.5%
Other	0.3%	0.7%	0.7%
Rotary Kiln	17.5%	17.6%	20.2%

Figure 13 - World DRI production by process (Midrex Technologies, 2019).

Despite being the most common shaft furnaces are not the only option, as there are processes like FINMET that operate with fluidized beds instead. One of the downsides of gas-based processes is the natural gas availability that limits its application mainly to developed countries that either produce or have easy access to it (Michishita & Tanaka, 2010). Such limitations do not apply to coal/oil-based DR processes. Hydrocarbons from coal are the most common reductant and its widely distribution and easy transportation make it a very capable alternative. The two main types of reactors used are rotary hearth furnaces and rotary kilns. Figure 13 shows that the latter, used in processes like SL/RN and Accar, is by far the most common. There, a mixture of coal, metallic charge and flux is fed at the elevated part of the kiln and reduction happens in a counter-current principle as iron oxides and hydrocarbons from coal react with oxygen from the air being blown at the bottom (Ghosh & Chatterjee, 2008). Coal-based rotary hearth furnace processes are often used to process waste material rather than producing high quality metallic iron, as the iron content of their product is not high enough to be used as feed to the electric furnaces (Battle et al., 2014) but they can easily recycle mill dust and other by-products (Kekkonen & Holappa, 2015). Even though most of the DRI is used as feed material for electric arc furnaces, it can also serve as charge both in basic oxygen furnaces and open-hearth furnaces (Sohn & Sridhar, 2005).

- **Smelting reduction** includes both a reduction and a melting process, producing hot metal from iron ore. Most of its variations do it in two separate steps. This is the case with COREX, the first commercialized application of this process (X. Zhou et al., 2015). There a pre-reduction takes place in a reduction shaft with the iron still in the solid-state. Then, the solid sponge iron is melted and the remaining oxygen is removed in a melter-gasifier vessel due to the gasification of coal. The reducing gas that exits the melter-gasifier is processed and re-injected in the reduction furnace to take part in the pre-reduction of the solid iron ore (Papst, 1989). The use of non-coking coal is economically and environmentally advantageous as coking plants are not required and emissions are negligible (Liming Lu et al., 2015). However, the use of export gas is still of the utmost importance since it allows to cover the high energy demands of this process and without it there is no feasibility (Ghosh & Chatterjee, 2008).

2.2.1.3. Refining

After crude iron is obtained comes the need to remove its carbon and impurities in order to refine it into steel. Nowadays the basic oxygen furnace and the electric arc furnace are the main ways to do it. Figure 14 shows the evolution of crude steel production by refining process over the years. Basic oxygen processes dominate by a hefty margin as they are responsible for more than two thirds of the annual steel production. Even if the trends are clear and unlikely to change it is crucial to consider lesser used alternatives whose historical importance is undeniable and largely surpasses its current utility.

- The **Bessemer** process was presented by Henry Bessemer in 1856 and was a turning point in the steelmaking industry. Large scale production was then possible and the steel production increased soon after (Holappa, 2019). It consisted in a cylindrical refractory vessel with an opening an the top and tuyeres at the bottom. The vessel would be put in a horizontal position prior to the liquid iron discharge so that it would

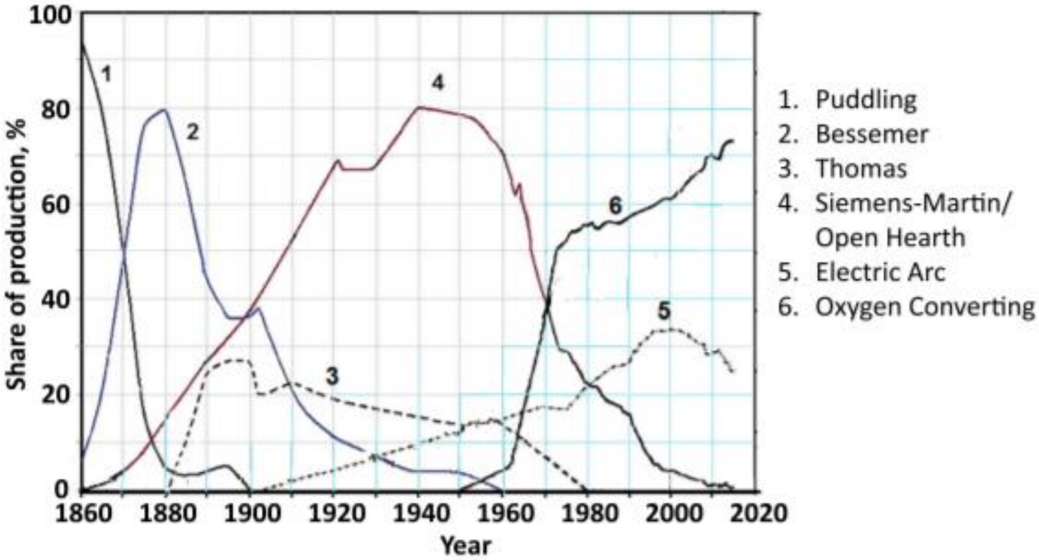


Figure 14 - Share of crude steel production by process (Holappa, 2019).

not drain through the tuyeres. As air was blown through them the vessel would go back to a vertical position since the pressure from the air injected would keep the liquid iron there. The oxygen in the air blown would then oxidate most of the impurities present in the liquid iron and produce oxides that would either be expelled to the atmosphere or form slag (Hemon, 1960). The refined liquid steel would then be tapped from the converter. Even though this allowed the removal of carbon and silicon, it could not remove sulphur and phosphorous. While these issues were later solved and led to the creation of a version of this process using a basic oxide, the same did not happen for the high levels of nitrogen and the Bessemer process ended up losing ground to the Open-hearth process later invented (Ghosh & Chatterjee, 2008). As Figure 14 highlights the amount of steel produced using the Bessemer process continued to decrease and eventually disappeared.

- **Open-hearth** processes were first used in the 1860's and remained the most used refining process for nearly a century. Open-hearth furnaces (OHF) could either be stationary or tilted, with the second allowing an easier tapping process and being the most used at the time the process disappeared (Philbrook & Bever, 1964). They consisted in shallow trays made of refractory materials with ports at both ends, doors on one of the sides and a tap hole in the other. These ports played a major role as they were alternately used as burners and escape openings. Both air and fuel gas were pre-heated and conducted to the burner side of furnace where combustion would occur to ensure that the necessary heat was produced. The combustion off-gas would then exit the furnace through the escape openings that would conduct it to the checkers where its heat would be stored. Around 20 minutes later the direction of the process would be reversed using the switching valves shown in figure 15 and the ports from each side would switch roles, with the former burner becoming an escape opening and vice-versa

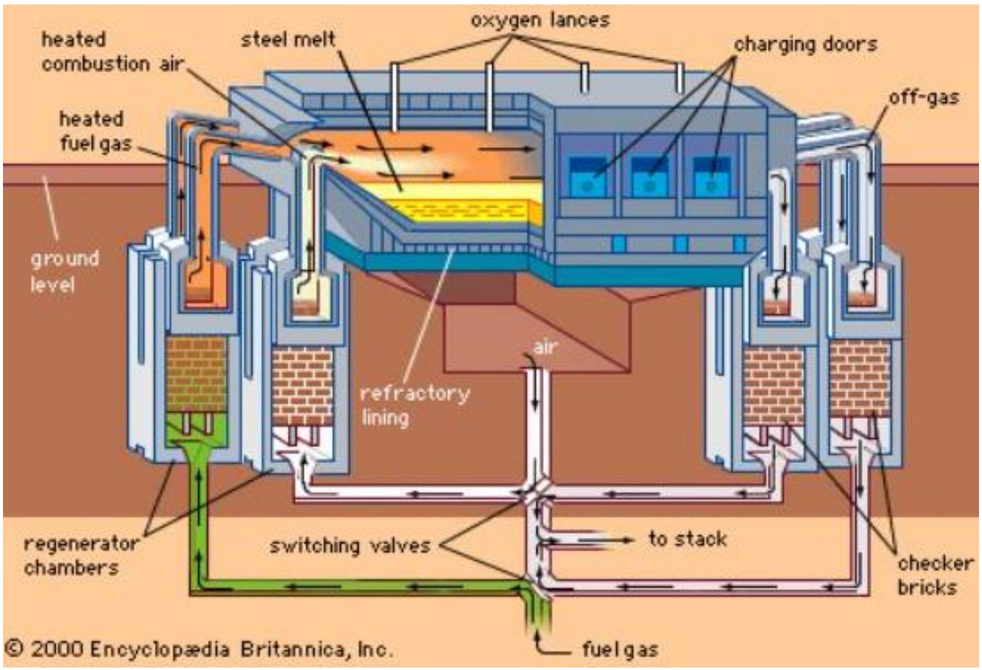


Figure 15 - Open-hearth furnace (OHF) diagram (Encycl. Br., 2000).

(Eyres & Bruce, 2012). Same happened with the regeneration system with the regenerator chambers switching roles with the checkers. The heat previously stored in the checkers would then be used in the regenerator chambers to pre-heat both the air and fuel. The oxygen needed for oxidation came from the iron itself and from atmospheric air being fed to the furnace. Charging took place through the multiple doors and these also enabled inspection and sampling. According to Ghosh & Chatterjee (2008) the ability to easily add materials through the doors and flush out slag during the process was a great advantage, since it allowed to produce steel of almost all grades. Yet, it was not enough to make up for the length of the process and its need for external fuel. Therefore, in the 1960's it started to become less common as other processes emerged and today the quantity of crude steel produced by open-hearth processes is almost zero (see figure 14).

- **Basic oxygen furnaces (BOF)** are very similar to Bessemer converter, with the refining being achieved by blowing pure oxygen through a water-cooled lance from the top into a metal bath contained in a basic lined converter (Eyres & Bruce, 2012). This made refining faster and more efficient when compared to the Bessemer process as the use of pure oxygen instead of air meant that no nitrogen would dissolve in the metal (which was one the main problems of the Bessemer process), the volume of gas that needs to be heated is smaller and the amount of heat generated is greater (De Beer et al., 1998). The idea of replacing air by pure oxygen was not new but the high cost of obtaining it and the severe wear associated with blowing it from the bottom made it an unviable option for several decades. These issues were eventually overcome as the progress achieved in the air separation made the use of pure oxygen economically attractive and

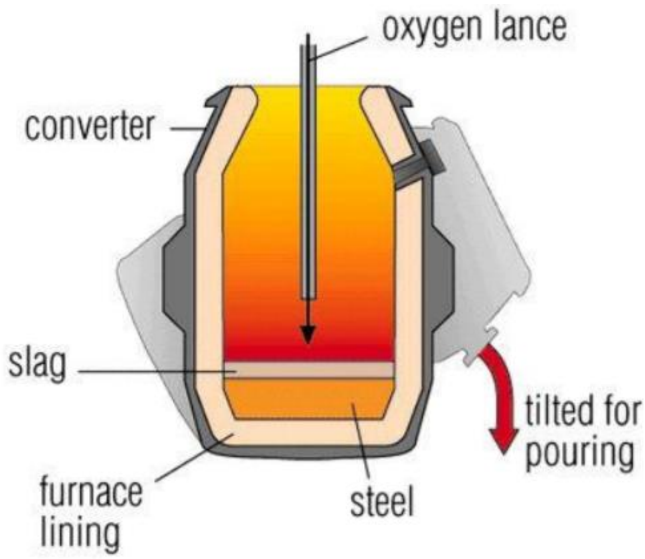


Figure 16 - Basic oxygen furnace (Kennison, 2014).

Robert Durrer's experiments with an inclined jet inspired Vöest, Austrian steel company, to come up with the first top-blown converter - commonly known as Linz-Donawitz (LD) process – in 1952 (Holappa, 2019). Since then both bottom-blown (with reinforced bottom tuyeres) and combined top and bottom-blown converters have been developed to obtain a better temperature control and more precise determination of the blowing endpoint (Ghosh & Chatterjee, 2008). These adjustments culminated in modern BOF that use up to 30 per cent of additional scrap metal and recover their off-gas, which can led them to be net energy sources (Worrell et al., 2007). This scrap is melted using the sensible heat of the molten pig iron and the heat released from the combustion of its carbon content (Jamison et al., 2016). A typical modern top-blown BOF is illustrated in figure 16. The vessel is initially tilted to one of the sides (left side in figure 16), from which is fed with scrap and hot metal through a charging port. It is then aligned with the top lance that blows the oxygen into it, with extra stirring being provided from the injection of inert gas ate the bottom (Vos et al., 2019). Meanwhile, the oxygen injection can be interrupted and the vessel rotated towards the charging side so that a sample of metal and, if needed, slag can be collected to analyse the temperature and composition. Once the oxygen injection is finally stopped the vessel is inclined to the opposite side and the steel goes through a tap hole into a ladle that will take it to the casting station. Either a pneumatic stopper or arresting devices ensure the slag does not go with the steel so that it can tapped right after through the charging port. On average, the entire process takes around 30 to 40 minutes (Ghosh & Chatterjee, 2008). Figure 14 shows that BOF processes surpassed OHF processes in the beginning of the 1970's and are now responsible for more than 70 per cent of the would annual steel production.

- In an **electric arc furnace (EAF)** the charge is melted and refined using electric current, as an electric arc is struck between it and the graphite electrodes. The charge can be 100 per cent scrap metal as the use of electrical energy means the furnace no longer needs to use crude iron for the energy of its carbon content (Jamison et al., 2016). This allows significant energy savings and emission reductions as cokemaking, agglomeration and ironmaking processes are not required. Nonetheless, mixing scrap metal with DRI or even hot metal is a common practice since it helps to produce high quality steel quality and overcome an eventual scrap shortage (Worrell et al., 2007). EAF processes appeared in the late 19th century but were only massified in the 1960's (Harvey, 2010). Their use has ramped up since then and nowadays they account for

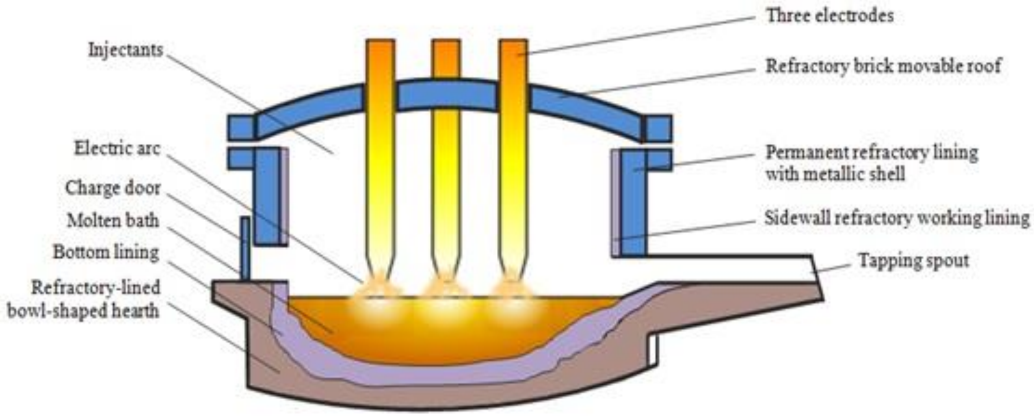


Figure 17 - Cross-section of an electric arc furnace (El-Akruti et al., 2016).

around 30 per cent of the world's total steel production (see figure 14), even though at first they were only used to produce speciality steels (De Beer et al., 1998). Figure 17 shows the cross-section of a conventional EAF. Aside from the heat source, an EAF has a similar configuration to those used in open hearth processes, as in both cases the furnace has a shallow tray shape, a roof, a front door and a tap hole (Ghosh & Chatterjee, 2008). In modern EAFs charging is carried out in several phases and the scrap is layered according to size and density to ensure a faster formation of liquid pool of steel and accelerate the initial bore-in period, the voltage is adjusted for better arc stability and damage prevention, oxygen lances and oxy-fuel burners are used to accelerate the melting process and allowing refining to take place simultaneously, deslagging operations are executed during melting and refining to prevent phosphorous reversion, carbon and lime can be injected both during the charging phase and later on, and tapping takes place at the bottom with the addition of slag-forming materials to help the process and deoxidizers to lower the oxygen content (Singh, 2020).

Further refining might take place later while the molten steel is being transported in the ladle to the caster. Ghosh & Chatterjee (2008) designate this as the secondary steelmaking process. During this stage the goal is to reduce yet again the amount of gases and other impurities and homogenize the steel. As its temperature drops during these processes the molten steel is heated again to ensure it is ready to be casted.

2.2.1.4. Shaping

In order to reach the final semi-finished or finished products, the molten steel must go through several shaping and finishing processes. These will allow it to solidify and acquire the desired shape and properties.

2.2.1.4.1. Casting

First off, there is the **casting**. After the liquid metal is poured into the ladder from the BOF or EAF, it is taken to the caster where it cools down to the solid state. The steel can be either be casted into individual ingots or continuously, with the latter being responsible for casting over 90 per cent of today's steel production (Louhenkilpi, 2014). However, this process, albeit being invented by

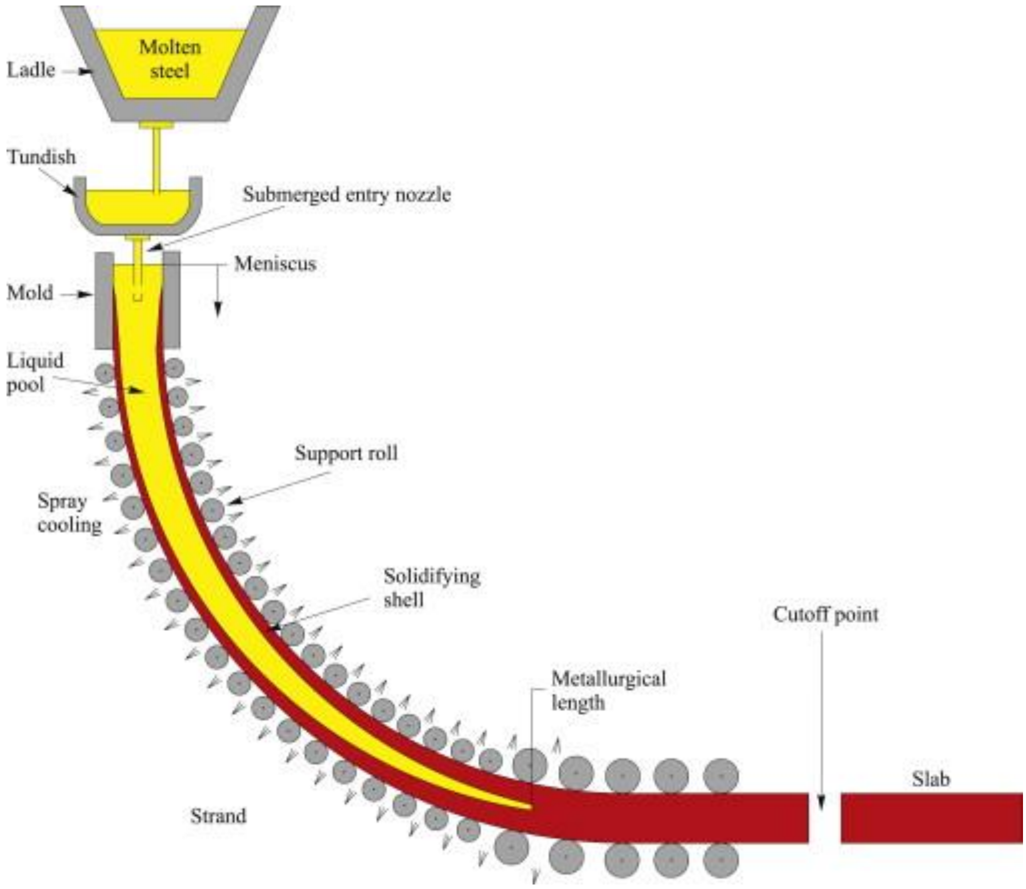


Figure 18 - Continuous casting process (Vertnik & Šarler, 2014).

Bessemer in mid-nineteenth century, only became commonly used in the steel industry around the 1960s (Ghosh & Chatterjee, 2008). Unlike with the ingot casting process, solidification happens continuously as the molten steel keeps being injected into the mold and withdrawn from it. Figure 18 illustrates a continuous casting process that cools down molten steel into solid steel slabs. The molten steel is poured from the ladle into a tundish, where gravity is used to filter the impurities and a nozzle controls the rate at which the liquid steel enters the mold. Its walls are water-cooled to ensure the solidification of the metal surface – forming a solid shell with a liquid interior – and the mold is oscillated to avoid sticking (Vynnycky, 2019). Sets of rolls ensure that steel is withdrawn from the mold at the same rate that it is being injected. As the rolls keep the strand moving down, sprays are used to cool its surface and the solidification process continues until all the liquid steel has solidified. By then the strand, now moving horizontally, is cut to produce slabs with a desired length. These will then be taken to a rolling mill.

After its implementation in the 1960s, continuous casting soon proved to be a better option than the ingot casting methods, both in terms of steel quality and energy efficiency. The latter is particularly noteworthy as the ingot stripping and reheating processes that were no longer required allowed for significant energy savings (Ghosh & Chatterjee, 2008).

The improvements regarding energy efficiency were not over and in 1989 thin slab casting was introduced (Hoen et al., 2016). Unlike with conventional continuous casting or even ingot casting methods, its products are casted close to the final shape. This near net shaping casting process diminishes the need for hot rolling processes and, consequently, reduces energy consumption (Jamison et al., 2016).

2.2.1.4.2. Rolling and Finishing

Most steel products require further processing before being sold, with rolling and finishing processes transforming them into finished steel products. These will shape and strengthen the steel.

In rolling processes the steel strip passes through a gap between two rotating rolls that simultaneously draw it and compress it to reduce its thickness (Rossomando & Filho, 2006). Depending on whether it occurs above or below the recrystallization temperature of the material the process is classified as hot or cold rolling (Woodard & Curran, Inc., 2006). In **hot rolling** processes the cast steel is heated in a preheating furnace up to the desired temperature, increasing the material's workability and ductility (Serajzadeh, 2014). As hot rolled steel cools off it tends to shrink, resulting in less precision and uneven surface. Therefore, hot rolled steel is used in when dimensional tolerances and finishing requirements are less tight, such as railroad tracks and construction projects (*Reliance Foundry*, n.d.).

When precision and finishing quality are a priority the hot rolled steel is further processed through **cold rolling**, with its thickness being reduced once again. Due to the compression of material occurring al lower temperatures this stage often includes heat treatment to prevent the it from getting excessively hard and eventually cracking (Jamison et al., 2016). Although more expensive and energy intensive, the cold rolled steel is better suited for applications where precision and aesthetics matter, not requiring much additional surface finishing (Velling, 2019).

Depending on the application of the steel products they may undergo final **finishing** processes to improve their mechanical properties. One of the most common examples is annealing, through which the steel is softened and has its internal stresses relieved. When the goal is to harden the steel the choice usually falls on quenching and tempering (Eyres & Bruce, 2012).

2.2.2. Steel production from scrap metal

According to Harvey (2010) up to 90 per cent of the energy used in steel production from iron ore is spent on the preparation and reduction of the ore. While an in-dept analysis of the energy consumption of the entire process and possible savings will be done later, the benefits of avoiding such energy intensive processes seem immediate. By using scrap metal and recycled steel instead it is possible to skip the cokemaking, agglomeration and reduction processes, and thus produce steel at a much lower energy cost and with less emissions. Furthermore, it allows for smaller production facilities and a lower initial investment (Ghosh & Chatterjee, 2008).

Once the scrap is melted it goes through the shaping processes to produce semi-finished and finished steel products, as presented in the previous section. This way a typical mini-mill differs from an integrated steel plant in the absence of any ironmaking process and the use of an EAF to remelt the scrap steel instead of a BOF that produces steel from crude iron. On the other hand, the casting and rolling procedures are common to both facilities.

Steel's recyclability is also key to this route attractiveness, as it can be entirely recycled (World Steel Association, 2016). In fact, and according to the IEA Iron and Steel Technology Roadmap from 2020, current recycling rates are around 85 per cent. They advise, however, that the constant increase of steel consumption means that scrap on its own is not enough to supress the industry's requirements (International Energy Agency., 2020a).

2.3. Energy use in steel production

Steelmaking routes are classified according to the type of raw materials used and the refining process they go through. Raw materials can either be hot metal produced from iron ore or recycled steel scrap. As mentioned is section 2.2.1.3 today's refining processes occur almost exclusively in basic oxygen furnaces (BOF) and electric arc furnaces (EAF).

Figure 14 shows that BOF are responsible for 70 to 75 per cent of today's steel production with the remain being produced almost entirely by EAF.

Even though the majority of EAF processes operate with a 100 per cent scrap steel charge, there are some plants where DRI and crude iron account for an important fraction of the charge (Yang et al., 2014). In BOF, 75 per cent of the raw materials used is hot metal and 25 per cent is steel scrap (Harvey, 2010; Yang et al., 2014).

The combination of both the type of raw materials and refining processes used shows there are two main steelmaking routes (World Steel Association, 2019):

- The **blast furnace-basic oxygen furnace (BF-BOF) route** via which 75 per cent of steel is produced and that represents the primary steel production route;
- The **electric arc furnace (EAF) route**, also considered as the secondary steel production route (it is not related with the secondary steelmaking process mentioned in section 2.2.1.3), responsible for 25 per cent of the world's steel products. This comprehends two alternatives – often complementary – that will be analysed separately: the Scrap-EAF route and the DRI-EAF route.

2.3.1. Minimums, best practice values and average intensities

Some of the most cited studies regarding energy consumption were reviewed and their energy intensity values were compared with brief comments being made to explain eventual discrepancies between them. This analysis will be broken down by process and consider some of their major steps. It starts with a hypothetical scenario where the theoretical amounts of energy required are presented and then several adjustments are made to approximate it to operating conditions.

Both Fruehan et al (2000) and (Gonzalez Hernandez et al., 2018) do not considered electricity production and therefore underestimate the primary energy intensity. Their energy intensities will still be labelled as primary, even though that is not entirely true. Aside from EAF processes this will likely not have a great impact as electricity is not a significant source of energy for the other routes.

2.3.1.1. Blast furnace ironmaking

According to De Beer et al (1998) the theoretical minimum of an iron oxides reduction process corresponds to the Gibbs free energy of the reaction. If hematite, the most common oxide, is taken as reference the theoretical minimum energy required is 6.8 GJ/(tonne of Fe). If the melting process is included this energy goes up to 8.6 GJ/t (Fruehan et al., 2000).

When the actual BF reduction process is considered the hot metal produced contains around 5 per cent of carbon which increases the **theoretical minimum** energy required to 9.8 GJ/t as there is a noteworthy amount of energy associated with its presence (Fruehan et al., 2000).

Real operating conditions require additional flux such as limestone to remove gangue minerals like SiO_2 and Al_2O_3. With the reduction and melting of these agents and the formation of slag there is a rise in the energy requirements that helps to reach a **practical minimum** of 10.4 GJ/t (Fruehan et al., 2000).

As we get closer to actual operating conditions Fruehan et al (2000) proposes that the actual energy requirements are between 13 and 14 GJ/t, whereas Gonzalez Hernandez et al (2018) states that the **average** energy requirement is 14.7 GJ/t. This same study reports the **best practice** value to be 11.6 GJ/t. Higher estimations are made by Phylipsen et al (2002) and Worrell et al (2007) with 15.5 GJ/t and 12.4 GJ/t respectively.

Primary energy intensity (GJ/t)				
	(Fruehan et al., 2000)	(Gonzalez Hernandez et al., 2018)	(Phylipsen, Blok, Worrell, et al., 2002)	(Worrell et al., 2007)
Theoretical min.	9.8	-	-	-
Practical min.	10.4	-	-	-
Best practice	-	11.6	15.5	12.4
Average	13-14	14.7	-	-

Table 1 – Energy intensities of the BF ironmaking process in GJ/t.

It is also important to note that coke production is the biggest responsible for BF's high energy intensity as single handily requires on average 8 GJ/t (Gonzalez Hernandez et al., 2018).

2.3.1.2. Direct reduction

In DR processes the iron ore is heated up only to 900°C which makes its **theoretical minimum** energy required to be less than in blast furnaces processes. According to Fruehan et al (2000) it corresponds to 8.4 GJ/t. Same study states that when the analysis simulates real operating conditions the energy requirements increase to a **practical minimum** of 9.4 GJ/t. This raise is a consequence of the carbon present in the product and the gangue minerals contained in the iron ore that result in slag formation. On the other hand, it is assumed that all the iron ore was reduced and there is no FeO in the products.

Studies from Phylipsen et al (2002) and Gonzalez Hernandez et al (2018) presented **best practice** energy requirements of 10.9 GJ/t and 11 GJ/t respectively, with the later also reporting an **average** energy consumption of 11.9 GJ/t.

By not pre-heating the scrap and using an optimal mixture of 60 per cent DRI and 40 per cent scrap Worrell et al (2007) came up with a lower best practice value of 9.2 GJ/t.

Primary energy intensity (GJ/t)				
	(Fruehan et al., 2000)	(Gonzalez Hernandez et al., 2018)	(Phylipsen, Blok, Worrell, et al., 2002)	(Worrell et al., 2007)
Theoretical min.	8.4	-	-	-
Practical min.	9.4	-	-	-
Best practice	-	11	10.9	9.2
Average	-	11.9	-	-

Table 2 - Energy intensities of the direct reduction process in GJ/t.

2.3.1.3. Basic oxygen steelmaking

The energy consumption of oxygen steelmaking processes depends heavily on the boundaries of the analysis. The process itself consumes very little energy and can even be a net source of energy as the oxidation of carbon and other impurities is exothermic and produces a considerable amount of heat that can be used in a form of gas to melt the scrap being fed to the very same furnace. According to (Harvey, 2010) this off gas can be equal to 176 percent of the energy input of process.

This is confirmed by Phylipsen et al (2002) and Worrell et al (2007) studies that showed a **best practice** value of be -0.3 GJ/t. Furthermore, Gonzalez Hernandez et al (2018) reported an even bigger energy generation of 0.4 GJ/t in the most efficient plants, even though the **average** energy consumption is 0.2 GJ/t.

On the other hand, if the primary energy behind the hot metal used in considered the process becomes quite energy intensive. Following such practice (Fruehan et al., 2000) presented a **theoretical minimum** energy consumption of 7.9 GJ/t, a **practical minimum** of 8.2 GJ/t and an actual consumption between 10.5 and 11.5 GJ/t when considering an isolated BOF.

Primary energy intensity (GJ/t)				
	(Fruehan et al., 2000)	(Gonzalez Hernandez et al., 2018)	(Phylipsen, Blok, Worrell, et al., 2002)	(Worrell et al., 2007)
Theoretical min.	7.9	-	-	-
Practical min.	8.2	-	-	-
Best practice	-	-0.4	-0.3	-0.3
Average	10.5 – 11.5	0.2	-	-

Table 3 - Energy intensities of the BOF refining process in GJ/t.

The difference between these energy intensities relies on where the energy required to produce the hot metal is considered as an input and therefore does not impact the energy intensity of the total steelmaking process.

2.3.1.4. Electric arc furnace

Unlike previous processes where electricity is barely used, in EAF processes it is the main energy source. This causes the primary energy intensities calculated without the electricity production to be substantial lower as a considerable fraction needs to be divided by the electricity efficiency, which is roughly 0.4 (Harvey, 2010; Phylipsen, Blok, Worrell, et al., 2002).

Both Fruehan et al (2000) and Gonzalez Hernandez et al (2018) did not consider electricity production and came up with **average** energy intensities of 2.1 to 2.4 GJ/t and 2.7 GJ/t respectively, with the latter reporting a 2 GJ/t consumption for optimal cases.

A **theoretical minimum** of 1.3 GJ/t and a **practical minimum** of 1.6 GJ/t were also presented by Fruehan et al (2000) that justifies the difference with the presence of impurities in the iron ore.

Phylipsen et al (2002) and Worrell et al (2007) reported higher **best practice** values as, unlike the studies mentioned before, they took into account the energy spent in fuel and electricity production. With this their reference plants achieved energy consumptions of 3.7 GJ/t and 5.5 GJ/t.

Primary energy intensity (GJ/t)				
	(Fruehan et al., 2000)	(Gonzalez Hernandez et al., 2018)	(Phylipsen, Blok, Worrell, et al., 2002)	(Worrell et al., 2007)
Theoretical min.	1.3	-	-	-
Practical min.	1.6	-	-	-
Best practice	-	2	3.7	5.5
Average	2.1 – 2.4	2.7	-	-

Table 4 - Energy intensities of the EAF refining process in GJ/t.

2.3.1.5. Steelmaking routes

The combination of isolated processes to build an entire route results in new and different energy consumptions and recovery opportunities. This means that theoretical and practical minimums of isolated processes hardly translate to integrated plants and, therefore, the analysis of entire routes was focused more on actual energy intensities.

Primary energy intensities for the **BF-BOF** route are barely affected by the energy used to produce electricity, as all the gathered values are identical. Gonzalez Hernandez et al (2018) presented a best consumption of 20.6 GJ/t while De Beer et al (1998) and Worrell et al (2007) had values of 19GJ/t and 16.3 GJ/t respectively. Such thing is due to electricity being a minor energy source in this route, as mentioned before. As will be discussed ahead, Worrell's smaller energy intensity results from the choice of an alternative casting method.

As for the average energy intensity Gonzalez Hernandez et al (2018) reported an energy intensity of 26.3 GJ/t.

Both in **DRI-EAF** and **Scrap-EAF** routes the extensive use of electricity makes the primary energy intensities that were calculated considering it considerably larger than those where that did not happen. In the first case Gonzalez Hernandez et al (2018) got a final optimal consumption of 4.2 GJ/t, whereas De Beer et al (1998) and Worrell et al (2007) presented best practice values of 18.5 GJ/t and 18.6 GJ/t respectively. Regarding the Scrap-EAF route Gonzalez Hernandez et al (2018) reported a minimum energy intensity of 2.1 GJ/t while De Beer et al (1998) and Worrell et al (2007) presented reference consumption values of 5 GJ/t and 6 GJ/t respectively.

Only Gonzalez Hernandez et al (2018) addressed the average energy intensity of both routes with 11.2 GJ/t for the DRI-EAF roue and 2.8 GJ/t for the Scrap-EAF route, showing that the energy used to produce the DRI charge increases dramatically the overall energy consumption of steel production when compared to a 100 per cent scrap-fed EAF.

Primary energy intensity (GJ/t)				
		(Gonzalez Hernandez et al., 2018)	(De Beer et al., 1998)	(Worrell et al., 2007)
BF-BOF	**Best practice**	20.5	19	16.3
	Average	26.3	-	-
DRI-EAF	**Best practice**	4.2	18.5	18.6
	Average	11.2	-	-
Scrap-EAF	**Best practice**	2.1	5	6
	Average	2.8	-	-

Table 5 - Energy intensities of each steelmaking route in GJ/t.

It must be noted that not all these studies share the same boundaries in the overall energy intensity analysis. While the primary energy intensities provided by both De Beer et al (1998) and Worrell et al (2007) include hot rolling and finishing, the ones from Gonzalez Hernandez et al (2018) do not, and therefore refer to crude steel instead of finished steel products. According to De Beer et al (1998) these processes can take from 1 GJ/t in both DRI-EAF and Scrap-EAF plants to 2.1 GJ/t in BF-BOF plants. Worrell et al (2007), on the other hand, claims that using hot rolling for bars plus cold rolling and finishing adds up to 2.4 GJ/t in both DRI-EAF and Scrap-EAF plants and 4.6 GJ/t in BF-BOF plants. By replacing casting and rolling with thin slab casting Worrell et al were able to reduce the BF-BOF best practice value, thus explaining its difference from the energy intensities presented in other studies. According to the authors this alternative method only 0.5 GJ/t.

2.3.2. Evolution of primary energy intensity

Data from a World Steel Association fact sheet from 2019 (World Steel Association, 2019) shown in Figure 19a illustrates that between 1970 and 2000 the average of the primary energy intensity around the world decreased almost 50 percent and seems to have reached a plateau since then.

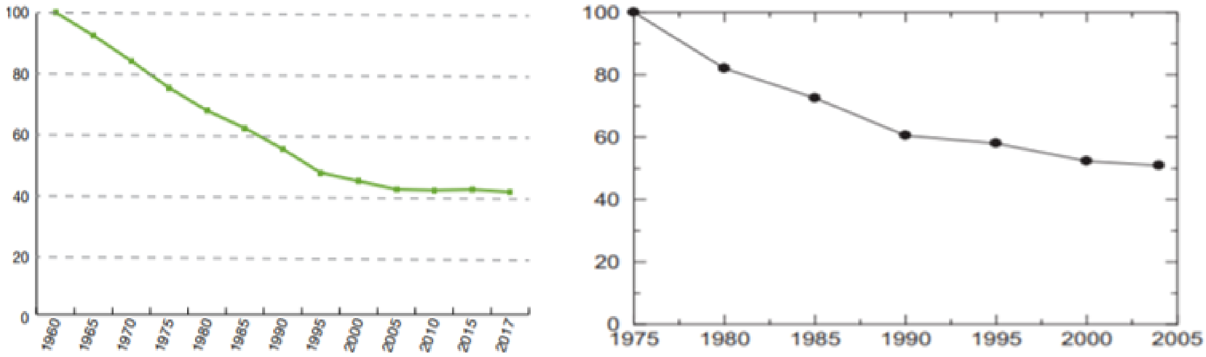


Figure 19 - Evolution of indexed global energy consumption per tonne of crude steel: a) World (World Steel Association, 2019)*; b) North America, EU and Japan (Kasai et al., 2014).*

Figure 19b shows an analysis from Kasai et al (2014) of the primary energy consumption in plants from Europe, Japan and North America that reported a very similar reduction. In both cases the evolution until the end of last century happened at a fast and almost constant pace, not showing any signs of abrupt changes.

De Beer et al (1998) highlights the replacement of OHF with BOF and the reduction of electricity and electrode consumption in EAF shown in Figure 20 as some of the major changes that led to energy savings in steel industry during this decades. Both these changes occurred gradually until the ends of the 1990's.

According to Harvey (2010) this progress in EAF did not stop in 1990, since by 2005 the energy consumption in most efficient plants had been reduced by another 50 per cent. The same did not happen with the substitution of OHF by new and more efficient technologies, which got slower since then, as illustrated in Figure 14.

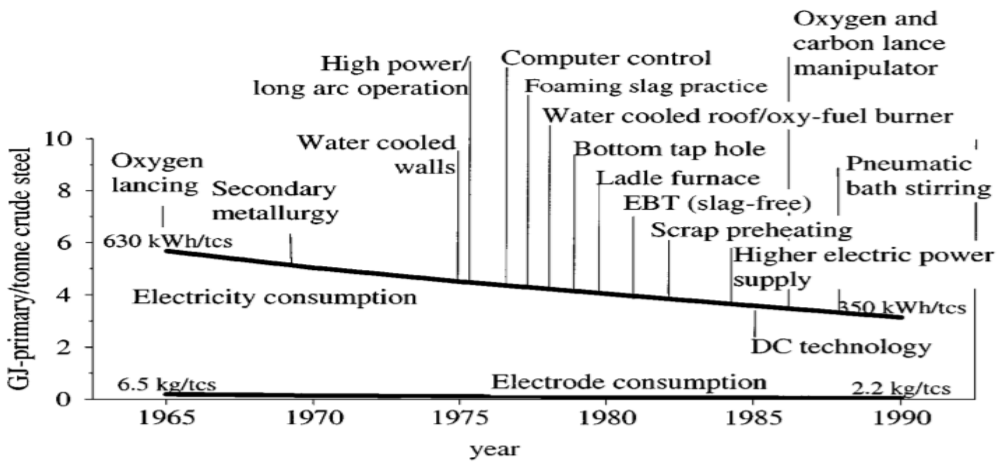


Figure 20 - Development in the energy use of electric arc furnaces (De Beer et al., 1998).

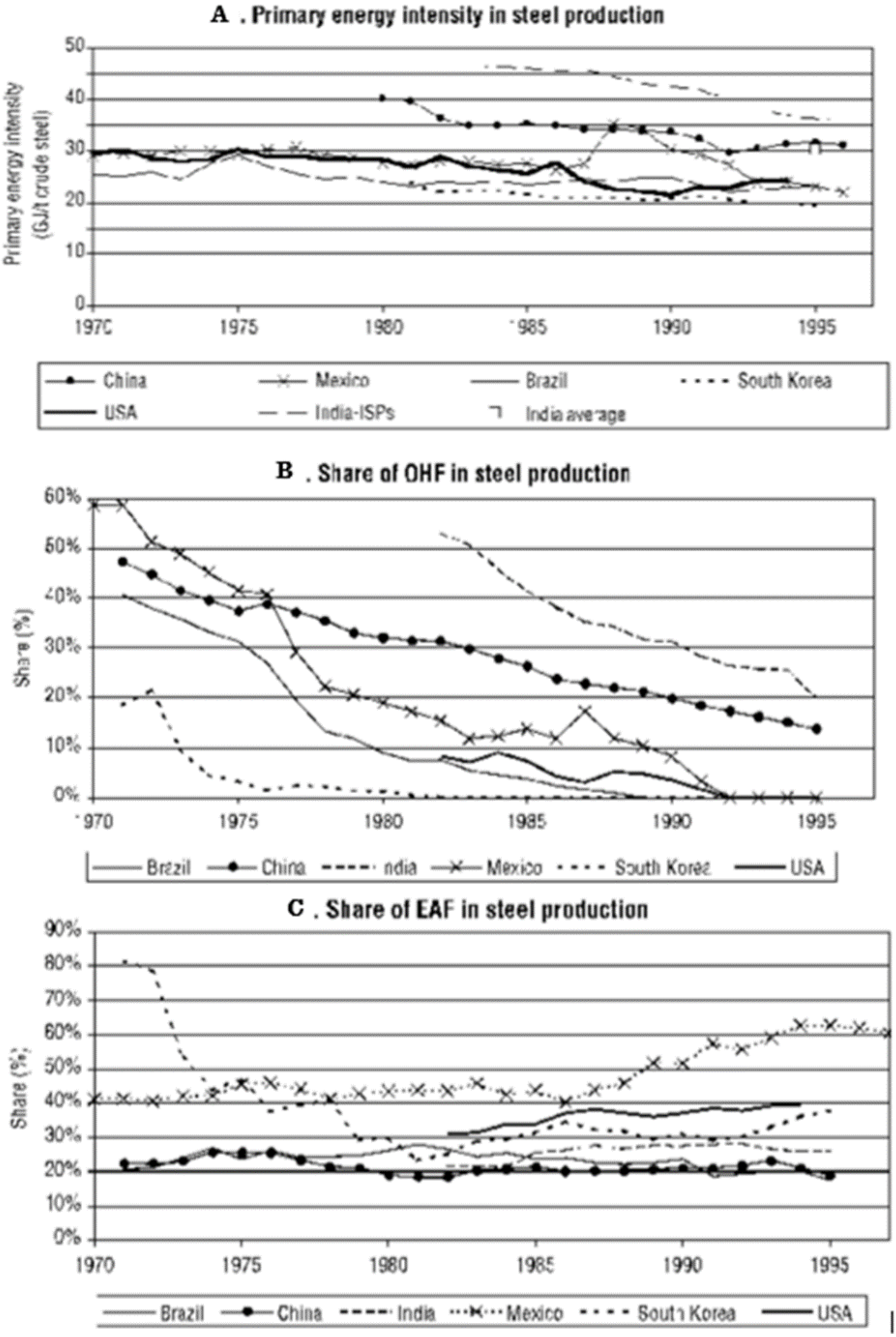


Figure 21 - Evolution of a) primary energy intensity, b) share of open-hearth furnaces and c) electric arc furnaces in steel production (modified from Phylipsen, Blok, & Bode, 2002).

The combination of these two trends and the rate at which they happened at different times explains the significant reduction in the primary energy intensity of steel production between 1970 and 1990 and its deceleration since then.

When the analysis focus on specific countries or regions it becomes obvious that this evolution did take place in the same way and at the same time everywhere. In countries like United States and South Korea steel production was not that inefficient to begin with, making the room of improvement smaller. According to Worrell et al (2001) the primary energy intensity of steelmaking in the United States dropped only 27 per cent from 35.6 GJ/t in 1958 to 25.9 GJ/t, which is far less than the world average of nearly 50 per cent.

This is corroborated by Phylipsen, Blok, & Bode (2002) in an article from 2002 where they compared the industrial energy efficiency in the United States with major developing countries. The comparison regarding the primary energy intensity is presented in Figure 21, alongside with the share of OHF and EAF in steel production. Figure 21a shows that in countries like China and India the energy efficiency was considerably lower and only by the end of the 20th century they came close to the primary energy intensities the United States had in 1970. From Figures 21b and 21c it is clear this delay was a consequence of the energy saving changes occurring much later in these countries. In 1995 both China and India still produced a significant share of their steel using OHF and the increase of production through EAF since 1970 was almost zero, explaining why their primary energy intensity was still above 30 GJ/t.

With the evolution of indexed energy efficiency of steelmaking covered it is useful to know what the actual values of the primary energy intensity were over the years and where is stands right now.

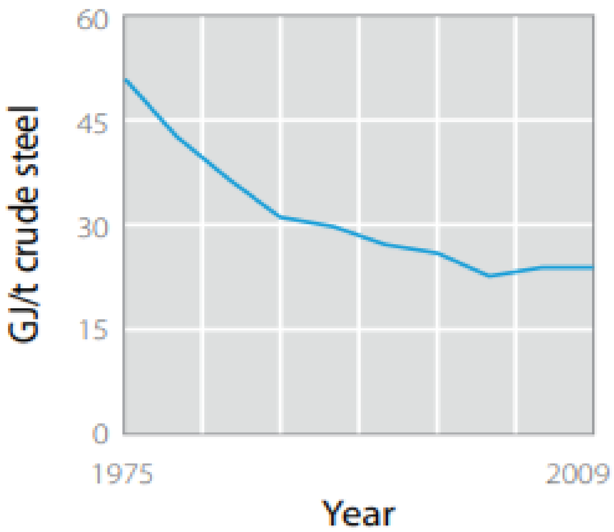


Figure 22 - Evolution of primary energy intensity of steel production (Allwood & Cullen, 2012).

In the book *Sustainable Materials: with both eyes open* from 2012 (Allwood & Cullen, 2012), Julian Allwood and Jonathan Cullen presented the graph shown in Figure 22. By putting together data from multiple sources and interpolating the missing values they were able to establish an evolution of the primary energy intensity in steel production from 1975 to 2009. It shows that between 1975 and the late 1990's the primary energy intensity decreased around 50 per cent from a little over 50 GJ/t to nearly 25 GJ/t and that it stalled since then.

The evolution of primary energy intensity presented in Figure 23 confirms this situation. The graph was put together from an IEA chart with data from 2000 to 2018. The energy intensity is shown to have stayed in the 20 to 22 GJ/t range for most of the time, with the 20 GJ/t barrier only being truly broken very recently.

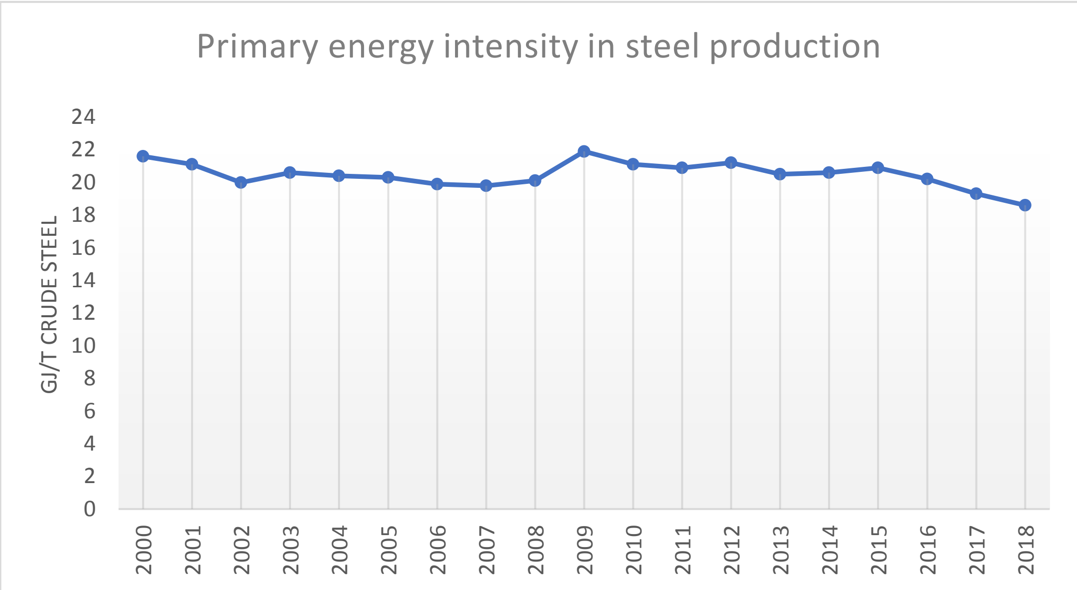


Figure 23 - Evolution of primary energy intensity of steel production (modified from IEA, 2020).

2.3.3. Evolution of the energy sources used

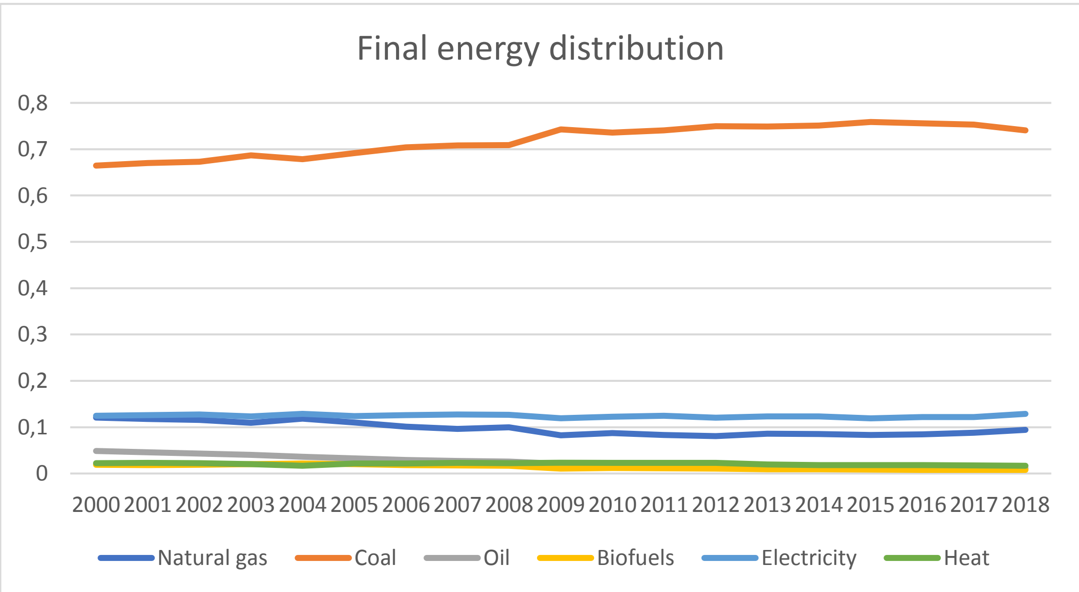


Figure 24 – Distribution of final energy consumption by energy source (modified from IEA, n.d.-b).

As a result of this stagnation, more precisely of the absence of new technologies or steelmaking processes behind it, the distribution of the final energy consumed by the industry per energy source as remained the same over the last 20 years. The data from the IEA presented in figure 24 shows that coal, which has been by far the most used energy source, had its share slightly increase from around 66 to 74 per cent. On the other side, oil went from representing nearly 5 per cent of the total final energy consumption to a little above 1 per cent. After coal, natural gas and electricity have been the main energy sources. In 2000 natural gas represented 12 per cent and electricity represented 12,5 per cent of final energy consumed. By 2018 these shares had changed to 9,4 and 12,9 per cent, respectively. Both biofuels' and heat's share have been varying between 1 and 2 per cent during this period.

2.3.4. Future scenarios

According to the IEA the distribution of crude steel production by route will change noticeably until 2050, regardless of the scenario. In the STEPS scenario, introduced in section 2.1.4.1, the BF-BOF route is responsible for only 52 per cent of the total production by then, which represents a big decrease from the 70 per cent registered in 2019. Moving on the opposite direction are the Scrap-EAF and DRI-EAF routes, as their shares grow from 22 to 36 per cent and from 7 to 11 per cent, respectively. In an alternative and far less conservative scenario, the IEA expects the BF-BOF' share to be further reduced to 30 per cent due to the surge of new routes equipped with breakthrough technology that drastically reduces CO_2 emissions (IEA, 2020b), some of which will be discussed in section 2.4.3.2.

The increase of production using EAFs is related to the large growth of scrap availability projected for the coming years. The World Steel Association predicts that by 2050 the scrap

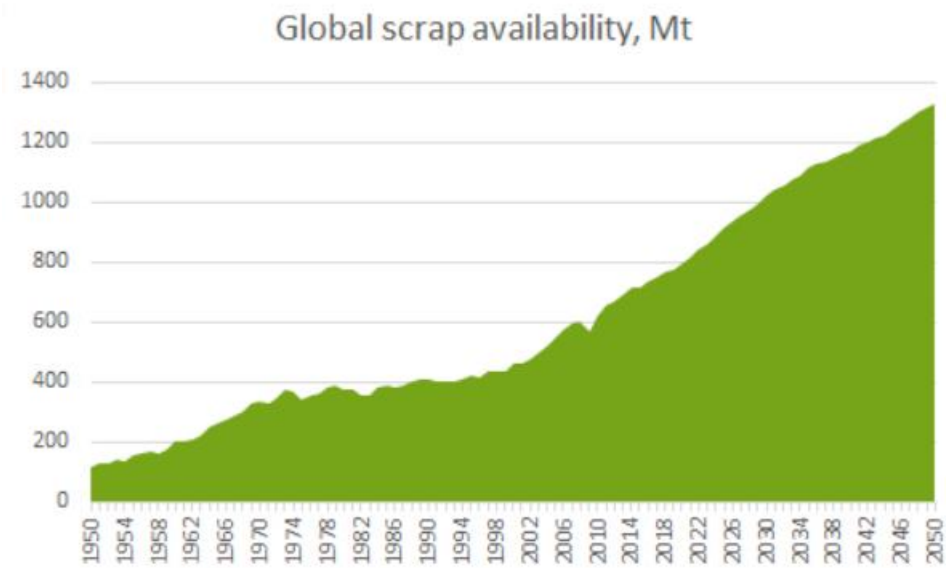


Figure 25 – Global scrap availability (modified from Çiftçi, 2018).

consumed will account for 50 per cent of the annual crude steel production, instead of the current 33 per cent (Çiftçi, 2018). This increase, shown in figure 25, is largely due to the expected scrap availability resulting from China's production increase over the last decades (World Steel Association, 2021g). Moreover, the vast majority of its furnaces will need to be replaced before 2050, thus creating a big opportunity to replace conventional integrated steel plants with mini mills or other alternative and more environmental-friendly routes. Figure 26 displays the installed capacity of blast and DRI furnaces by age. China's recent boom heavily contributed for the current world average age of 13 years (International Energy Agency., 2020a).

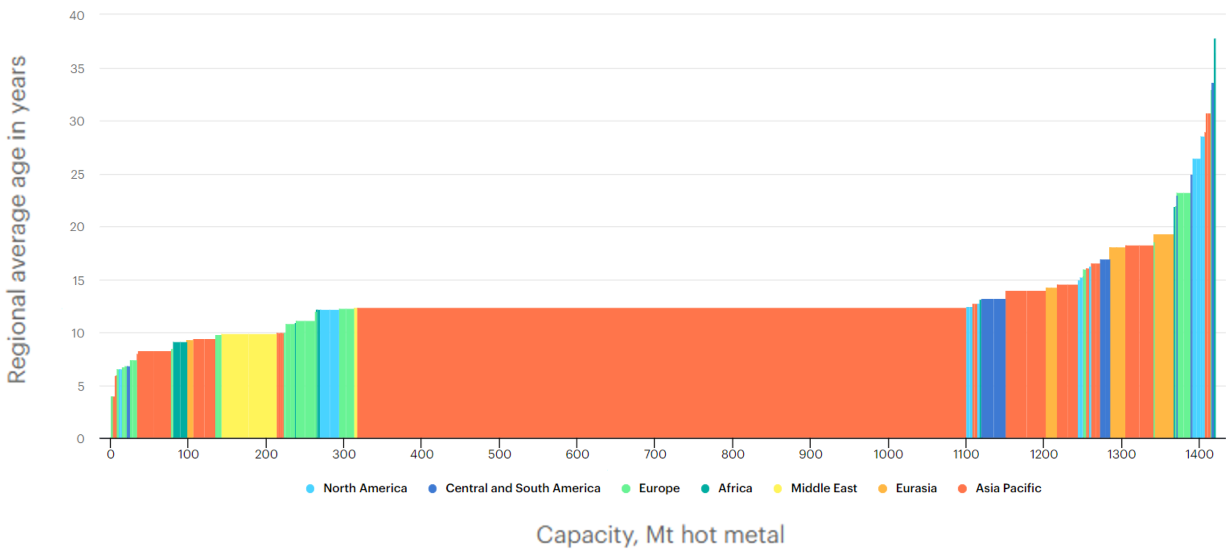


Figure 26 - Age profile of global production capacity for the steel sector (blast furnaces and DRI furnaces) (modified from IEA, 2020a).

2.4. CO_2 emissions in steel production

Environmental concerns have been a major driving factor of the iron and steel industry's evolution over the last years, as the realization of its importance becomes unavoidable. One the main takeaways is the need to reduce CO_2 emission across all sectors and the iron and steel industry is no different, with it playing a big role in pushing for the introduction of new technologies and prioritization of environmental friendlier routes. Therefore, it is mandatory to take such concerns into account when analysing the evolution of the industry and forecasting its future.

In this section the CO_2 emissions of steel production will be analysed, presenting first the processes responsible for the largest amount of CO_2 emitted and then discussing steel production's current CO_2 intensity and its evolution over the years. This section ends with the presentation of breakthrough technologies that can contribute to make iron and steel industry more environmentally friendly, some of which will be later used to project its future.

2.4.1. Largest contributors

Most of the CO_2 emitted during steel production comes from the combustion of off-gases that are recovered and used as fuel in the same process or in other stages of steel production, especially coke oven gas and blast furnace gas (IPCC, 2006). Coke oven gas is a by-product of the production of coke in the coke ovens and if often burned to heat them. Furthermore, it can also be used in sinter production and blast furnaces as an energy source. Blast furnace gas is produced during the combustion of coke in blast furnaces and, just like coke oven gas, it can be used to fuel its own process or other processes like sinter and coke production.

It is not surprise that the iron making, coke production and sinter production are the most CO_2 emission intensive ones. Table 6 lists the emission factors presented by the IPCC in the Best Available Techniques Reference Document on the Production of Iron and Steel from 2001 (IPCC, 2001) from the main processes of the iron and steel industry. They are the average CO_2 of several European plants and are the standard values used by the IPCC (IPCC, 2006).

Process	Emission factor (tonnes of CO_2 per tonne of product)	Source
Sinter production	0.188 – 0.220	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 4.1, Page 29
Pellet production	0.016 – 0.032	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 5.1, Page 95
Coke production	0.520 – 0.594	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 6.2, Page 122
Iron making (all emissions)	0.871 – 2.000	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 7.3, Page 186
Iron making (only direct emissions)	0.298 – 0.532	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 7.1, Page 183
DRI production	0.70	IPPC Best Available Techniques Reference Document on the Production of Iron and Steel from 2001, Table 10.1, Page 322 and 2006 IPCC Guidelines for National GHG Inventories, Vol.3, Chapter 4, Table 4.1, Page 25

Table 6 - CO_2 emission factors of the main iron production processes.

The production of pig iron in blast furnaces emits the most CO_2 with 0.871 to 2 tonnes per tonne of pig iron produced, assuming all the blast furnace gas produced is burned. If only the direct emissions are considered its emission factor comes down to 0.298 to 0.532 tonnes of CO_2 per tonne of pig iron produced. DRI and coke production are other two large contributors with emission factors of 0.7 and 0.520 to 0.594 tonnes of CO_2 per tonne of product, respectively. Ore preparation processes have very different CO_2 intensities as the sinter production's emission factor of 0.188 to 0.220 tonnes of CO_2 per tonne of sinter is much higher than the pellet production's of 0.016 to 0.032 tonnes of CO_2 per tonne of pellet.

Among the steelmaking processes the EAF emits by far the smallest amount of CO_2 as carbon does not play as big a role as it does in both the OHF and BOF processes. This is shown by the average emission factor values taken from the 2006 IPCC Guidelines for National Greenhouses Gas Inventories presented in table 7. It states that the EAF process emits only 0.08 tonnes of CO_2 per tonne of steel produced, while the OHF and BOF emit 1.72 and 1.46 tonnes, respectively.

Method	Emission factor (tonnes of CO_2 per tonne of steel)	Source
OHF	1.72	2006 IPCC Guidelines for National GHG Inventories, Vol.3, Chapter 4, Table 4.1, Page 25
BOF	1.46	
EAF	0.08	

Table 7 - CO_2 emission factors of the main steelmaking methods.

BF-BOF's dependence of carbonaceous materials makes it much more CO_2 intensive than the Scrap - EAF route. This is corroborated by the data shown in table 8 that was taken from the IEA Iron and Steel Technology Roadmap from 2020. It claims that the BF-BOF and Scrap-EAF routes have emission factors of 2.2 and 0.3 tonnes of CO_2 per tonne of steel produced, respectively. If the EAF route changes from scrap to DRI base it comes up to 1.4 tonnes of CO_2 per tonne of steel produced, as the production of DRI alone is responsible for a large amount of CO_2 emissions.

Route	Emission factor (tonnes of CO_2 per tonne of steel)	Source
BF - BOF	2.2	IEA Iron and Steel Technology Roadmap from 2020, Box 1.3, Page 43
DRI - EAF	1.4	
Scrap - EAF	0.3	

Table 8 - CO_2 emission factors of the main steelmaking routes.

It is important to point that according to Mathiesen & Mœstad (2004) the emission related to the transportation of fuels and other materials only accounts for 0.14 tonnes of CO_2 per tonne of steel produced, which is well under the amount of CO_2 emitted at a conventional integrated steel plant.

2.4.2. Evolution of CO_2 intensity

Figure 27 was taken from an article recently published in *Nature Communications*, in which Wang et al (2021) analyse the evolution of the iron and steel industry's GHG intensity since 1900. It shows that the tonnes of CO_2 emitted per tonne for steel produced have been cut down almost to half since 1970. However, this reduction occurred until mid to late 1990's and the industry's CO_2 intensity has remained nearly the same ever since.

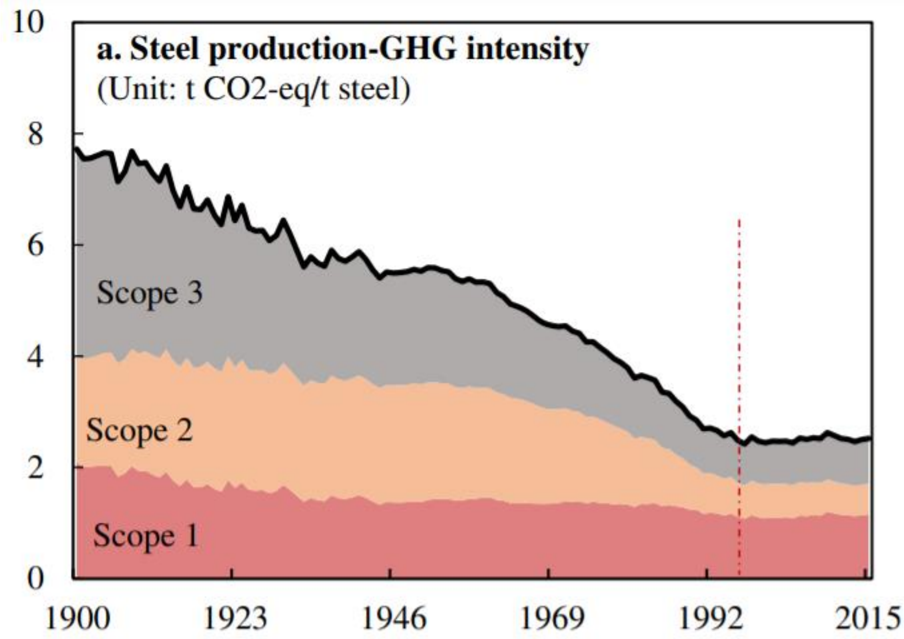


Figure 27 - Evolution of steel production GHG intensity. Scopes 1, 2, and 3 correspond to the total, primary and secondary production routes respectively (modified from Wang et al., 2021).

It is very similar to what was observed in the evolution of the industry's energy intensity over the last 20 to 25 years (section 2.3.2), as the increase in the share of steel production from EAF's stopped and the main production routes came closer to their efficiency limits. This resemblance is illustrated in figure 28, where the evolution of the European Union's steel production CO_2 and energy intensities are compared. The European Union's CO_2 intensity shows a similar evolution to the world's one shown in figure 27, despite presenting a smaller reduction. In both situations all that reduction happened before 2000 and has remained nearly the same since then. The European Union's steel production energy intensity displays the exact same evolution pattern.

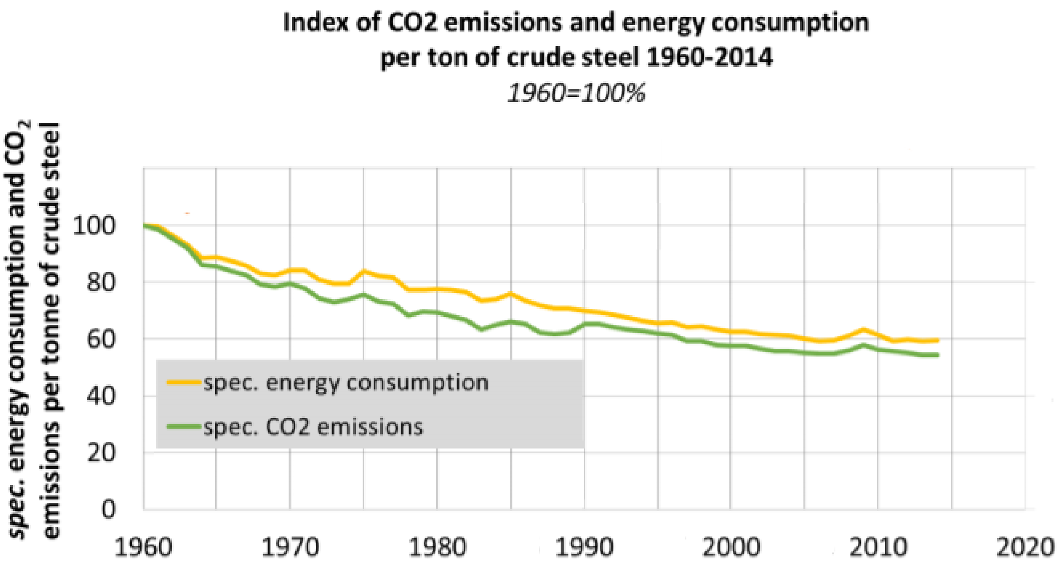


Figure 28 - Evolution of energy and CO_2 intensity of steel production (modified from European Commission, 2018).

This stagnation is backed up by the data presented by the World Steel Association in the Sustainable indicator 2020 report that is displayed in figure 29. It shows that between 2007 and 2019 the iron and steel industry's CO_2 intensity as always been around 1.8 tonnes of CO_2 per tonne of crude steel produced, with its minimum being 1.75 tonnes in 2012 and its maximum being 1.87 tonnes in 2015 and 2016. Furthermore, and according to Kundak et al (2009), the CO_2 intensity of steel production was already around 1.8 tonnes of CO_2 per tonne of crude steel produced in 1994, thus corroborating once again the stagnation over the last 20 to 25 years.

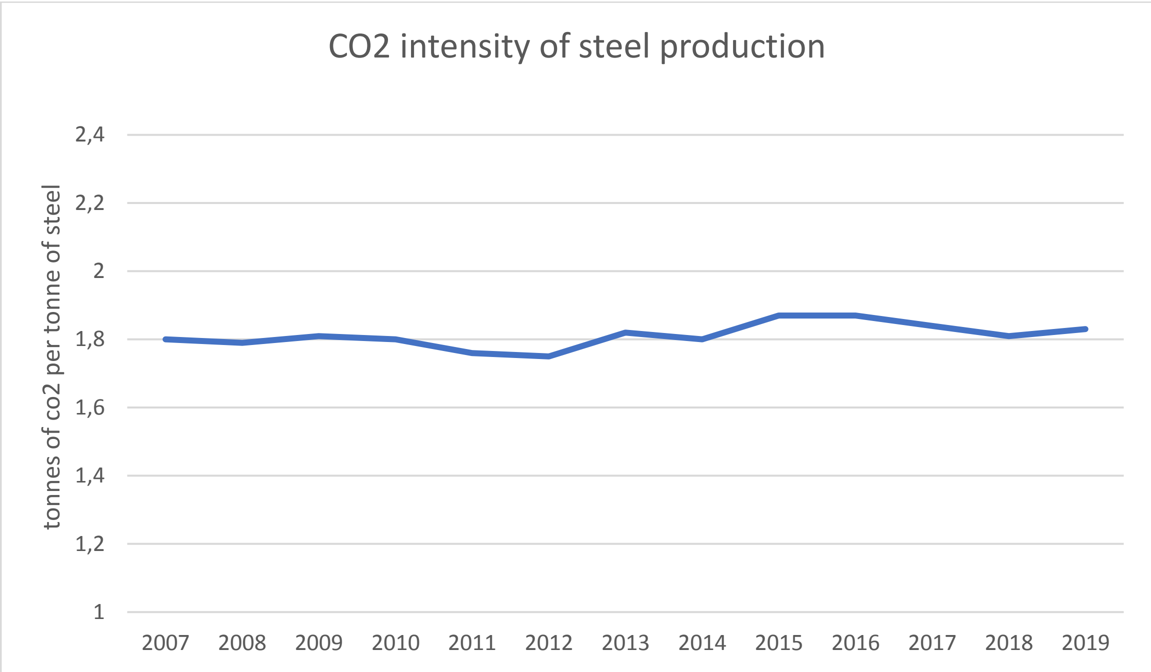


Figure 29 - Evolution of CO_2 intensity of steel production (modified from World Steel Association, 2020b).

2.4.3. Future scenarios

Decarbonizing steel is an undeniable necessity and a goal shared by most countries, driving top steelmakers to double down on their efforts to develop and implement groundbreaking technologies. However, there is no clear-cut strategy to be followed and this challenge can and should be tackled from different angles according to the intricacies of each situation.

2.4.3.1. Long-term goals

IPCC's reports on emissions reduction targeted 2050 and 2070 as the deadlines to reach net zero emissions to limit global warming to 1.5 and 2ºC, respectively. These would require CO_2

emissions in 2030 to be already 45 and 25% smaller than they were in 2010 (IPCC, 2018). Considering that steel production is expected to continue increasing, albeit at a slower rate, its CO_2 intensity would have to be reduced even more. The IEA states that in order to keep in track to meet the climate goals the iron and steel industry's emissions must decrease at least 50% by 2050 (International Energy Agency., 2020a).

2.4.3.2. Strategies

Reducing CO_2 does not always require implementing new technologies and changing the processes currently used. In fact, according to Holappa (2020), the CO_2 intensity of steel production could be reduced by 15 to 20 per cent by updating integrated and EAF plants with the **best available technologies** and closing outdated facilities.

Further reductions can be achieved through the adoption of several **technology modifications** to the already existing steelmaking processes that would improve energy and CO_2 intensity beyond the state-of-the-art, some of which have already been implemented worldwide (European Commission, 2018). These include coke dry quenching (CDQ), top-pressure recovery turbines (TRTs), top gas recycling in oxygen blast furnace (TGR-OBF), heat recovery from slags, among others, and have been the focus of initiatives like the Ultra-Low CO_2 Steelmaking (ULCOS) in Europe and the COURSE 50 in Japan (International Energy Agency., 2020a). If added to an across-the-board adoption of the best available technologies their implementation could cut down CO_2 intensity by 40 to 50 per cent, reducing it to around 1 tonne of CO_2 per tonne of steel (Holappa, 2020).

Another pivotal step in reducing CO_2 emissions is **increasing the share of scrap steel** and, consequently, reducing the dependence on iron ore. It would allow for a bigger share of EAF production, whose carbon emissions are much less than those of the conventional plants' ones. In section 2.4.1 it was presented that the average CO_2 intensities of the BF-BOF and scrap based EAF routes are 2.2 and 0.3 tonnes of CO_2 per tonne of steel respectively, granting that even a slight increase in the share of EAF production would have an immediate and meaningful impact on the industry's CO_2 intensity. According to the World Steel Association scrap consumption will increase from 30 to 50 per cent until 2050, as it was already discussed in section 2.3.4.

The share of electricity use would increase likewise and so would the demand for **electricity decarbonization**. In 2017 its world average CO_2 intensity was 484 gCO_2/kWh, with China and India, the two biggest steel producers, standing way above it with 620 and 723 gCO_2/kWh respectively. On the contrary, the European Union and the United States averaged 282 and 420 gCO_2/kWh (IEA, n.d.-a). This shows that just by reducing China's and India's electricity CO_2 intensity to the levels of most western countries its world average would decrease noticeably and so would the steel production CO_2 intensity.

While these strategies can certainly help reducing the industry's CO_2 emissions they are not enough to put the sector in line with the carbon neutrality goals. That is only possible if the industry moves away from the conventional carbon-based processes, adopting processes that are either carbon-free or use small amounts of it. Such drastic changes require the development and implementation of **breakthrough technologies** that allow for alternative steel production methods.

2.4.3.2.1. Breakthrough technologies

Near-zero emission technologies can be divided in "CO_2 management" and "CO_2 direct avoidance" technologies. The first still use carbon as the reducing agent but mitigate its associated CO_2 emissions, while the second ones reduce CO_2 emissions by using little to no carbon at all (International Energy Agency., 2020a).

The mitigation of CO_2 emissions can be done using **Carbon Capture and Storage (CCS)** or **Carbon Capture and Utilisation (CCU)** technologies (or a combination of both, CCUS), which use capture systems to collect the CO_2 emitted and pipelines to transport it to the storage sites in CCS or facilities where it will be utilised in CCU (World Steel Association, 2020b). Carbon storage, which usually takes place in geological formations such as aquifers and empty oil and gas wells, has been successfully implemented at a commercial scale in a gas-based DRI plant in the United Arab Emirates, where it is expected to capture 0.8 million tonnes of CO_2 per year (World Steel Association, 2021a). In CCU the CO_2 captured is often used to produce bio-oils, plastics, chemicals and fuels that will be later used, thus reducing the net CO_2 emissions. A large-scale facility is being constructed by ArcellorMittal in Belgium and is expected to produce 80 million litres of ethanol per year (World Steel Association, 2021b). Altogether, and according to the IEA, CCS and CCU technologies could potentially reduce 6 per cent of the total direct emissions between 2020 and 2050 (International Energy Agency., 2020a).

Despite their undeniable potential to reduce emissions, "CO_2 management" technologies should play a transitional role in the decarbonisation of steel production and be seen as temporary mitigation methods, as the storage capacity of empty wells is limited and can aggravate the use of fossil fuels (Holappa, 2020) and the CO_2 used to produce fuels usually ends up being released anyway (International Energy Agency., 2020a).

Two of the main CO_2 direct avoidance" technologies are the use of **hydrogen** and **electrolysis** to directly reduce iron ore. Unlike conventional reduction processes, they do not produce any CO_2, as all their emissions are indirect and due to the CO_2 intensity of the generation o the electricity used in them (World Steel Association, 2021b). From the two, the use of hydrogen is the one that is a later development stage, with several plants already exploring it (World Steel Association, 2021e).

3. Methodology

3.1. System boundaries

Most of the previous work, including some of the studies mentioned in sections 2.3.1 and 2.3.2, analyses the steelmaking process under the "crude steel boundary" (International Energy Agency., 2020a). This designation comprises all the processes iron ore (or steel scrap) goes through until the formation of crude steel, which, according to the World Steel Association, corresponds to the "steel in the first solid state after melting, suitable for further processing or for sale" (World Steel Association, n.d.-a). The Indian Ministry of Steel clarifies that it includes ingots in conventional mills and semi-finished products in modern mills with continuous casting (India, n.d.), meaning that finishing and some semi-finishing processes are excluded from those analysis.

This work, however, uses a cradle to gate boundary, thus including every process that iron ore and steel scrap go thought until they leave the steel mills. Therefore, the final product being analysed are semi-finished and finished steel products instead of crude steel.

The difference between these two – highlighted in figure 30 – can vary a lot from mill to mill depending on its production goals, but often consists in the hot rolling and finishing processes. Figure 30 serves the sole purpose of showing the processes included in each analysis and, therefore, only the main material flows (outputs) are represented. A detailed version with all the energy and material flows considered in the analysis performed is shown in section 3.3.

Due to data availability and historical importance this analysis is focused on the BF-OHF and BF-BOF primary steelmaking routes and the Scrap-EAF secondary steelmaking route.

3.2. Share of annual crude steel production by process

All the data regarding the world's annual crude steel production and its distribution by process was taken from a Word Steel Association file given by Sofia Henriques. It displayed the tons of crude steel produced by each refining process as well as the total production until 2017.

This data was used to illustrate how the share of each refining process in steel production has changed over the years.

Despite referring to crude steel production any conclusions drawn from this data can be applied to the production of semi-finished and finished steel products, since the conversion ratio from crude steel to those – carefully explained in section 3.5.1 – is assumed to be the same across all steelmaking routes.

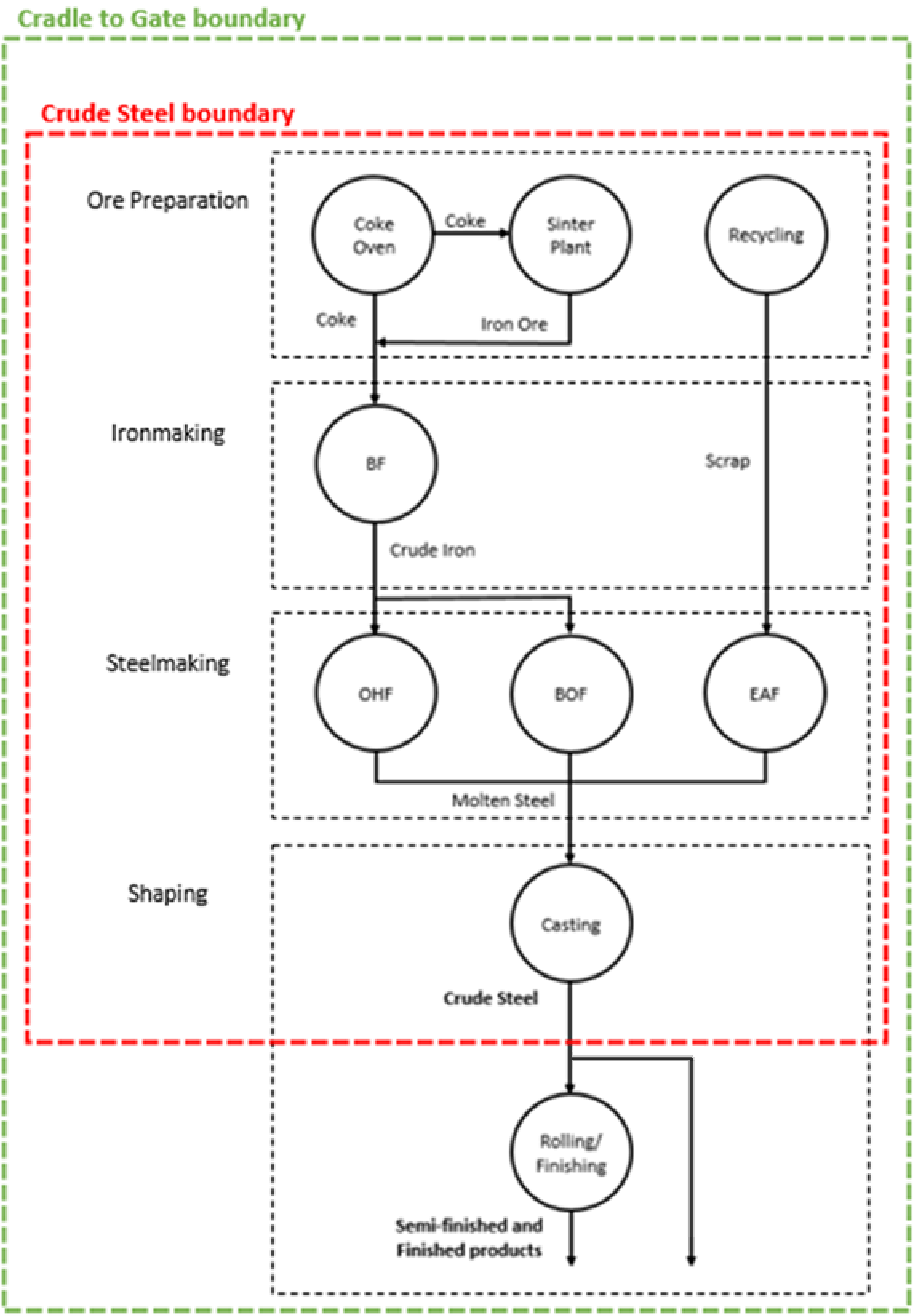


Figure 30 - System boundaries.

3.3. Energy intensity

The analysis of energy intensity was broken down in two levels:

- **Final energy intensity**: final energy consumption per tonne of finished steel;
- **Primary energy intensity**: primary energy consumption per tonne of finished steel;

Figure 31 illustrates the difference between these energy consumptions. The final energy consumption corresponds only to the energy consumed onsite, and therefore the energy required to produce electricity or any of the other fuels is not considered. Primary energy consumption, on the hand, considers both the energy consumed onsite and the energy that was used to produce the secondary energy sources, which requires analysing the transformation process responsible for each of them.

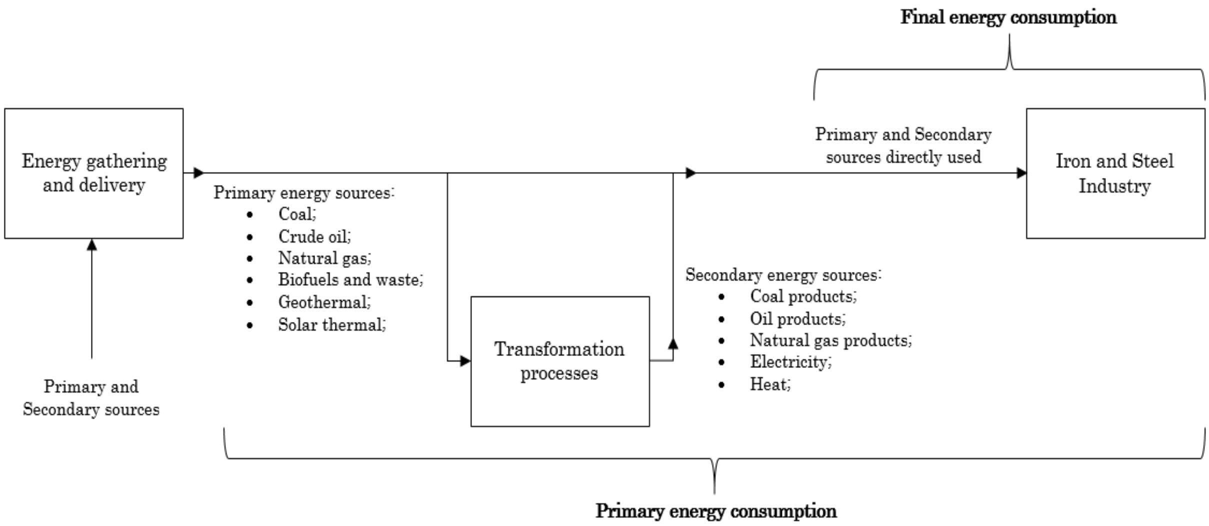


Figure 31 - Energy consumption route.

It must be noted that the iron and steel industry energy consumption goes beyond the electricity and fuels used, as energy produced in processes such as cokemaking and reduction can be recycled and used somewhere else. These trades, whose implications are discussed in section 3.3.2.1, are illustrated in Figure 32. This diagram maps the main energy and material flows – divided according to their nature and origin – for the BF-OHF, BF-BOF and Scrap-EAF routes. The primary and secondary sources directly used in steelmaking were put together since the transformation processes involved in the production of the latter – which will be considered when calculating the primary energy consumption – occur offsite. Even though the diagram only shows on-site power plants, the offsite electricity production, and respective transmission and distribution losses, are included in the analysis. The "EoL Scrap" shown in the diagram corresponds to the scrap obtained from end-of-life products, despite the manufacturing and consumption stages not being represented here.

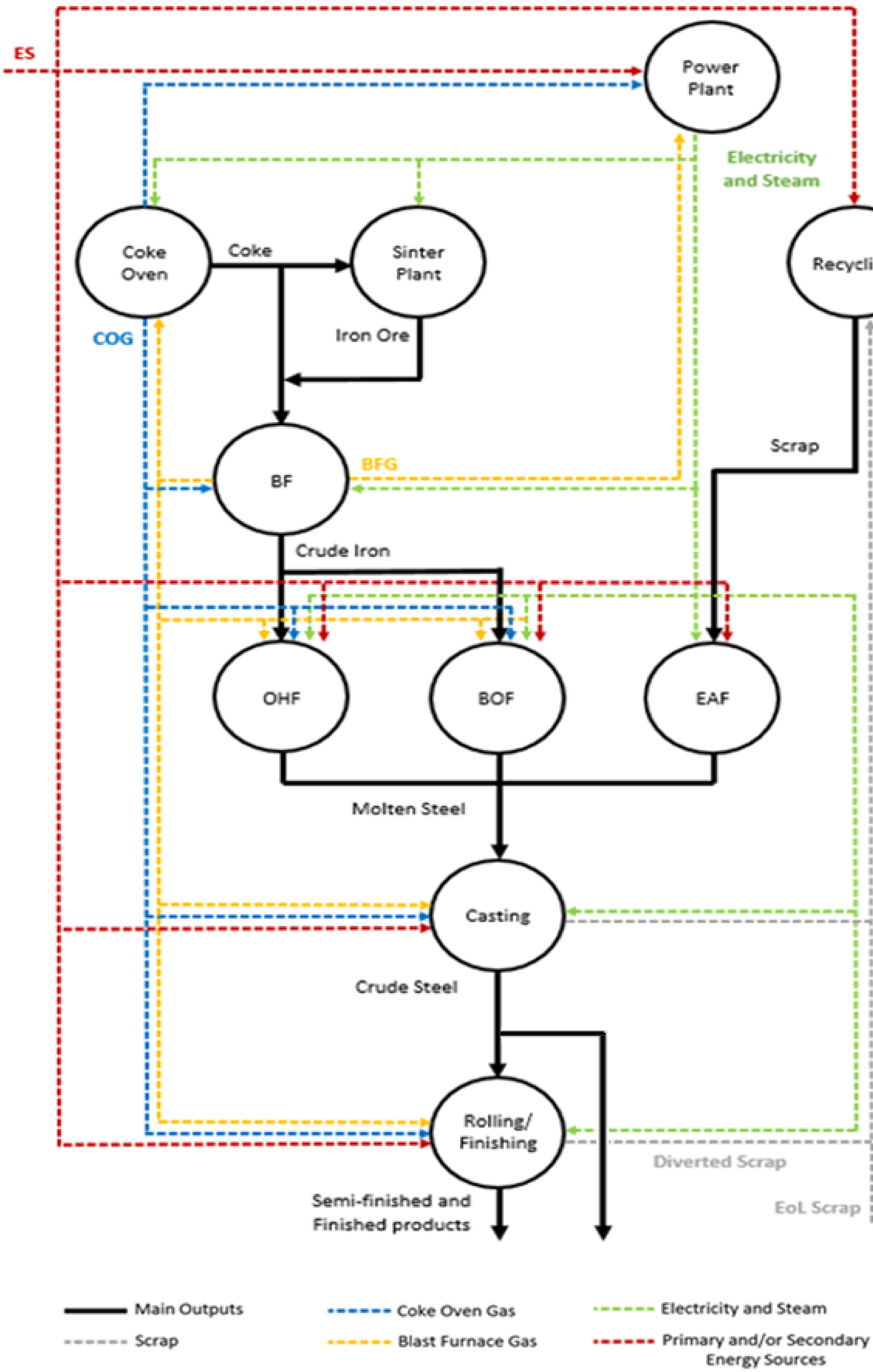


Figure 32 - Energy and material flows for the BF-OHF, BF-BOF and Scrap-EAF routes.

Steelmaking energy consumptions were calculated from the IEA World Energy Balance. There, is listed the energy used by industry from each source for every year as well as the energy used in transformations processes to produce the secondary energy sources. Considering this and having in mind the consumption route illustrated in Figure 31, the energy inputs were divided in three major categories:

- **primary energy sources:** oil, different types of coal, natural gas, biofuels, waste and other renewables;
- **secondary energy sources:** electricity, heat and oil, coal and biofuel products;
- **final energy produced and used at the steel plant:** energy produced in coke ovens, blast furnaces and gas works that is used to fuel other processes and produce electricity and heat;

3.3.1. Final energy consumption

The final energy consumption only accounts for the energy that is consumed in integrated steel plants and mini mills. In the IEA World Energy Balance this corresponds to all the energy sources used directly in the steelmaking industry and the energy required to feed the cove ovens, blast furnaces and gas works.

Both primary and secondary energy source consumption were directly available at the IEA World Energy Balance so it was only necessary to convert it from tonnes of oil equivalent to gigajoules. The energy used in coke ovens, blast furnaces and gas works was calculated by multiplying their energy output by the transformation process efficiency factor described in equation 1.

$$e_p = \frac{\sum inputs}{\sum outputs}$$

Equation 1 - Process efficiency factor.

3.3.2. Primary energy consumption

Computing the primary energy consumption does not require any further calculations when dealing with primary energy sources as no transformation processes need to be considered. However, both secondary and final energy sources do not match the primary energy their production required and so it was necessary to backtrack all these energy inputs listed in the IEA World Energy and analyse the transformation processes behind them.

3.3.2.1. Efficiency and energy distribution of the transformation processes

The first step was to list the transformation processes responsible for each of those inputs and name all the inputs of the transformation processes themselves. With this came the realization that it was a rather complex path as most of the final and secondary energy sources that were inputs of the iron and steel industry used other final and secondary energy sources in its own production, even though exceptions like the **Charcoal production plants** could be analysed straight away as they only used primary sources of energy. Therefore, each of the next steps required some simplifications regarding the inputs used.

Besides every transformation being listed once in the IEA Energy Balance with its inputs and outputs, there are a few that appear a second time with different input values. These correspond to the energy used in those facilities to operate the equipment, for lighting and heating, etc. Even if these could be neglected in some cases, there are others like the Oil refineries and BKB/peat briquette plants where they are actually bigger than the main ones, making it necessary to add the values from both balances. The distribution of the second energy input differs from the main one by considering electricity and heat and listing some of the transformation's own outputs as inputs. However, these energy consumptions were assumed to have the same distribution as the main ones, otherwise the problem would get much more challenging and require a heavy mathematical analysis with a complexity level beyond the goal of the study. The exception was the use of the processes' own outputs, which were not added to the energy input due to corresponding to recycled energy.

The final efficiency factor (e_{fp}) of each transformation process was calculated according to equation 2, where:

- x_i is the fraction of inputs being considered and is calculated using equation 3;
- e_p is the process own efficiency factor presented in section 3.3.1;
- e_{fp_i} is the final efficiency factor of the process responsible for the inputs being considered and is only relevant when dealing with other final or secondary energy sources ($e_{fp_i} = 1$ for all primary energy sources);

$$e_{fp} = \frac{e_p \times \sum_{i=1}^{n}(x_i \times e_{fp_i})}{\sum_{i=1}^{n} x_i}$$

Equation 2 – Final efficiency factor.

$$x_i = \frac{input\ i}{\sum inputs}$$

Equation 3 - Fraction of inputs.

If the transformation process does not require neglecting any of the inputs nor contains other final or secondary sources of energy as inputs equation 1 equals:

$$e_{fp} = e_p$$

Equation 4 - Final efficiency factor when $\sum_{i=1}^{n} x_i = 1$ *and* $e_{fp_i} = 1$ *for* $i = 1, \dots, n$.

Table 9 illustrates the path taken to calculate the final efficiency factor for the transformations processes responsible for the iron and steel inputs. It shows the order through which the processes were analysed and how each step cleared the path for the following ones.

Oil refineries were chosen as the starting point because they are both responsible for many of the products used as inputs in other transformation processes and only one of its own inputs is not a primary source of energy. To make it even easier that input is refinery feedstocks, which not only accounts for only 3 per cent of the total amount of inputs but is also obtained in petrochemical plants from almost exclusively oil products in a very efficient process. It is then plausible to assume refinery feedstocks as a primary oil-based energy source. By doing so it is possible to calculate the efficiency factor of oil refineries as none of its energy inputs corresponds to final or secondary energy sources anymore.

The next move was to analyse the **patent fuel plants** where oil refineries' products are used as inputs. Besides them the only input that is not a primary energy source is coke oven coke and it can be neglected as it is only used in insignificant quantities (never reached 1 per cent and was often under 0.1). **BKB/peat briquette plants** came next since the patent fuel plants' products they used were sorted out in the previous step and no longer were an issue. Same goes for the **coke ovens** that were then possible to analyse by neglecting the contribution from blast furnaces and gas works as both were close to zero.

Assessing the **charcoal production plants** allowed to calculate the **blast furnaces'** final efficiency factor that was then used to compute the **gas works** efficiency. **Main activity producer** and **autoproducer plants** of both electricity and heat could be evaluated straight away as all the final and secondary energy sources had all been already figured out. It is important to note that when the products (usually off-gases) of the coke ovens, blast furnaces and gas works are used to fuel other processes inside the integrated steel plant they have $e_{fp_i} \neq 1$, despite corresponding to recycled energy. This is due to the primary and secondary sources used in their production not being directly considered in the industry's energy balance from IEA, thus requiring these amounts need to be traced back to be accounted for.

Order	Process	Final and secondary energy sources used as inputs
1^{st}	Oil refineries	○ Refinery feedstocks (assumed as an oil product)
2^{nd}	Patent fuel plants	○ Oil refineries' products (from step 1) ○ Coke ovens' products (neglected)
3^{th}	BKB/peat plants briquette	○ Patent fuel plants' products (from step 2) ○ Coke ovens' products (neglected)
4^{th}	Coke ovens	○ Oil refineries' products (from step 1) ○ Patent fuel plants' products (from step 2) ○ BKB/peat briquette plants (from step 3) ○ Blast furnaces' plants products (neglected) ○ Gas works' plants products (neglected)
5^{th}	Charcoal plants	
6^{th}	Blast furnaces	○ Oil refineries' products (from step 1) ○ Patent fuel plants' products (from step 2) ○ BKB/peat briquette plants' products (from step 3) ○ Coke ovens' products (from step 4) ○ Charcoal production plants' products (from step 5)
7^{th}	Gas works	○ Oil refineries' products (from step 1) ○ BKB/peat briquette plants (from step 3) ○ Coke ovens' products (from step 4) ○ Blast furnaces' plants (from step 6)
8^{th}	Main activity producer electricity plants + Autoproducer electricity plants + Main activity producer heat plants + Autoproducer heat plants	○ Oil refineries' products (from step 1) ○ Patent fuel plants' products (from step 2) ○ BKB/peat briquette plants' products (from step 3) ○ Coke ovens' products (from step 4) ○ Blast furnaces' products (from step 6) ○ Gas works' products (from step 7)
9^{th}	Heat pumps + Electric boilers	○ Electricity (from step 8)

Table 9 - Path to backtrack all iron and steel inputs.

From the analysis of main producer and autoproducer electricity plants a final efficiency factor for electricity was determined through a weighted average that took into account the annual production of each process. This made the analysis of both **heat pumps** and **electric boilers** possible, from which a final efficiency factor for heat was computed using the same weighted average approach.

During this process a few other reasonable simplifications with minimum impact on the results had to be made:

- Other hydrocarbons were considered to be entirely a primary energy source, even though a substantial part of them is produced in transformation processes (coke ovens, coal liquefaction plants, GTL plants and non-specified transformations). Despite these quantities not being insignificant like in other cases, other hydrocarbons are not directly used in the iron and steel industry and only appear as inputs in transformation processes like oil refineries where they account for about 0.4 per cent of total energy input.
- Natural gas was also considered entirely as a primary source of energy as its production in blended gas processes never surpassed 0.4 per cent of the total annual production.
- Coke oven gas was assumed to be produced only by coke ovens, neglecting non-specified transformation processes that are responsible for about 0.02 per cent of it.
- Other recovered gases were assumed to be solely produced in blast furnaces as they account for over 99% of its production, with the rest coming from non-specified transformations.
- Both main activity producer and autoproducer CHP plants had to excluded from the analysis as there was no information to separately calculate the process efficiency factor for electricity and heat for each process. Had they been considered and the overall efficiency factor values of these two processes would have corrupted the values of both electricity and heat final efficiency factor.

This meant that some transformation process no longer required analysis as their contributions to certain products were not taken into consideration.

Parallel to calculation of the processes final efficiency factors, it was also computed the distribution by fuel of their energy consumption. This was achieved by summing the fraction of each primary source used directly with the fraction of the same primary source that was used to produce each of the final and secondary energy sources.

3.3.2.2. Electricity transmission and distribution losses

The efficiency of electricity production calculated from the World Energy Balance from IEA only accounts for the primary and secondary energy sources used, thus neglecting the energy losses that occur in its transmission and distribution. This results in an overestimation of the electricity's efficiency.

To overcome this issue its overall efficiency factor calculated from the IEA data was divided by the efficiency of its transmission and distribution process. Figure 33 shows the world average percentual values of these losses over between 1970 and 2014. For the 2015-2018 period, and in the absence of reliable data, it was assumed the 2014 value. Since both a country's electricity and steel production are linked with its economic development, the world average transmission and distribution losses should be very similar to the one obtained weighting each country's steel production.

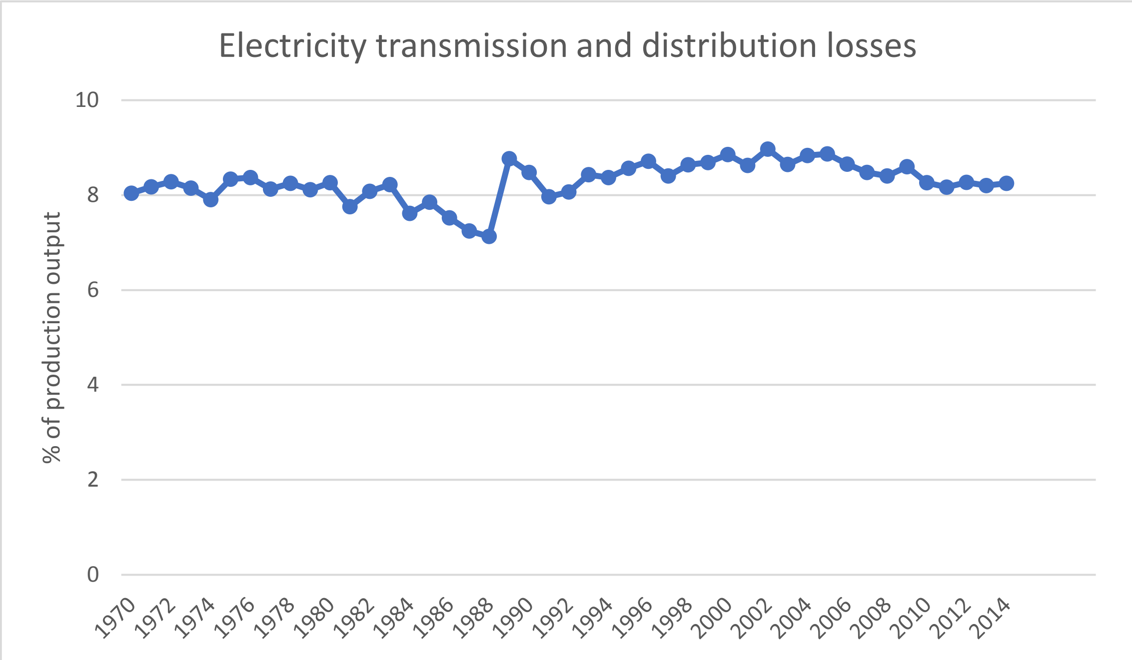


Figure 33 – World average electricity transmission and distribution losses since 1970 in percentage (World Bank, 2018).

3.3.2.3. Primary energy consumption and final energy distribution

The transformation processes' final efficiency factor values and energy distribution obtained in the previous stage were used to calculate the primary energy consumption and the final energy distribution. The inputs that had been previously classified as primary sources of energy were arranged according to their type (natural gas products, coal products, oil products, biofuels, waste and renewables).

The final energy used from those sources was multiplied by the final efficiency factor to get the total primary energy used from them. The **total primary energy consumption** was then obtained by adding the onsite primary energy consumption with the primary energy used to produce both secondary and final energy sources.

Despite the final energy consumption being available straight away, the **final energy distribution** could only be calculated as it required the distribution by energy source of the energy consumed in the coke ovens, blast furnaces and gas works to compute the final energy used from each primary energy source (plus electricity and heat). Once that was calculated it was only necessary to sum the final energy used from each energy source and divide it by the total amount.

3.3.3. Energy intensities of steel

Having already calculated the final and primary energy consumed each year in the production of steel, it was only necessary to divide it by the annual total production of steel in order to calculate the respective energy intensities. These annual totals were taken from the Word Steel Association file given by Sofia Henriques that had been used to calculate the shares of steel production. It must be noted that despite them referring to the amount of crude steel produced annually the energy intensity values do not correspond to the production of crude steel, as rolling and finishing processes were considered. They are used because they are the closest available estimation of the amount of steel, finished or not, that is produced every year.

3.3.4. Energy intensity of steelmaking routes

Access was given to a World Steel Association file with the energy intensity for the OHF, BF-BOF and Scrap-EAF routes. It contains the yearly global average for every five years until 2007 and for every year from then on until 2017. The total energy intensity of the iron and steel industry is also displayed for the same years.

By multiplying the average energy intensity of each source by its share of crude steel production for the same year it was possible to calculate each route's contribution to the global average energy intensity. As the Bessemer process only disappeared completely in 1990, the total energy intensity of the preceding years does not exactly correspond to the sum of OHF, BF-BOF and Scrap-EAF contributions. However, the difference is almost inexistent as this process' steel production was already residual by then. Therefore, the sum of those three contributions was assumed to be the total all along.

It must be noted that these energy intensity values do not include the rolling and finishing processes, so any considerations on the energy intensity of each route or the total average require adding a corrector factor (detailed in section 3.5).

3.4. CO_2 emissions

Following the guidelines from the CO_2 Data Collection User Guide from the World Steel Association (World Steel Association, 2021c) the CO_2 emissions were divided in 3 categories:

- **Direct emissions:** CO_2 emitted directly from site chimneys during steel production;
- **Upstream emissions:** emissions related to the production and delivery of secondary energy sources used as fuels, such as electricity, heat and products of oil refineries:

- **Credit emissions:** carbon embodied in the products of the iron and steel industry. It includes both the steel produced and off-gases used elsewhere, mainly the blast furnace gas;

The iron and steel CO_2 emissions are then calculated using the following formula:

$$CO_2\ emissions = Direct\ emissions + Upstream\ emissions - Credit\ emissions$$

It is important to mention some adjustments had to be made to respect the analysis boundaries previously defined. As there is no information regarding the amount of electricity and heat used that are produced onsite using off-gases and the CO_2 intensity of their generation, they had to considered as being exclusively produced offsite. However, it was not necessary to discount the coke oven and blast furnace by-products used in their production as the IEA's World Energy Balance only considers as inputs of the iron and steel sector the off-gases that are actually used in the steelmaking process.

Since the fuels used on coke ovens, blast furnaces and gas works are not included in the energy balance all their products will have to be considered as produced offsite, even though the 2006 IPCC Guidelines for National Greenhouses Gas Inventories state that by default they should be considered as produced onsite. This means that their upstream emissions will have to be considered.

3.4.1. Direct emissions

The direct CO_2 emissions of the iron and steel industry were calculated using the carbon balance methodology, assuming complete carbon oxidation. The quantity of each fuel used, taken from the IEA World Energy Balance, was multiplied by its CO_2 content, which was calculated using the carbon content and net calorific value of the fuels. These values were taken from a GHG Protocol Initiative's file that was based on the 2006 IPCC Guidelines (GHG Protocol Initiative, 2007) and are listed in Table A.1 (see Appendix A). No CO_2 emissions were calculated from the consumption of **industrial waste** as there were no carbon content nor net calorific values available.

3.4.2. Upstream emissions

Upstream emissions only need to be considered for non-primary energy sources as they correspond mostly to the CO_2 emitted in their production. In the iron and steel energy these emissions are calculated for the generation of both electricity and heat and the production of oil products and by-products of coke ovens, blast furnaces and gas works.

The data regarding the CO_2 emissions related to the generation of **electricity** was given by Ricardo Pinto and complied its annual CO_2 intensity since 1970. These values where then multiplied by their respective annual electricity consumption.

For the **heat** generation emission however, the lack of reliable data forced the utilization of a constant CO_2 intensity value for the period studied. This value, of 0,195 tonnes of CO_2 per tonne of heat, was taken from the World Steel Association CO_2 Data Collection User Guide (World Steel Association, 2021c). To obtain the CO_2 intensity in tonnes of CO_2 per GJ of heat it was necessary to use the specific enthalpy of saturated steam at 1 bar (2,675 MJ/kg).

The upstream emissions of **oil products** were calculated using their upstream CO_2 emission factors listed in the same World Steel Association file. However, as these are not specified for each oil product and are classified in light oil, heavy oil and kerosene, the oils products had to be matched with the best suitable category. This was done according to the description of each product available in the IEA World Energy Statistics Database Documentation from 2016 (IEA, 2016) and their density. The net calorific value and density of each fuel are then used to obtain its upstream CO_2 emission factor in tCO_2/GJ. All of the values used are listed in table 10.

Fuel	NCV (MJ/kg)	Density (kg/m^3)	Category	Upstream CO_2 emission factor (t$CO_2/unit$)	
Natural gas liquids	1)		NGL	0,665	$tCO_2/(k.Nm^3)$
Refinery gas			NGL	0,665	$tCO_2/(k.Nm^3)$
Liquefied petroleum gases (LPG)			NGL	0,665	$tCO_2/(k.Nm^3)$
Motor gasoline excl. biofuels	44,3	750	Kerosene	0,247	tCO_2/m^3
Other kerosene	43,8	800	Kerosene	0,247	tCO_2/m^3
Gas/diesel oil excl. biofuels	43	850	Kerosene	0,247	tCO_2/m^3
Fuel oil (residual)	40,4	950	Heavy oil	0,276	tCO_2/m^3
Naphtha	44,5	740	Light oil	0,247	tCO_2/m^3
White spirit & SBP	40,2	790	Light oil	0,247	tCO_2/m^3
Lubricants	40,2	825	Light oil	0,247	tCO_2/m^3
Bitumen	40,2	1030	Heavy oil	0,276	tCO_2/m^3
Petroleum coke	32,5	-	-	-	-
Other oil products	40,2	900	Light oil	0,247	tCO_2/m^3

Table 10 - Net calorific values, densities and upstream CO_2 emission factors of the oil products used.

As most oil products correspond to a group of fuels instead of a single one, the densities values' choice followed certain criteria to ensure the smallest margin of error possible. Therefore, it is important to clarify the reasoning behind the values listed above:

- **Motor gasoline excl. biofuels** has a density ranging from 715 to 780 kg/m^3 (Engineering ToolBox, n.d.), which led to choosing 750 kg/m^3 as its approximate value;
- **Other kerosene** defines kerosene other than the one used for aircraft transport and its density goes from 775 to 840 kg/m^3 (Engineering ToolBox, n.d.), thus making 800 kg/m^3 a reasonable average value;

- **Gas/diesel oil excl, biofuels'** density was defined as 850 kg/m^3, as it comprises a variety of fuels whose density ranges from 750 to 1010 kg/m^3 (Engineering ToolBox, n.d.), including gas/diesel oil, heavy fuel oil and light heating oil (IEA, 2016);
- **Fuel oil** corresponds to oils that make up the distillation residue and their density is always higher than 900 kg/m^3 (IEA, 2016), which led to 950 kg/m^3 being defined as the default density;
- **Naphtha's** density was defined as 740 kg/m^3 (Aqua-Calc, n.d.);
- **White & spirit SBP** includes both white and industrial spirit (SBP), whose distillation range is similar to naphtha and kerosene (IEA, 2016). There are both light oils and have an approximate density of 790 kg/m^3 (VWR International, n.d; FINU CHEMICAL SERVICES, n.d.);
- **Lubricants'** density was defined as 825 kg/m^3 as it usually varies between 700 and 950 kg/m^3, depending on the quality, viscosity and additive content of the lubricant (Neste, n.d.);
- **Bitumen's** density varies with its penetration grade and 1030 kg/m^3 was chosen as most of them, from the bitumen 40/50 to the 85/100, have a density range between 1000 and 1060 kg/m^3 (SEBCO, n.d.);
- **Other oil products** comprise oil products not classified above like tar, grease or benzene (IEA, 2016), for whom 900 kg/m^3 was chosen as the default value due to being somewhere in the middle of these products' densities;

These products were then matched with the closest designation available, which could be kerosene, light oil or heavy oil. **Motor gasoline excl. biofuels** and **gas/diesel oil excl. biofuels** were classified as kerosene as they present distillation range, density and net calorific value. The remaining oil products were classified are light or heavy oil according to their density and following the API gravity limits defined by the U.S. Energy Information Administration. They state that heavy oils have an API gravity of 22 degrees or below and for light oils it usually exceeds 38 degrees (EIA, n.d.), which corresponds approximately to 920 and 840 kg/m^3, respectively. The only case that falls in the middle is the **other oil products** and it was classified as light oil due to most of the products it includes being in that category. **Petroleum coke** was not taken into account as it does fit any of the available categories. For both **refinery gas** and **LPG** it was used the NGL upstream emissions factor and net calorific value to calculate their upstream CO_2 emission factor in tCO_2/GJ.

Using the correspondent upstream emission factors and energy calorific values listed in the World Steel Association CO_2 Data Collection User Guide it was possible to calculate the upstream emissions of the **coke ovens, blast furnaces** and **gas works by-products**.

3.4.3. Credit emissions

According to the 2006 IPCC Guidelines the iron and steel industry credit emissions correspond to the CO_2 embodied in the steel produced, in the recovered pig iron and is not used to produce steel and in the blast furnace gas that is recovered and used elsewhere (IPCC, 2006). However, as there is no information regarding the amount of pig iron reutilised it was assumed that all the pig iron was converted to steel. Furthermore, the blast furnaces by-products used in the iron and steel industry listed in the IEA World Energy Balance do not include the off-gases used to fuel other processes, thus having no credit emissions to discount. This means that only the steel credit emissions had to be taken into account.

The 2006 IPCC Guidelines states that every tonne of **steel** produced contains 0,01 tonnes of carbon (IPCC, 2006), which was used to obtain steel's embodied CO_2 and annual credit emissions. It was assumed that steel's carbon content remained unchanged during the period studied.

3.4.4. CO_2 intensity

To calculate the annual CO_2 intensity of the iron and steel industry it was only necessary to divide its CO_2 emissions by the correspondent annual crude steel production. The same procedure had been done when calculating the energy intensity and, just like in that case, the annual crude steel production values were taken from the Word Steel Association file given by Sofia Henriques.

3.5. Calculation of reference values

Part of the analysis of the results will be their validation, thus requiring reference values. For cases like the annual crude steel production this is pretty straight forward but for others, like the energy intensity or CO_2 emissions, a crafty approach is required. Most of the issues faced are due to the boundaries of the analysis performed in this work being different from those of most of the studies reviewed.

3.5.1. Energy intensity

The energy intensity values presented in section 2.3. could not be used directly as reference values since they refer to the energy intensity of crude steel. Therefore, it was necessary to come cup with a correction factor that took into account the energy consumed in the rolling and finishing processes.

As not all the crude steel produced is further processed and, the one that is, can form a large variety of finished steel products, it is necessary to determine the amount of semi-finished and finished steel produced per year and its distribution by product.

3.5.1.1. Semi-finished and finished steel production

The annual semi-finished and finished steel production was taken from the 2020 World Steel Association "World Steel in Figures" report (World Steel Association, 2020a). These values were put together by compiling data from national sources and, whenever that was not available, by calculations based on the crude steel production and continuous casting ratio.

Since it only presented data points for every five years for the period 1975-1990, both interpolation and extrapolation were required to obtain the annual semi-finished and finished steel production values of the missing years.

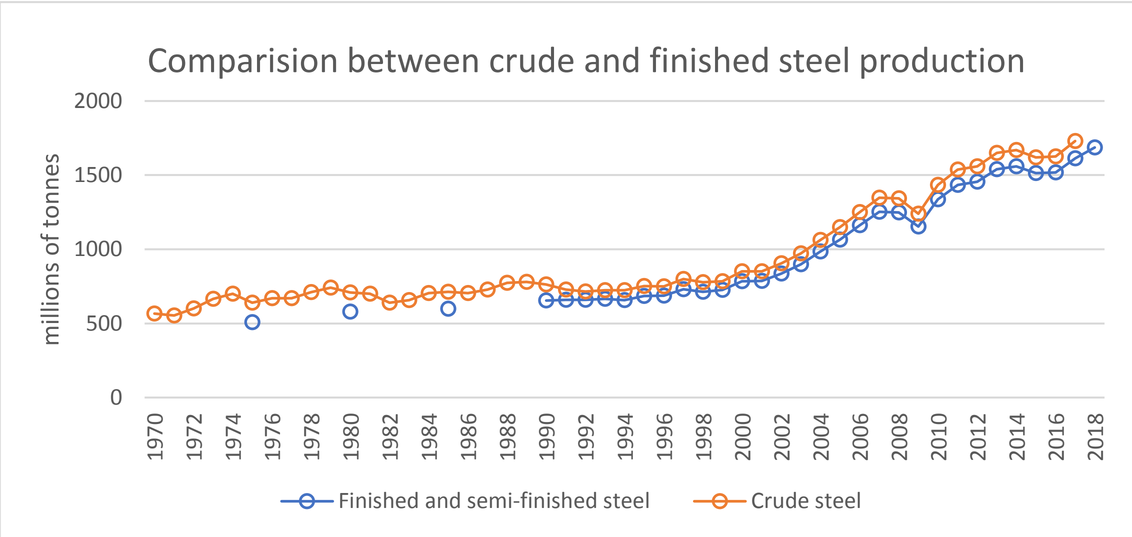


Figure 34 - Comparison between world crude steel and finished steel production since 1970.

Figure 34 shows a comparison between the annual crude and finished steel production data gathered by the World Steel Association. It is clear that production fluctuations are very similar in both cases, proving that a conversion ratio from finished to crude steel production is a viable option to obtain the missing values. This ratio is illustrated in Figure 35.

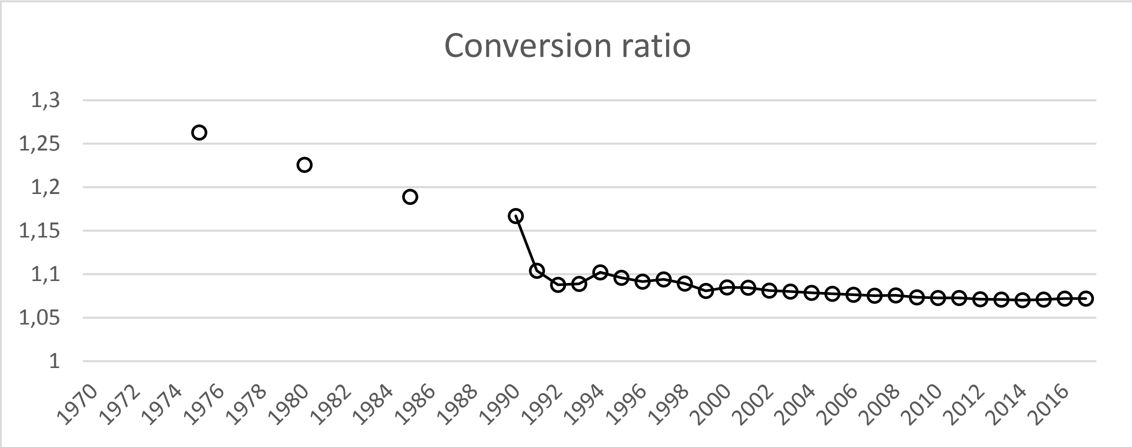


Figure 35 - Evolution of the conversion ratio from finished steel to crude steel production.

The ratio values since 1990 display a completely different evolution to those prior to that and therefore were not considered in the curve fitting process. This was performed using online tools available at "mycurvefit.com". The results are presented in Figure 36 and were then used to calculate the finished steel production of the missing years.

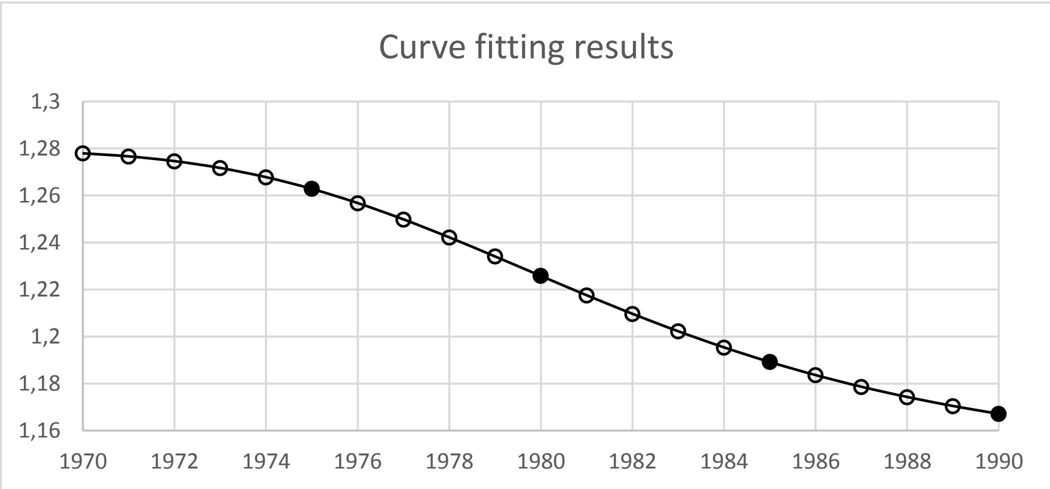


Figure 36 - Curve fitting of the conversion ratio values of the 1970-1990 period.

3.5.1.2. Finished steel production by product

Due to the lack of data for the entire world since 1970, the distribution of finished steel production around the world had to be assumed to be the same as the one of the European Union between 2010 and 2019 that is presented in the "2020 European Steel in Figures" report by Eurofer (EUROFER, 2020). This is distribution is represented in figure 37.

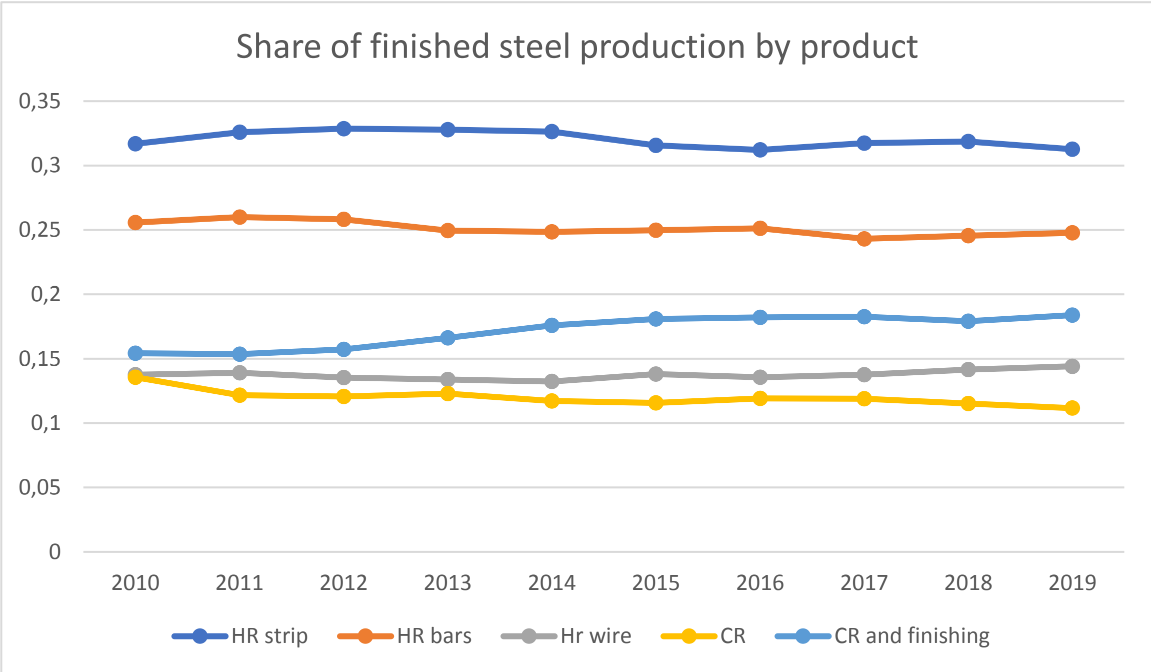


Figure 37 - Share of finished steel production by product. Products are classified according to the processes they went through. Hot rolling processes can be for strip (HR strip), bars (HR bars) and wire (HR wire) and both the cold rolled (CR) and cold rolled and finished (CR and finishing) products went also through hot rolling for strip beforehand (modified from EUROFER, 2020).

3.5.1.3. Correction factor

The final correction factor was achieved by multiplying the average share of finished product type by its energy intensity. The energy intensity values of these processes were obtained by multiplying the best practice value of each process presented by Worrell et al. (2007) by the efficiency factors determined by Jamison et al. (2016).

Worrell et al. (2007) stated that the best practice energy intensity values for hot rolling are 2.2 GJ/t for strip, 2.4 GJ/t for bars and 2.9 GJ/t for wire. Cold rolling requires additional 0.9 GJ7t and finishing 1.4 GJ/t, adding up to the totals shown in table 11.

Jamison et al. (2016) claimed that the ratio between the average energy intensity and the best practice value is 1.6 for the hot rolling processes and 2.2 for cold rolling. However, these ratios only refer to the onsite consumption (and potential savings). If the offsite consumption is considered the difference between the average and best practice values is watered down and both ratios go down to around 1.3. Therefore, this was considered to be the efficiency factor by which all energy intensity best practice values had to be multiplied.

Process	Best practice values (GJ/t)	Efficiency factor	Average energy intensities (GJ/t)
Hot rolling strip	2.2	1.3	2.86
Hot rolling bars	2.4		3.12
Hot rolling wire	2.9		3.77
bfHot rolling strip + cold rolling	3.1		4.03
Hot rolling strip + cold rolling + finishing	4.5		5.85

Table 11 - Energy intensity values for rolling and finishing.

These average energy intensities were then multiplied by the ten-year average production share of their respective products and divided by the finished steel to crude steel production ratio of each year.

Lastly, these values were corrected to take into account the efficiency improvements that happened over time, using the data regarding the average energy intensities of the different steelmaking from the World Steel Association. The 2010 energy intensity value of each route was used as the reference and the values before it (since 1970) were divided by it, in order to have an indexed evolution of the energy intensity of each route. The annual average of the three routes was then multiplied by the respective correction factor previously obtained.

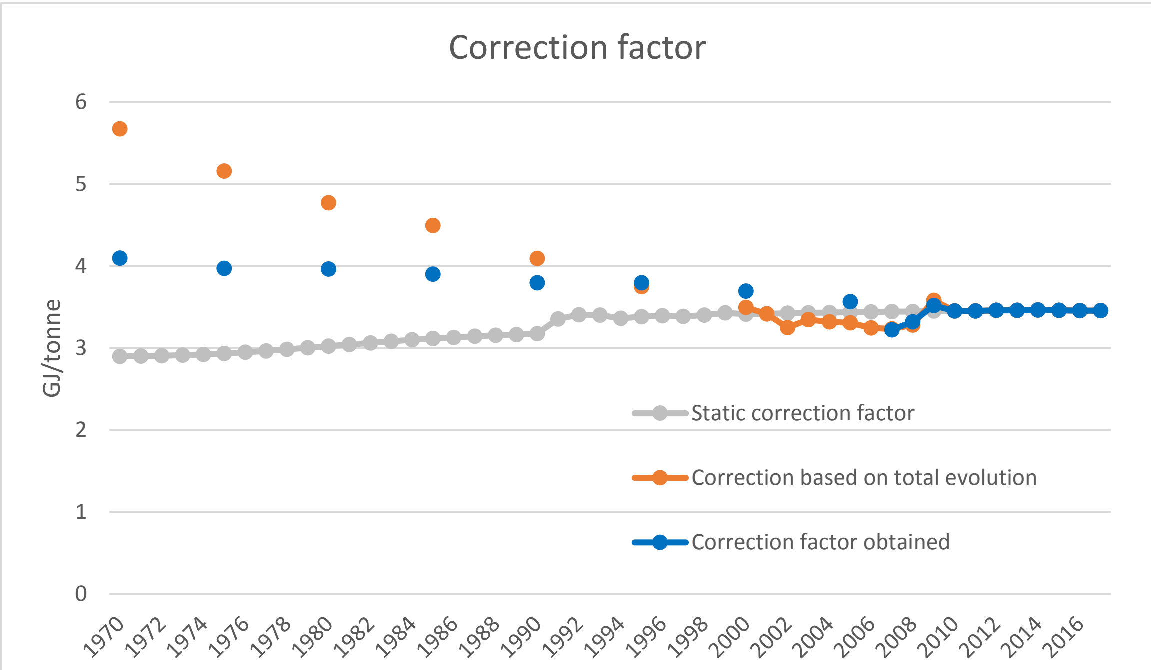


Figure 38 – Comparison of the correction factor values obtained considering efficiency improvements to those that do not consider them (Static correction factor) and those that do but based on the evolution of the industry's average energy intensity (Correction factor based on total evolution).

By averaging the evolution of the energy intensity of each route it was possible to isolate the time factor, which would not have been the case had the evolution of the industry's average energy intensity been used, as it is affected by the change of production share of each route over time.

Figure 38 compares the correction factor obtained with the correction factor without considering any efficiency improvements over time and with the correction factor that considers it based on the evolution of the industry's average energy intensity.

3.5.1.4. Corrected reference values

In the absence of a single piece of data covering the last 50 years, the reference values were put together by aplying the evolution of the indexed primary energy intensity from a World Steel Association report from 2019 to the data collected by IEA since 2000.

The annual correction factors calculated in the previous section were then applied to these reference values, bringing them into line with the boundaries established for the energy consumption analysis. Figure 39 shows the reference values with (after the correction) and without (before the correction) the rolling and finishing processes included.

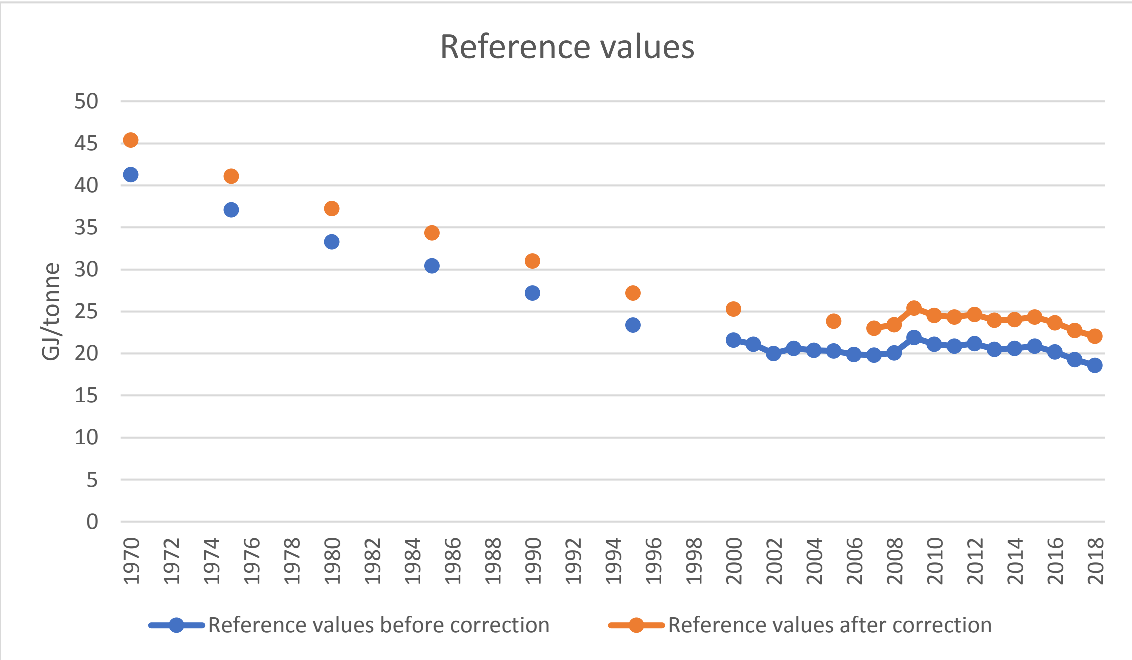


Figure 39 – Comparison of the energy intensity reference values before and after the correction.

3.5.2. CO_2 intensity

Just like with energy intensity, the CO_2 intensity values taken from literature (presented in section 2.4) do not consider the rolling and finishing processes. However, unlike with energy intensity, this does not require the application of a correction factor since the CO_2 emissions associated with those processes are much smaller to those resultants of the combustion of the off-gases and therefore their exclusion is not significant.

The only issue is the lack of a single piece of data containing the annual steel production CO_2 intensity since 1970. To overcome that it was necessary to aply the evolution of the indexed CO_2 intensity from an article recently published in Nature Communications by Wang et al (2021) to the data collected by the World Steel Association since 2007, similarly to what had to be done for the energy itensity.

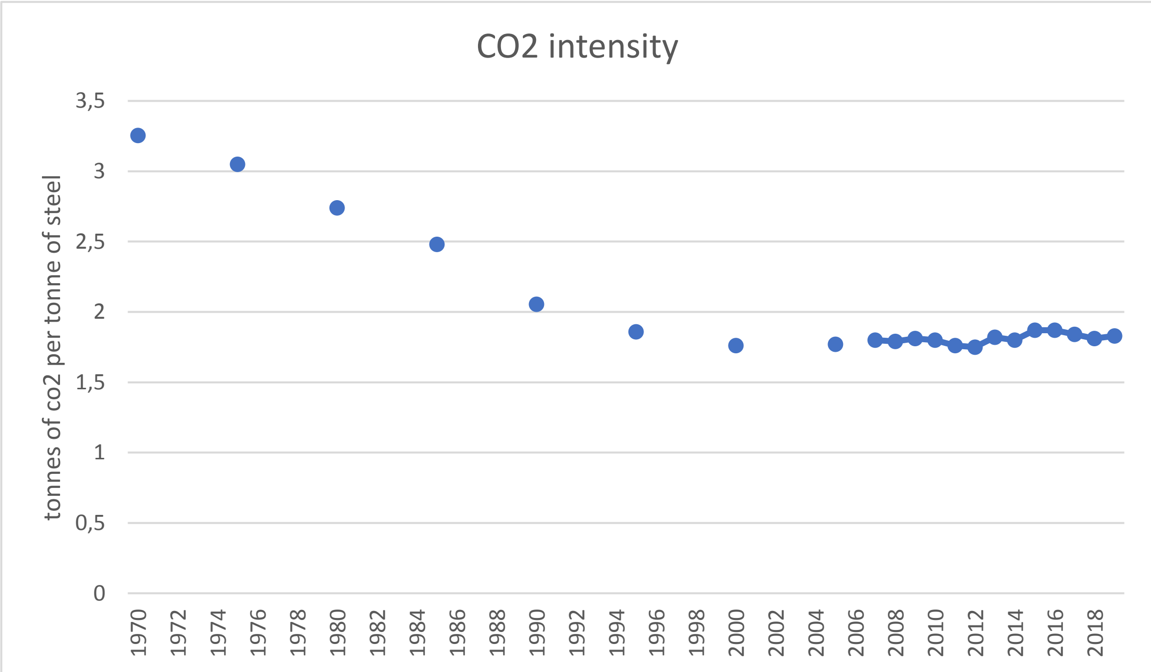


Figure 40 – Reference values for the CO_2 intensity.

3.6. Energy and CO_2 intensity long-term scenarios

The energy and CO_2 intensity scenarios were based on four different changes:

1) Change of the steelmaking routes production shares;
2) Implementation of the best available technology (BAT) for each route;
3) Improvements on the efficiency of electricity generation and reduction of its CO_2 intensity;
4) Introduction of breakthrough technologies and implementations of alternative processes;

They are applied to the current situation in an incremental fashion, starting with the changes of the distribution of crude steel production by route and following the order above.

Due to data availability constrains the starting point chosen was 2019, with the following values being considered:

Route	Production share	Energy intensity (GJ/t)	CO_2 intensity (tCO_2/t)
BF-BOF	0.71	23.9	2.2
DRI-EAF	0.07	19.1	1.4
Scrap-EAF	0.22	9.6	0.3

Table 12 - Production shares, energy intensities and CO_2 intensities of the main steelmaking routes.

The production shares and average CO_2 intensities were taken from the IEA Iron and Steel Technology Roadmap from 2020, with the latter being listed in table 8. The average energy intensities of the BF-BOF and Scrap-EAF routes are from the World Steel Association data provided by Ricardo Pinto. Since this data does not consider the DRI-EAF and the average value calculated by Gonzalez Hernandez et al (2018) that was presented in section 2.3.1.5 does not consider electricity production, its energy intensity had to be taken from Jamison et al (2016). These energy intensities do not consider hot rolling or finishing processes, thus require the application of the latest correction factor calculated in section 3.5.1.3.

It must be pointed out that due to the use of data from different sources the energy and CO_2 intensity values obtained for 2019 do not match those presented in sections 2.3.2 and 2.4.2. Nonetheless, this does not affect the validity of the analysis as it will be done on an indexed basis, focusing on the percentual improvements in both situations.

3.6.1. Production shares

The evolution of the production shares was based on the projected values for 2050 by IEA. It states that with the current policies the BF-BOF route will represent 53 per cent of the total crude steel production, the DRI-EAF route will account for 11 per cent and the remaining 36 per cent will come from the Scrap-EAF route (see section 2.3.4).

The World Steel Association projection on scrap availability for the 2019-2050 period presented in section 2.3.4 was used to predict the growth of the Scrap-EAF's share from 22 per cent in 2019 to 36 per cent in 2050. This was done by applying the indexed variation of scrap availability to its share. The increase from 7 to 11 per cent in DRI-EAF route was assumed to occur at a constant rate and the reduction of the BF-BOF was calculated off the other two routes. This resulted in the distribution shown in figure 41.

The annual shares of each route were multiplied by their current average energy and CO_2 intensities to obtain the respective evolutions.

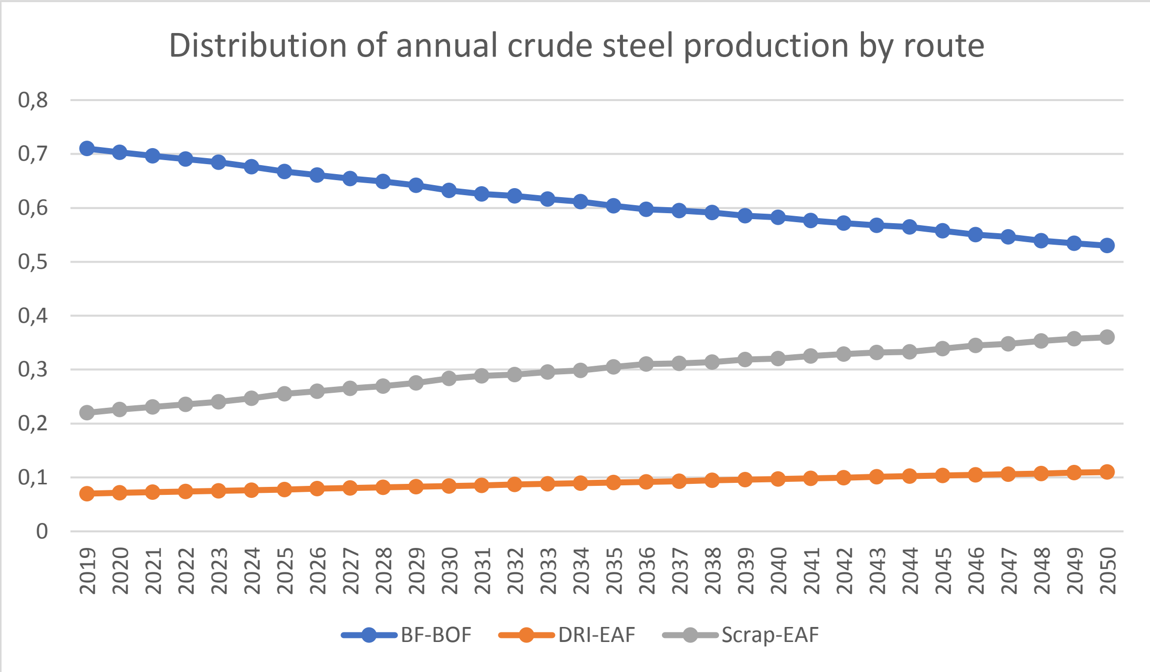


Figure 41 - Projected evolution of the distribution of crude steel production by route.

3.6.2. Best available technology (BAT)

Route	Energy intensity (GJ/t)	CO_2 intensity reduction (%)
BF-BOF	16.3	17.5
DRI-EAF	18.6	
Scrap-EAF	6	

Table 13 - BAT energy intensity values and percentual CO_2 intensity reduction.

Table 13 lists the best practice values used. The energy intensity values come from table 5 and have already been thoroughly discussed in section 2.3.1.5. For the CO_2 intensity the impact of the implementing the best available technology was not broken down by route. Instead, it was used an analysis from a study presented in section 2.4.3.2 that estimated its potential to reduce CO_2 intensity to be around 15 to 20 per cent (Holappa, 2020). For the following calculations it was assumed an average reduction of 17.5 per cent.

Since the scrap availability increases at an almost even rate (see figure 25) it was assumed that the implementation of BAT in the Scrap-EAF route would also occur at an even pace.

As for the BF-BOF and DRI-EAF routes, the application of BAT was determined by the age distribution of DRI and blast furnaces worldwide, with the data from the IEA presented in figure 26 (IEA, 2020a) being used to obtain the distribution of furnaces per remaining years. Figure 42 shows the fraction of integrated steel plants (ISP) that need to be replaced after a certain amount of years, considering that their typical lifetime is 40 years (International Energy Agency., 2020a).

For every year between 2019 and 2050 the best available technology was only applied to the fraction of integrated steel plants that had already passed their typical lifetime.

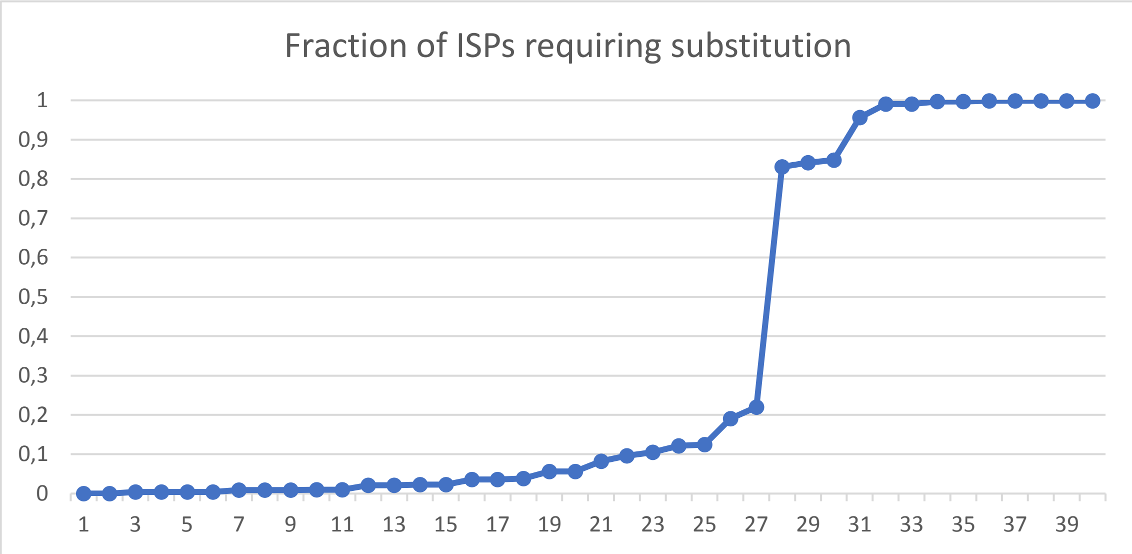


Figure 42 – Fraction of ISPs requiring substitution from 2019 on.

3.6.3. Improvements in electricity generation

The average efficiency and CO_2 intensity values listed in table 14 were taken from the IPCC's Fifth Assessment Report from 2014 (IPCC, 2014), with the coal's values being also used for oil due to the lack of specific data regarding it. For the renewable energy sources the efficiency is assumed to be 100 per cent.

Energy source	Generation share in 2019	Generation share in 2050	Efficiency (%)	CO_2 intensity (gCO_2/kWh)
Coal	0.367	0,218	39	820
Natural gas	0.235	0,209	55	490
Oil	0,03	0,003	39	820
Nuclear	0,104	0,083	33	12
Hydropower	0,158	0,132	-	24
Wind	0,053	0,153		12
Solar	0,027	0,189		48
Others	0,025	0,013		38

Table 14 - Generations shares, efficiency and CO_2 intensity of electricity generation for the main energy sources used.

These were multiplied by the electricity generation share of the respective energy source to calculate the average efficiency and CO_2 intensity of electricity generation, with the generation mix of 2019 coming from an article by Ritchie & Roser from 2020 published in *Our World in Data* and their evolution until 2050 being based on the EIA's International Energy Outlook 2019 (EIA, 2020). "Others" was assumed to be geothermal energy as it is the most used energy source from those not listed above according to the EIA's projection.

Both the increase in efficiency and the reduction of CO_2 intensity are shown in figure 43. Their application to the energy and CO_2 intensity of steel production was done according to the fraction of electricity used each year as an energy source, considering that on average it accounts for 7 per cent of the energy used in the BF-BOF route and 50 per cent in both the EAF routes (World Steel Association, 2019).

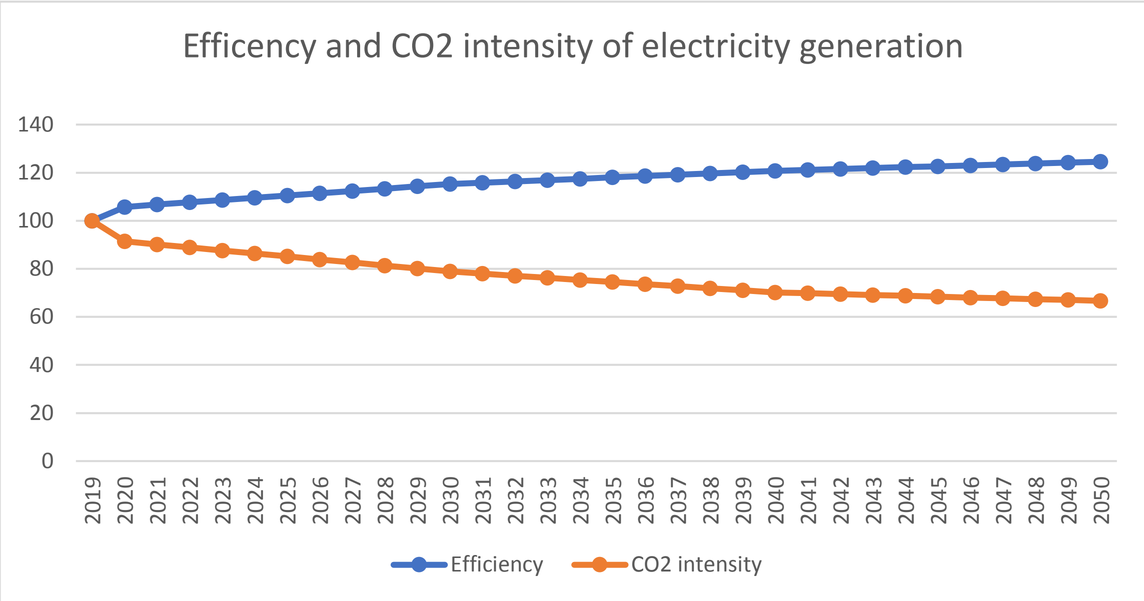


Figure 43 - Projected evolution of the efficiency and CO_2 intensity of electricity generation.

3.6.4. Breakthrough technologies

The introduction of breakthrough technologies was based on three different alternatives: gas-based DRI-EAF with CCUS, SR-BOF with CCUS and H_2-based DRI-EAF.

Steelmaking methods	Energy intensity (GJ/t)	CO_2 intensity (tCO_2/t)	Data of availability at commercial scale	Production share in 2050
Gas DRI-EAF + CCUS	13.3	0.57	already	0.02
SR-BOF + CCUS	19.4	0.57	2028	0.10
H_2 DRI-EAF	13.1	0.72	2035	0.08

Table 15 - Energy and CO_2 intensities, data of availability and production share of the alternative methods considered.

Their average CO_2 intensities, data of availability at commercial scale and expected production share in 2050 come from the IEA Iron and Steel Technology Roadmap from 2020. The energy intensity values of both the gas and H_2-based DRI-EAF were taken from an article by Bartlett & Krupnick (2021). These do not consider rolling and fishing processes and therefore the correction factor will have to be added to them. As no data was found regarding the energy intensity of the SR-BOF + CCUS process, its average value was obtained by adding 0.2 GJ/t to the best practice value listed by Worrell et al (2007), following what was found in the article by Bartlett & Krupnick.

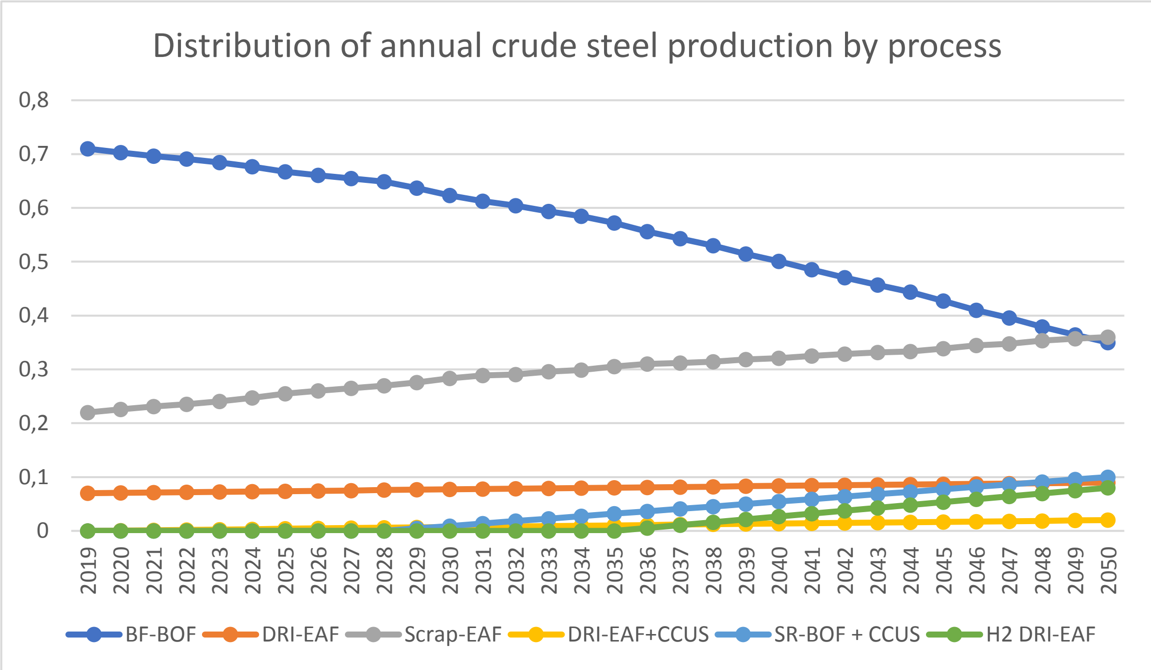


Figure 44 - Projected evolution of the distribution of crude steel production by steelmaking process.

The introduction of these three new steelmaking processes changed completely the distribution of steel production. Following the IEA's guidelines, it was considered that they surge as an alternative to the conventional BF-BOF route and therefore and it will be its share suffering the biggest impact. Apart from the gas-based DRI-EAF with CCUS, whose share was taken from the DRI-EAF share, the share of the new methods was discounted from the BF-BOF's one. For the SR-BOF with CCUS and the H_2-based DRI-EAF there was only considered steel production after their data of availability and its growth was assumed to be linear. This resulted in the distribution of the steel production shown in figure 44.

Each fraction of the three new steelmaking methods was then multiplied by the average intensities listed in table 15 and to the fractions of the BF-BOF, DRI-EAF and Scrap-EAF were applied the BAT intensities from section 3.6.2. For the application of the energy savings and emission reductions from electricity improvements it had to be calculated the new fraction of electricity used each year as an energy source. It was assumed that the energy used in the gas-based DRI-EAF with CCUS and the H_2-based DRI-EAF processes had a similar distribution by fuel to the DRI and scrap-based EAF, with electricity accounting for 50 per cent on average. For the SR-BOF with CCUS it was used the BF-BOF's electricity share of 7 per cent.

4. Results

In this chapter the results of work previously detailed are presented and analysed thoroughly. Further calculations are performed to better do so.

This chapter can be divided in three parts. The first part consists in the validation of the preliminary results. This includes the calculation of the **annual crude production by process**, **final and primary energy intensity**, **final energy distribution**, **primary energy intensity by route** and their **absolute contribution to the world average** and $\boldsymbol{CO_2}$ **intensity**.

Section 4.2 looks into the results presented in section 4.1 and explores links between them. The different parameters are no longer analysed individually but as a whole, so that broader conclusions can be drawn. The results one gave are used to complement the other, in an effort to get the best from each of the different data sources used and overcome eventual anomalies.

Finally, the conclusions taken from the previous analysis and reviewed studies are used to forecast the evolution of both the energy and CO_2 intensity and draw other possible scenarios, evaluating the likelihood of 2050 goals being met.

4.1. Presentation and validation of preliminary results

There were three main different data sources used in this work: the World Energy Balance from IEA and files regarding the annual crude steel production and energy intensity by route from the World Steel Association. The contributions of each to this work's goal are shown and discussed in sections 4.1.1 to 4.1.4.

Each section starts with the presentation and validation of the results, that are compared to those obtained by other authors. Then, the similarities and divergences are identified and explained.

4.1.1. Annual crude steel production by process

The World Steel Association data on the annual crude steel production provided by Sofia Henriques was used to analyse the evolution of the refining process in the steel industry. This data is plotted in Figures 45a and 45b that show the annual production by each process and its share of the total production over the last 50 years.

Figure 45a shows that the increase in steel production between 1970 and late 1990's was slow and fairly steady, having gone from nearly 500 million tonnes per year to around 800. This increase was met with severe changes in the fraction of steel produced by each process. In 1970 both the

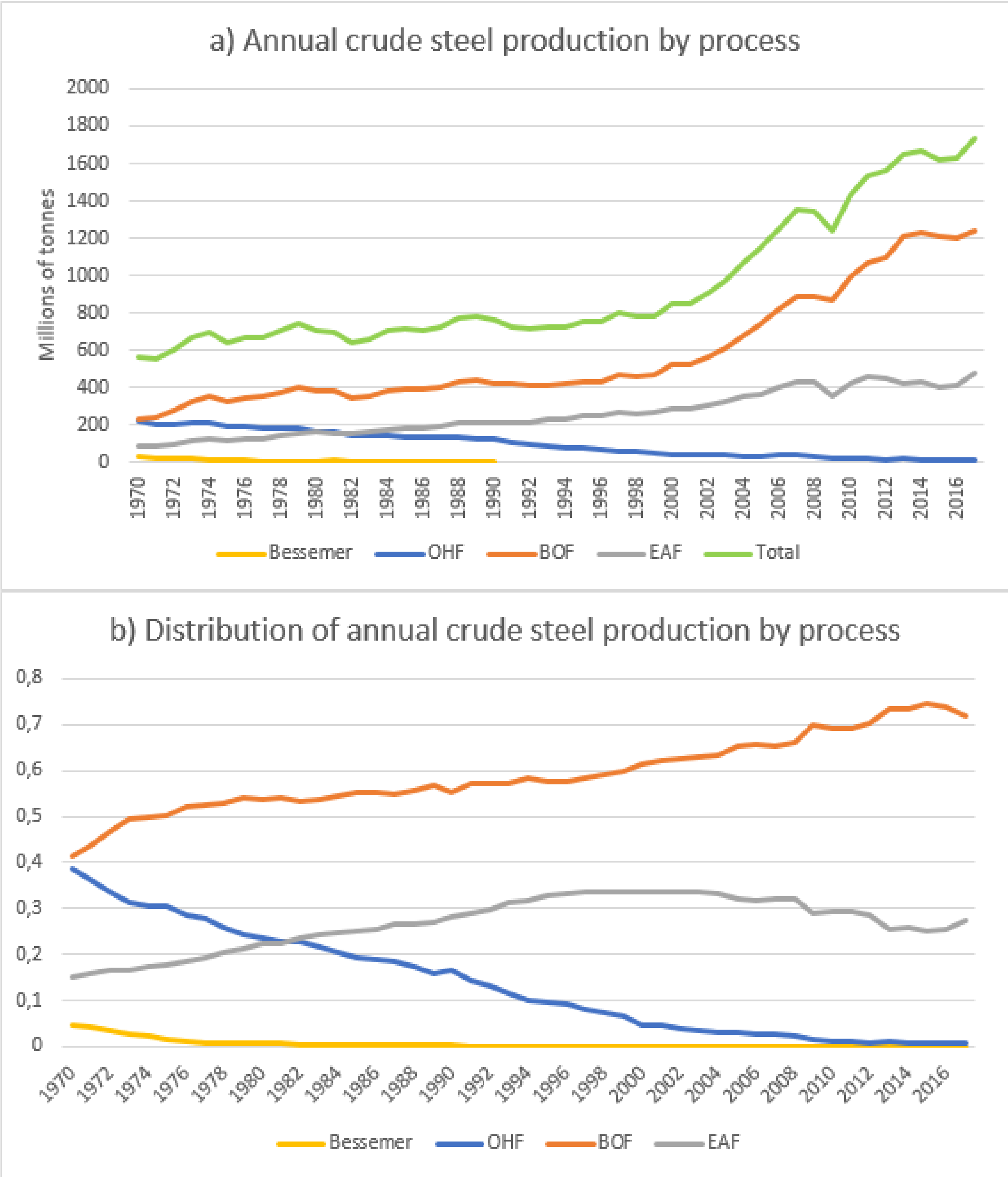


Figure 45 - Annual crude steel a) production and b) distribution by process (data provided by Sofia Henriques).

OHFs and BOFs, with a production a little bit over 200 million tonnes, were responsible for about 40 per cent each of the total crude steel production. Over the next 30 years the OHFs production fell to just 50 million tonnes per years and the BOFs production reached nearly 10 times that, transforming the even 40/40 per cent share in 5/60 per cent. Over this same period the steel production in EAFs rose from 86 million tonnes per year to 287. This upward trajectory meant that by 1982 it had already surpassed the OHF production and became the second most used steelmaking process. With its production increase faster than the total production increase the EAFs' had its share strengthened, having gone from just 15 per cent to nearly 35. On the other hand, Bessemer's production – that in 1970 was already just 5 per cent of the total production – continued to decline and eventually disappeared in 1990.

Since 2000 the annual crude steel production has grown very rapidly and is now more than twice as much as it was 20 years ago. In 2017 there were 1730 million tonnes produced worldwide. This was mainly due to BOF's production rising from 500 to over 1200 million tonnes of crude steel per year in just two decades, making it the by far the most used steelmaking process with over 70 per cent of today's production. EAF's production, however, has stalled after surpassing 400 million tonnes per year in the early 2000's, which led to its share of total production peaking at around 35 per cent at that time and decreasing to under 30 per cent in recent years. These last two decades also confirmed the decline in the use of OHFs, as its production is residual and accounts for less than 1 per cent of the total crude steel production.

This data is corroborated by the studies cited in sections 2.2.1.3 and 2.3.2. Both the evolution over the last 50 years and current values of production and distribution by process are in line with was expected and previously presented.

4.1.2. Evolution of steel energy intensity

The energy consumptions of iron and steel industry were obtained from the IEA World Energy Balance. Those were then used to calculate both its final and primary energy intensity, as well as the share of final energy used from each energy source.

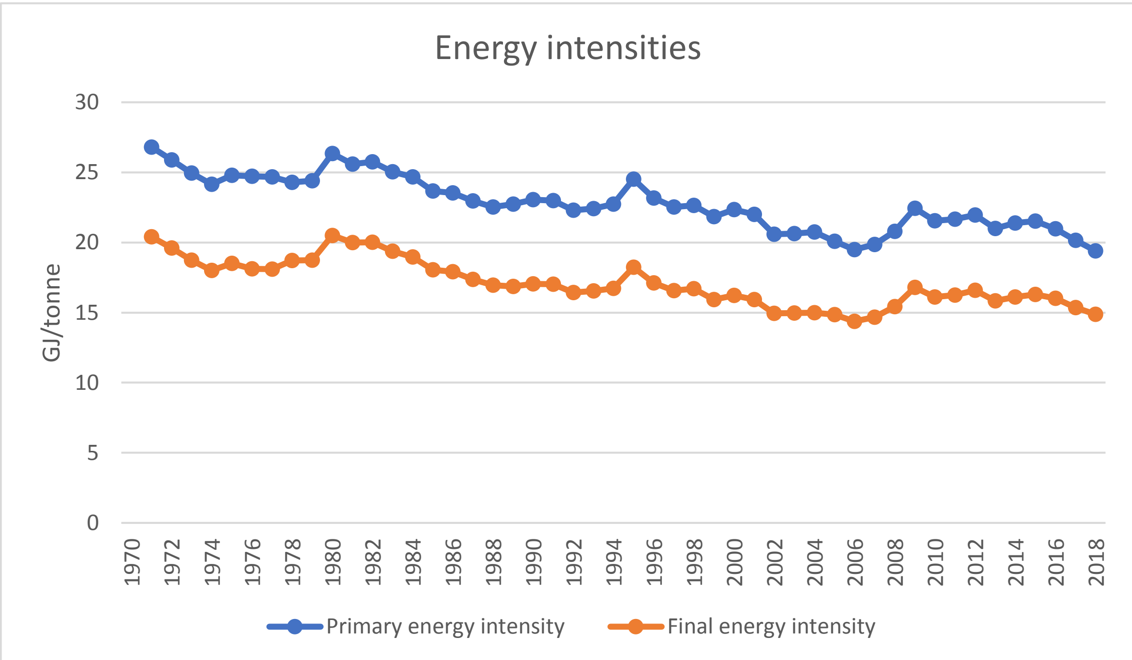


Figure 46 - Primary and final energy intensity (data from the IEA World Energy Balance).

The evolution of the finished steel final and primary energy intensity is illustrated is figure 46. Data shows that both have been reduced in over 5 GJ/t since 1970. The final energy intensity went from 20.4 GJ/t to 14,9 GJ/t and the primary energy intensity from 26.8 GJ/t to 19.4 GJ/t. Most of this reduction, however, happened until mid to late 1990's. In fact, by 1999 the final and primary energy intensity values were already at 15.9 GJ/T and 21.8 GJ/t respectively. They have not changed much since then, oscillating between those and the current values.

The validation of the preliminary results will be focused on the primary energy intensity since the studies previously mentioned do not refer to the evolution of the final energy intensity. Nonetheless, the results obtained portray very similar variations in both cases, thus suggesting that whatever is inferred from one can be applied to the other.

Those results are in part corroborated by World Steel Association (2019) and Allwood & Cullen (2012), as they unanimously state that when it comes to energy efficiency the iron and steel industry has reached a plateau in the last 20 to 25 years (see section 2.3.2). However, for the preceding years, the same studies present an evolution that is very different from the one seen in the results. From 1970 until mid-1990's the primary energy intensity values obtained are considerably smaller than what was expect. This discrepancy is illustrated in figure 47, where the

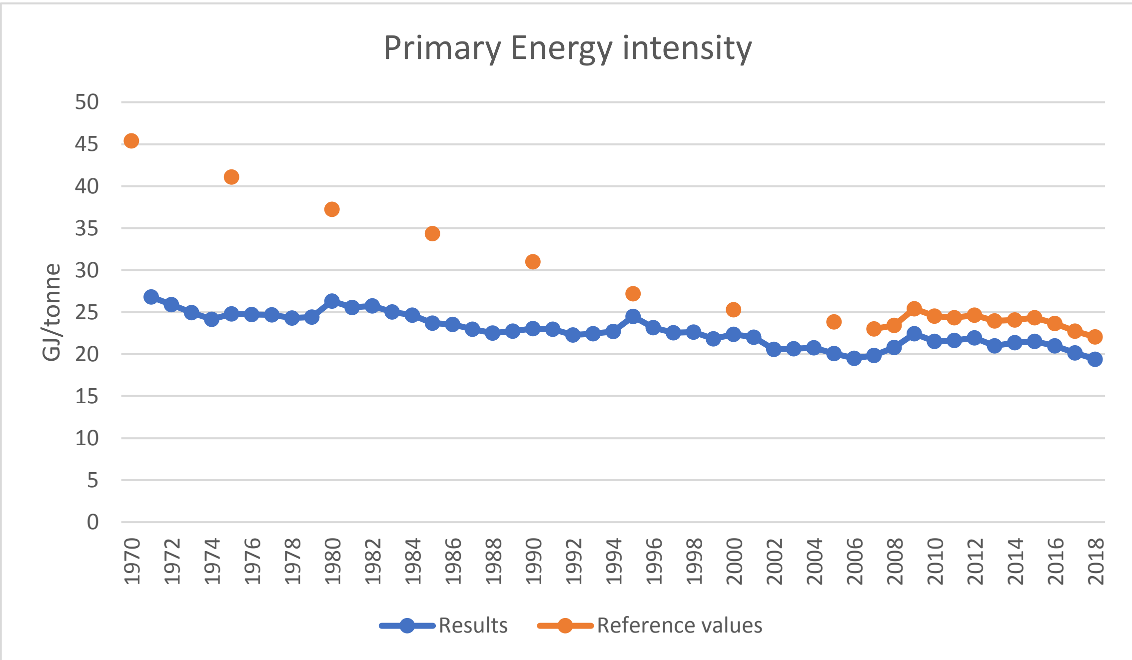


Figure 47 - Comparison of the primary energy intensity results with reference values.

results obtained are compared with the expected ones. The calculation of the reference values is detailed in section 3.5.1. Looking at the graph we can see that the results obtained for the last the 25 years are 10 to 15 per cent lower than the reference values. As we go further back this difference increases exponentially and for the early 1970's the results obtained are nearly 40 per cent smaller than what was expected.

The fact that such discrepancy only occurs with part of the results proves that it was not caused by any mathematical or conceptual errors in the analysis, as that would have presumably affected all the results the same way. This suggests that the issue may have to do with the data used in the analysis. When looking carefully into the IEA's World Energy Balance there are a few eyebrow-raising details that jump out. Several transformation processes present suspiciously high energy efficiencies, especially for the first 20 to 25 years. There are even years when certain transformation processes have an efficiency over 100 per cent. This is shown in figure 48, where the process efficiency factors of the transformation processes are plotted. These factors were put together by dividing the direct energy input by the energy output of each transformation process, as explained

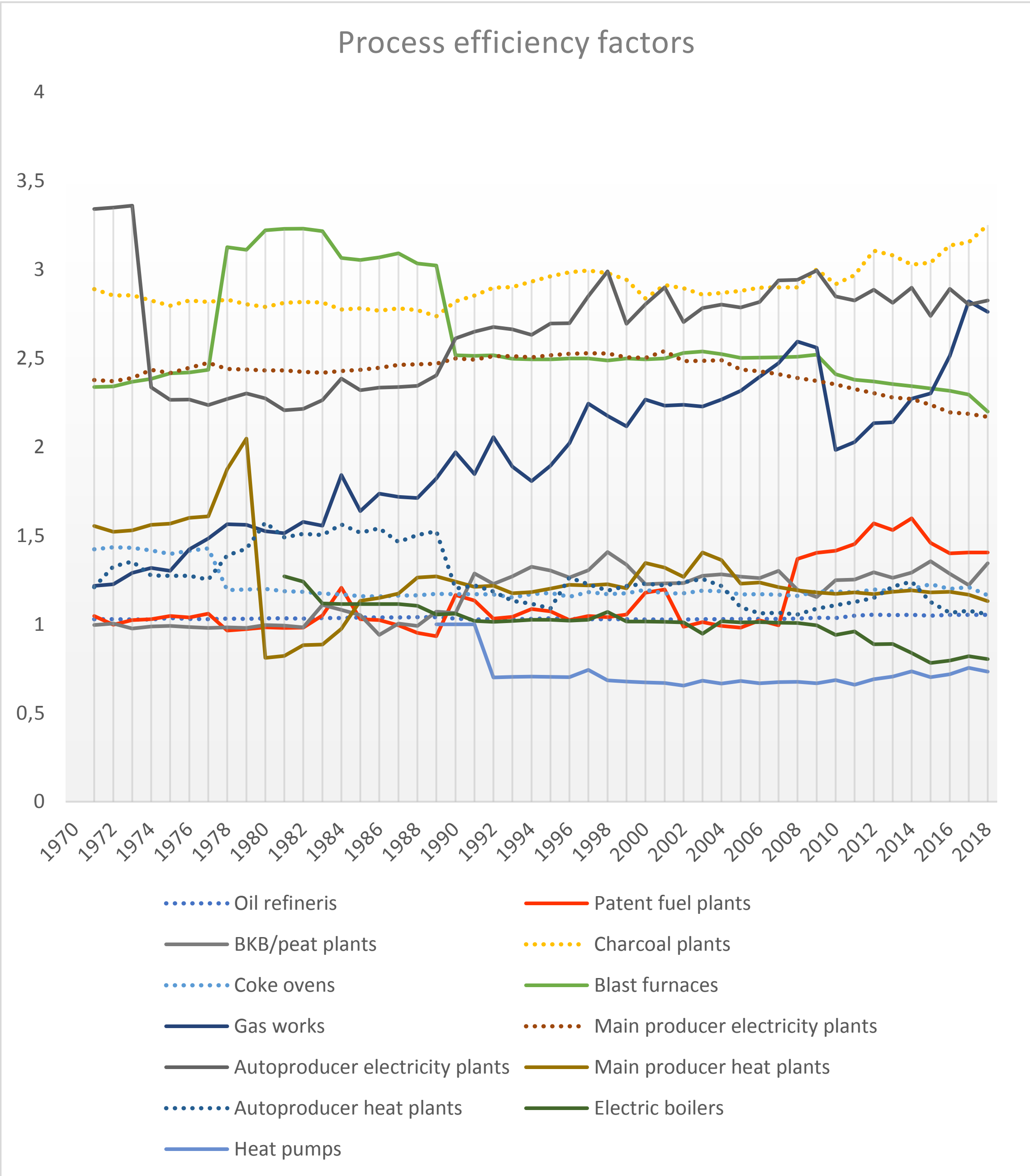


Figure 48 - Process efficiency factors of the transformation processes (data from the IEA World Energy Balance).

in section 3.2.1 Although the evolution shown is always quite chaotic, it is clear that there are a few anomalies. There are transformation processes – highlighted with full lines – whose data shows odd drops in the efficiency factor. Amongst these processes there are even cases like the BKB/peat briquette plants, the patent fuel plants, the main producer heat plants, the electric boilers and the heat pumps where it reaches values under 1. In those cases, the factor efficiency values were corrected to 1 to minimize the error

These very unlikely and often impossible events prove that the IEA data is clearly incomplete, a problem that is more significative before 1995 and that gets progressively worse as we go further back in time. Therefore, and despite the results obtained for the last 25 years confirming the stagnation suggested by several studies, this data is not reliable and should not be used to analyse the energy efficiency of steel production.

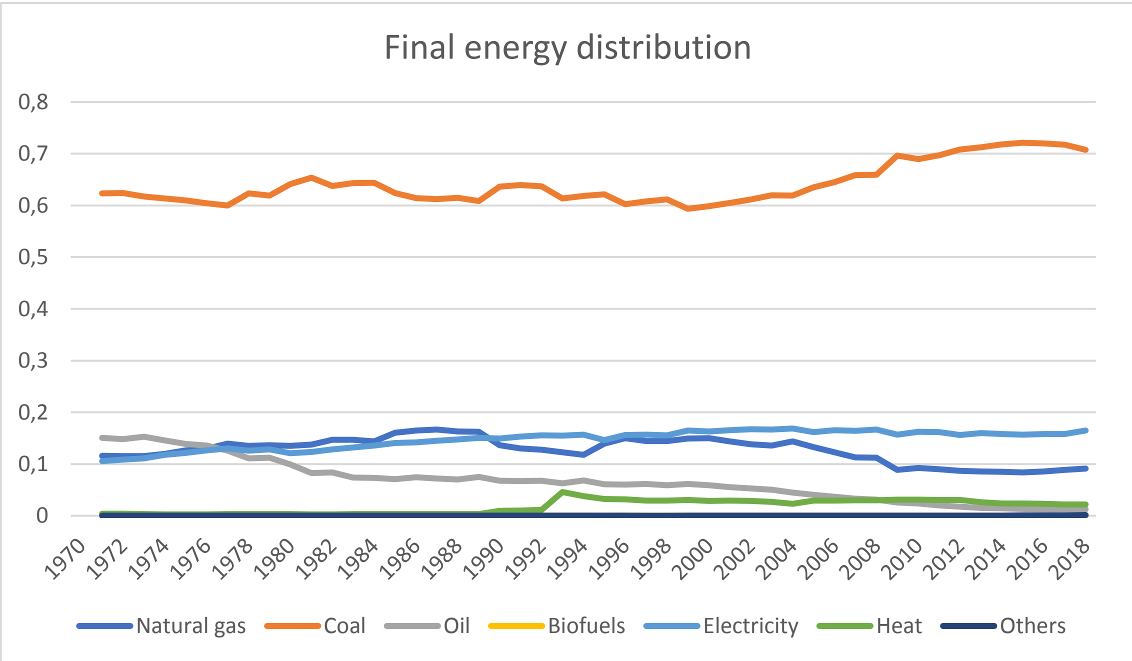


Figure 49 - Distribution of final energy consumption by energy source (data from the IEA World Energy Balance).

This distribution of the final energy consumption by energy source was calculated using the data from the same IEA document and it is illustrated in figure 49. Data shows that coal has been by far the biggest energy source of the steel industry, with its share oscillating between 60 and 65 per cent from 1970 to the beginning of the 21st century. It has progressively increased since then and is now just over 70 per cent. Oil, that in 1970 was the second most used energy source with 15 per cent of the final energy consumption, has become less important over time and now represents only 1 per cent of the total consumption. On the other side, electricity has had its share increased from 10,5 to 16,5 per cent. However, this happened mostly until the late 1990's as by 1999 it had already reached today's values. Off the remaining energy sources heat has had the biggest change, having gone from under 0,5 to over 4 per cent in the mid 1990's. Since then, its share has been reducing and is now just over 2 per cent. Natural gas has accounted for 10 to 15 per cent of the total consumption most of the time, having only gone under 10 per cent very recently after a sudden decrease in the early 2000's. Other energy sources, which include waste and renewables, have been residual throughout the all period.

The evolution of the final energy distribution by fuel since 2000 shown in the IEA data in section 2.3.3 is very similar to the one shown in the results obtained over the same period. However, there are some small differences in the values obtained for coal and electricity. In the results obtained they accounted for 59,8 and 16,3 per cent of the total consumption in 2000 and for 70,7 and 16,5 per cent in 2018, respectively. In the reference data, coal and electricity accounted for 66 and 12,5 per cent of the total consumption in 2000 and for 74 and 12,9 per cent in 2018, respectively. The values obtained for the remaining energy sources are very close to the expected ones.

Even though the results obtained do not match exactly the reference values, the difference is smaller than the one registered in the primary energy intensity. This is likely due to the transformation processes, and their associated errors, not coming into play here. In any case these results should be used carefully and major takeaways should be avoided, especially regarding the 1970-2000 period as there was no data available to verify them and they present odd situations like the sudden raise of share of heat in the mid 1990's.

4.1.3. Energy intensity by route

The average energy intensity by route was extracted from a file put together by the World Steel Association. Its data covers the BF-OHF, BF-BOF and Scrap-EAF routes over the last 50 years with data every 5 years until 2007 and every year from then on.

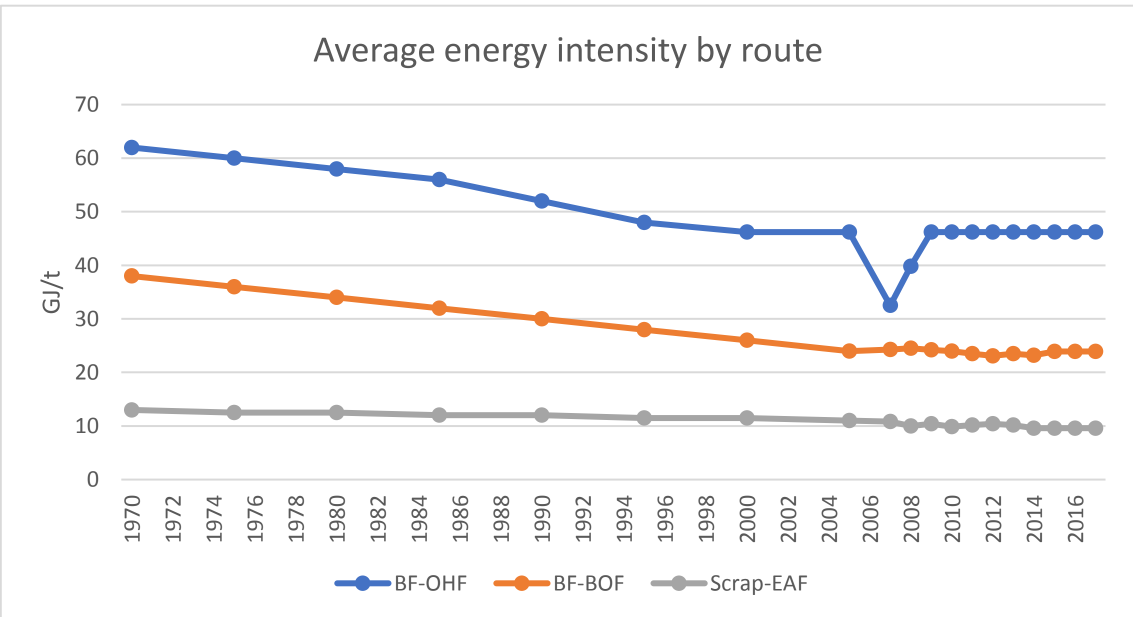


Figure 50 - Average primary energy intensity by steelmaking route. These results do not include hot rolling or finishing processes (data from the World Steel Association).

Figure 50 shows the evolution of the energy intensity of each route over this period. In 1970 the BF-OHF, BF-BOF and Scrap-EAF routes had an average energy intensity of 62 GJ/t, 38 GJ/t and 13 GJ/t, respectively. By 2017, the latest data point available, these energy intensities had come down to 46.2 GJ/t, 23.9 GJ/t and 9.6 GJ/t.

Most of this improvement in energy efficiency was done until 2000, as by then their average energy intensities were already very close to today's values. This is especially true with the BF-OHF and BF-BOF that had an average intensity of 46.2 GJ/t and 26 GJ/t respectively. The Scrap-EAF route presents a steadier evolution, with the 2000 average intensity of 11.5 GJ/t sitting half-way between the earliest and latest values.

Without enough reference data covering all the 50 years to directly compare these energy intensities to, the validation process is broken down in several phases that independently analyse different aspects of this evolution.

We start by comparing the latest average energy intensities of the BF-BOF and Scrap-EAF routes with their best practice and average values that were presented in section 2.3.1.5 (discounting hot rolling and finishing intensities). The studies cited – dating between 1998 and 2018 – came up with best practice values that go from 15.8 to 20 GJ/t and average energy intensities of 26 GJ/t for the BF-BOF route. For the Scrap-EAF these energy intensities vary greatly according to the boundaries of the analysis done, as they report best practice values that go from 2.1 GJ/t to 5.6 GJ/t and average intensities around 2.8 GJ/t. The BF-BOF is the most straight forward case, as the latest average energy intensities presented in the results are within the range of the reference values mentioned before, thus being corroborated by them. The same does not happen with the Scrap-EAF, as the intensities shown in the more recent results are above all the reference

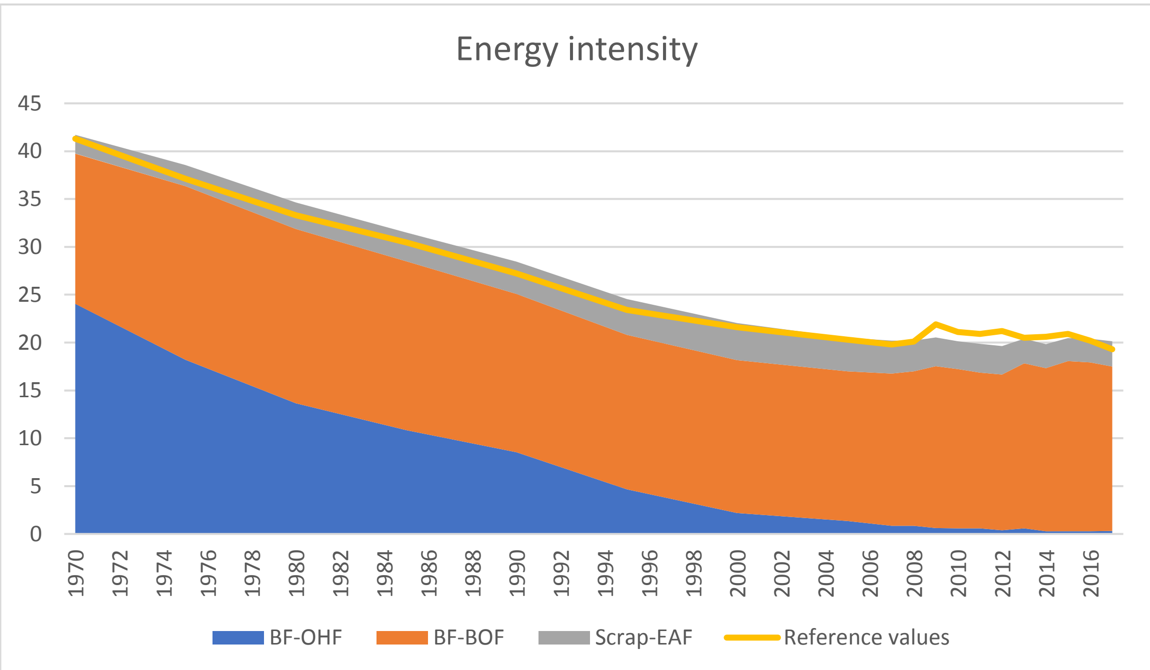


Figure 51 - Comparison of the total energy intensity calculated from the individual routes with the reference values.

values. However, this can be misleading as the energy intensities that are considerably smaller than the results were calculated without taking into account the primary energy involved in the production of electricity. In fact, if we put these aside and just consider the ones where those consumptions were not neglected the discrepancy between the Scrap-EAF results and the reference values no longer seems unreasonable. Its latest average energy intensity of 9.6 GJ/t is understandably higher than best practice values of 4 GJ/t and 5.6 GJ/t presented by De Beer et al. (1998) and Worrell et al. (2007) respectively.

Another way to test the reliability of these results is to multiply the energy intensity of each route by its steel production share and compare the total energy intensity given by the sum of the 3 routes with the reference values used in section 4.1.2. Because these 3 routes together are responsible for almost all the steel production throughout the years the sum of their weighted intensities is expected to be very close to the total average intensity. Since the data of the distribution of annual crude steel production by process has already been validated its use does not influence the outcome of the analysis of the reliability of these results. This comparison is shown in figure 51, where the sum of the routes' weighted intensities is plotted side by side with the total intensity reference values.

Despite the evolution of the routes' weighted energy intensities only being analysed in the second part of this chapter, it can be concluded straight away that their sum does match the reference values. Even though there are years where there is a small difference between the two, there are no significant discrepancies and both present the same evolution patterns. This indicates, once again, that the data regarding the energy intensity of each steelmaking route is reliable.

4.1.4. CO_2 intensity

The CO_2 emissions were calculated using the industry's energy inputs listed in the World Energy Balance from the IEA and the emission factors of each fuel. The annual CO_2 emissions were then divided by the annual crude steel production to obtain the respective CO_2 intensity. Its evolution since 1970 is displayed in figure 52.

Data shows that over this 50-year period the CO_2 intensity of steel production decreased nearly 0.5 tonnes of CO_2 per tonne of steel produced, having gone from 2.17 tonnes of CO_2 per tonne of steel in 1970 to just 1.67 tonnes in 2017. It was, however, an inconsistent reduction as most of it occurred until 1990 and after 2014. During the in-between years it oscillated around 1.85 tonnes of CO_2 per tonne of steel, with 1995 having the highest CO_2 intensity with 2.05 tonnes of CO_2 and 2017 the lowest.

Figure 52 also shows the reference values for the industry's CO_2 intensity that were put together by aplying the evolution of the indexed CO_2 intensity from an article by Wang et al (2021) to the data collected by the World Steel Association since 2007, as explained in section 3.5.2. These are

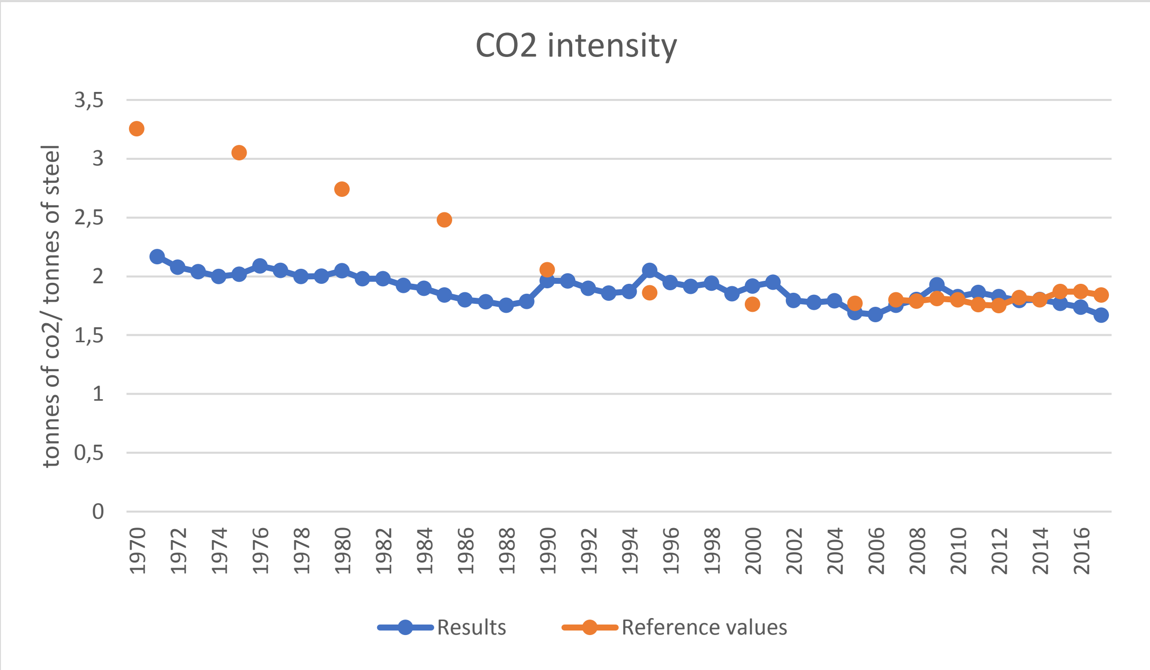


Figure 52 - Comparison of the CO_2 intensity results with reference values (data from the IEA World Energy Balance).

quite similar to the results obtained since 1990, despite the sudden fall of the latter in the recent years. During this period they have also been around 1.85 tonnes of CO_2 per tonne of steel, albeit with smaller oscillations. The big discrepancy happens in the 1970-1990 period, where, much like with energy intensity, the results are significantly different than the reference values. The CO_2 intensity obtained for 1970 from the IEA data is 33 per cent smaller than what it was expected.

The comparision of these results with the reference values shows once more that the data from the IEA is incomplete and can not be trusted. The big difference from the energy intensity situation is that here the eventual errors associated with the transformation processes data did not affect the results, since the emission factors used allowed to work directly with the industry' final energy consumption. This is likely the reason why the CO_2 intensity values obtained for the last 25 years are, appart from the years since 2014, closer to the reference values than the primary energy intensity ones. It can also be concluded that the data regarding the final energy consumtpion of the iron and steel industry is also incomplete, specially for earlier decades of the period analysed, as the discrepancies with CO_2 intensity values could not have been cause by the transformation processes' flawed data.

4.2. Analysis of the evolution of energy efficiency and CO_2 emissions

With the validity of the results obtained already assessed, it is now possible to use the trustworthy data to analyse the evolution of energy efficiency and CO_2 emissions in steel production. This includes the data regarding the share of crude steel production by route, the evolution of the energy intensity of each route and, albeit conservatively, the distribution by energy source of the final energy consumption since 2000 that was calculated from the IEA data.

The main goal of this section is to breakdown the industry's evolution and identify what has been causing its stagnation in both energy efficiency and CO_2 emissions over the last 20 to 25 years, so that there is a better understanding of what should be changed in the near future.

Figure 51 illustrates the contribution of each route to the world's average energy intensity. It shows that both the BF-BOF and the EAF have been responsible for nearly the same gigajoules throughout the entire period and that the decrease of the BF-OHF's share has been the greatest responsible for the industry's primary energy intensity reduction, suggesting that its deacceleration over the last 20 years might be the cause of the stagnation of the industry's energy intensity. This hints that the evolution of the shares of steel production might have been the major driving factor of the industry's efficiency improvements and, now that the substitution of BF-OHF plants is almost done, it would be necessary to either increase the share of EAF or replace the BF-BOF route with a more efficient alternative to further reduce the energy intensity of steel production.

However, an analysis of figure 50 shows that all three routes had their energy intensity heavily reduced since 1970. In fact, by isolating the efficiency improvements in each route from the change in their share of production it is possible to conclude that both factors have equally contributed to the decrease of the industry's average energy intensity. Figure 53 shows that multiplying each route's share of steel production for every year by the respective average energy intensity value from 1970 or multiplying their average energy intensities of every year by the shares of 1970 results in the same energy intensity reduction over time.

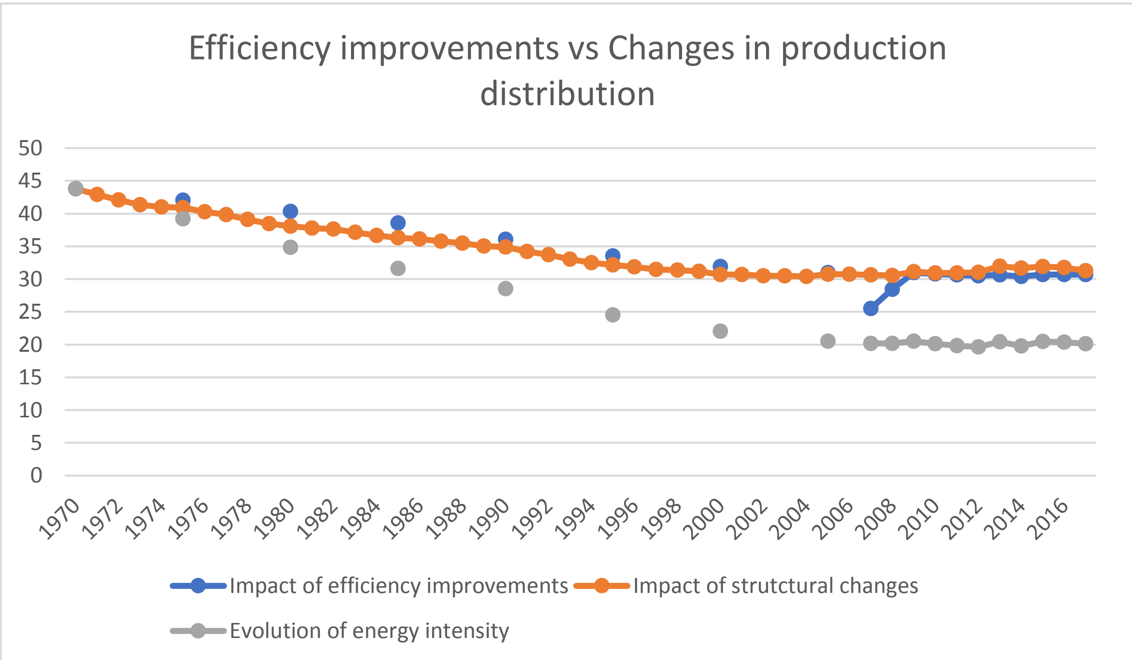


Figure 53 - Comparison of the effect of efficiency improvements in steelmaking routes and the variation of their production shares on the reduction of energy intensity.

Figure 50 also suggests that both the BF-BOF and the EAF route have reached maximum efficiency, as their energy intensities have been nearly the same for 20 years. However, such values are still well above the best practice values presented in section 2.3.1.5, thus can be further reduced.

Looking closely at figure 45 it is clear that the industry's evolution changed drastically in the mid-to-late 1990's. Until that point the demand caused by the gradual increase in crude steel production and the substitution of BF-OHF plants was mostly being met by the EAF route, whose share doubled during that period due to its increasing implementation in South Korea and several western countries. However, that changed with the production boom in China and, more recently, in India, which had a much smaller share of EAF in steel production and relied more on the BF-OHF and BF-OHF routes (see figure 21). This led EAF's share to decrease, as the large increase in demand was being met by the BF-BOF route, and the average energy intensity of each route (and total) to stagnate, as the effect of further efficiency improvements in most developed countries have been counterbalanced by the ever-growing importance of countries with more energy intensive steel industries.

The combination of the stagnation it provoked in both energy efficiency and production shares resulted in the distribution of the energy used by fuel remaining nearly the same in the last 20 years, as the results presented in figure 49 seem to corroborate. This caused the CO_2 intensity of steel production to stall as well.

It can be concluded that the recent stagnation of energy intensity is a consequence of the exponential increase of steel production in countries that are still several years behind the main developed countries in terms of efficiency. Furthermore, it shows that there is still room to reduce the energy intensity – and consequentially the CO_2 intensity – of every route and to increase the share of steel produced using EAFs, and successful reductions of the industry's energy and CO_2 intensities require both.

4.3. Energy and CO_2 intensity long-term scenarios

The main takeaways from the analysis of the industry's energy efficiency and CO_2 emissions evolutions are now used to draw potential scenarios and assess the likelihood of the climate goals set being achieved. Both the energy and the CO_2 intensity scenarios are presented in figure 54, with the effect of each of the incremental steps take being plotted separately.

By reducing BF-BOF's **share of steel production** from 71 to 53 per cent and increasing DRI-EAF's and Scrap-EAF's share from 7 to 11 per cent and 33 to 36 per cent, respectively, the industry's average energy intensity would decrease by almost 10 per cent over this period. That reduction would be even larger for CO_2 intensity as it would decrease just above 18 per cent, which is mainly due to the difference between the Scrap-EAF's and BF-BOF's average CO_2 intensities being much bigger than the difference between their energy intensities, thus making an increase in the use of

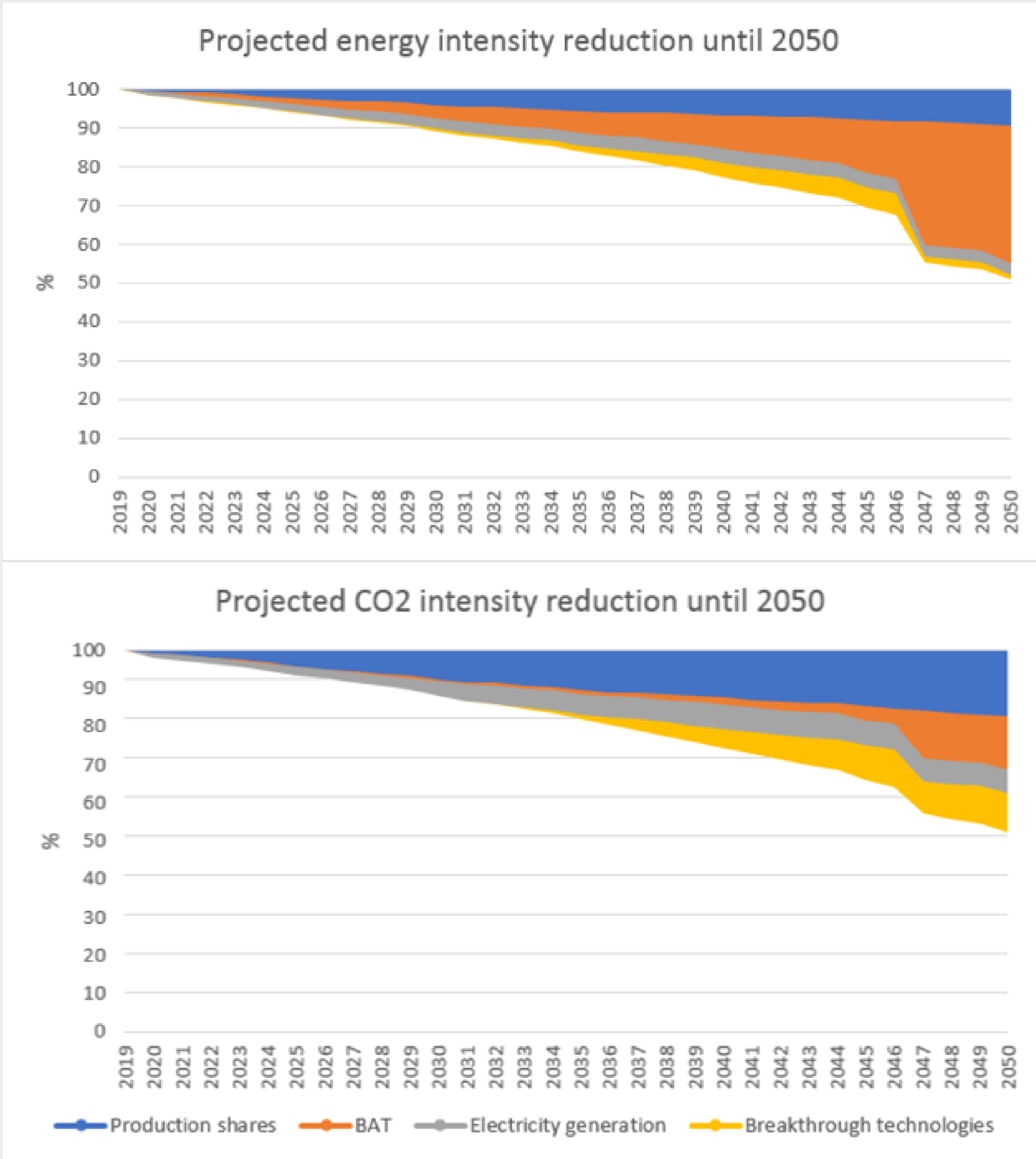


Figure 54 - Projected reduction of energy and CO_2 intensity until 2050.

Scrap-EAF more effective in reducing the first. Nonetheless, the results obtained show that an alteration of the production shares alone would allow for significant reductions in both areas.

If to the increase of production using EAFs, and the consequential decrease of production from the BF-BOF route, is added the **implementation of BAT** across all routes the reductions obtained in both energy and CO_2 intensity would increase drastically, especially for the first. By doing so they would decrease 45 and 31 per cent until 2050, respectively. Much of the energy intensity's decrease has to do with the BAT values used considering thin slab casting instead of continuous casting, which reduces the need for further processing and allows to save around 2 GJ/t in both the DRI-EAF and Scrap-EAF routes and over 4GJ/t in the BF-BOF route (see section 2.3.1.5). If the BAT values had considered continuous casting its estimated impact on energy intensity would be significantly smaller and much closer to the one on CO_2 intensity. In both scenarios the potential reductions are largely affected by average age of the blast and DRI furnaces, as the percentage of those requiring substitution would be a limiting factor to the implementation of BAT. Since their current average age is 13 years and they usually have a lifespan of 40 years, the potential impact of BAT in the next 27 years is very limited. However, after 2046, the very large amount of ISP that need to be replaced poses a great opportunity to implement the BAT and seriously tackle the industry's heavy energy consumption and CO_2 emissions.

Moving away from fossil fuels in **electricity generation** could further push the reduction of energy and CO_2 intensity to a total of 48 and 37 per cent, as the shift to cleaner energy sources would potentially increase the average efficiency of electricity generation by nearly 25 per cent and reduce its CO_2 intensity in one third. Their impact on the energy and CO_2 intensity of steel production may not seem impressive at first sight but their potential for future reductions – beyond those projected – is immense. It was considered that electricity accounts for 50 per cent of energy consumed in both EAF route and 7 per cent in the BF-BOF route, which, due to BF-BOF being responsible for the greatest amount of steel produced, mean that by 2050 electricity would still only account for 27 per cent of the energy consumed in steel production. Even though this limits the impact that a change in electricity generation would have on the industry's energy and CO_2 intensity, it also means that its potential to reduce them will only increase with the reinforcement of both the DRI-EAF and the Scrap-EAF production shares and the surge of alternative steelmaking methods that rely heavily on electricity as an energy source.

With the **implementation of near-zero emission technologies** both the energy and CO_2 intensity of steel production are projected to be reduced almost in half, as they would experience a total reduction of 49 and 48 percent respectively. Despite being efficient processes, their goal is to reduce emissions and therefore their impact on the industry's energy intensity is not expected to be significant. In fact, the SR-BOF with CCUS has a greater average energy intensity than the BAT for the BF-BOF process, thus its substitution does not contribute to reduce energy consumption. Furthermore, the main responsible for the extra 1 per cent reduction projected is not their implementation itself but the increase of the use of electricity consumed that comes with it, as efficiency improvements in its generation become more of a factor. Their impact on CO_2 intensity is much larger, with a projected extra reduction of 10 per cent. However, most of it is expected to occur only after 2035, when all three processes are already being used. This suggests that over a bigger period of time it would be possible to reduce the industry's CO_2 intensity much further, specially as there is still room to increase both their shares of production – together the three processes are expected to account for 20 per cent of the total crude steel production by 2050 – and the use of electricity in steel production.

Although the combination of these strategies is expected to be able to reduce the CO_2 intensity of the iron and steel industry by 48 per cent, it would not still be enough to reach the CO_2 emissions reduction targets set by the IPCC. This comparison is shown in figure 55, where their projected reductions until 2050 are plotted side by side with the reductions that are required to limit global

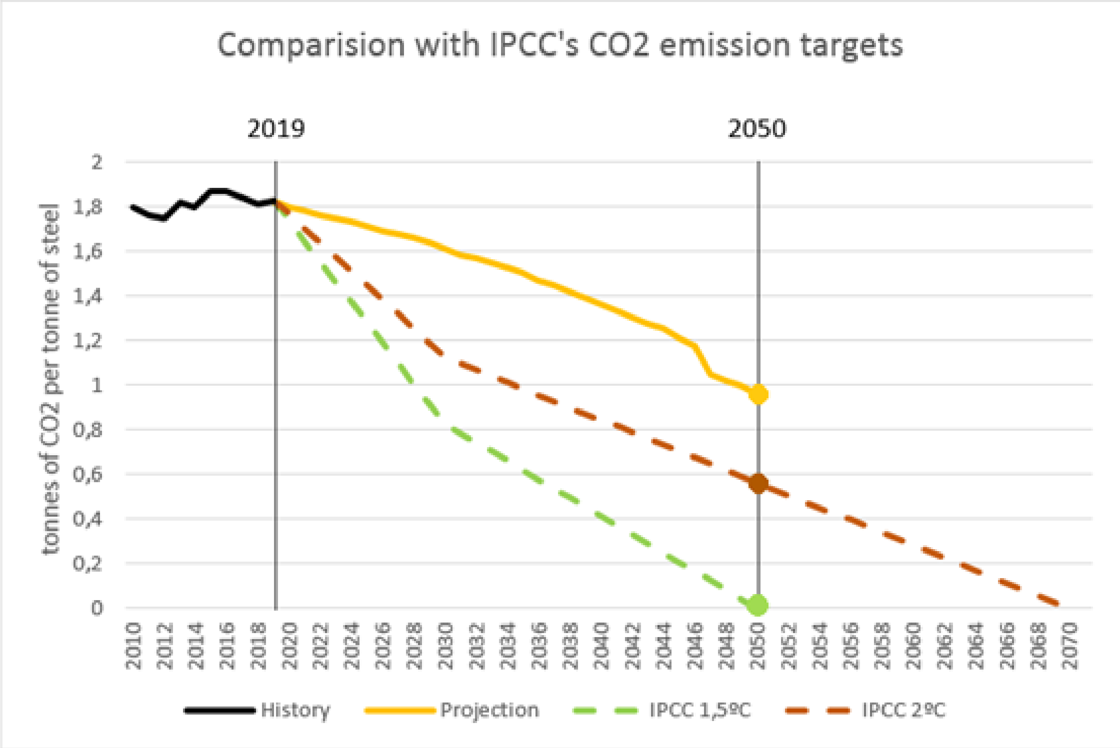


Figure 55 - Comparison between the CO_2 intensity reduction projected with those required to limit global warming to 1.5 and 2º C.

warming to 1.5 and 2°C (see section 2.4.3.1). Besides claiming that these scenarios require reaching net zero emission by 2050 and 2070, the IPCC also states that for the first scenario to happen the CO_2 emissions by 2030 should be 45 per cent smaller than those of 2010 and for the latter that required reduction decreases to 25 per cent. However, as the steel production will likely continue to grow, this requires CO_2 intensity to be reduced even more. With the IEA expecting steel production to grow from nearly 1900 million tonnes this year to 2500 in 2050, reducing the CO_2 in 25 and 45 per cent would require the CO_2 intensity to be reduced by 30 and 54 per cent. Looking at the graph it is clear that the projected reductions are nowhere near those indicated for 2030 nor they are on track to achieve net zero emissions by 2050 or 2070.

5. Discussion and conclusions

5.1. Discussion

The exponential growth of steel production that started in the mid to late 1990's aggravated the impact of iron and steel industry's high energy and CO_2 intensities. Not only it meant that their reduction over the preceding decades was no longer enough to lower its energy consumption and CO_2 emissions, but it also stopped that reduction. Therefore, minimizing the industry's impact on climate change requires tackling both the demand of steel and the energy and CO_2 intensities of its production.

Between 1970 and 2000 both the energy and CO_2 intensities were significantly reduced (around 50 per cent), with every tonne of crude steel produced requiring slightly over 20 GJ and emitting around 1.8 tonnes of CO_2 on average (by 2000). However, those improvements stopped and today´s values are nearly the same. This stagnation has been mainly due to the rapid increase of steel production in emerging countries where it is less energy efficient and more carbon intensive, which has been counterbalancing the improvements that have been occurring in some developed countries. First it was China, whose sevenfold increase of steel production between 1999 and 2019 made it the number one producer in the world with over 50 per cent of the total production. India, more recently, has also experienced a significant growth in steel production and expects it to accelerate in the coming years, meeting the country's populational growth and economic development. This highlights the importance of extending the technical improvements and structural changes to the emerging countries, otherwise those will not effectively reduce the industry's average energy and CO_2 intensities.

Some of the recent technological breakthroughs include the application of "CO_2 management" technologies such as Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) to the already existent steelmaking methods. These can be implemented by retrofitting operational plants with CO_2 capture and utilisation technology, thus presenting a valuable temporary solution to mitigate emissions in plants that most likely will not be replaced any time soon. Potential long-term issues like the aggravation of the use of fossil fuels reinforces that it should play a transitional role in the decarbonisation process, with the choice for the long-term falling on "CO_2 direct avoidance" technologies instead. Some of the most notable technologies include the use of hydrogen and electrolysis to directly reduce iron ore. Their adoption in the construction of future plants is fundamental for a sustainable and effective reduction of the industry's CO_2 intensity, as they minimize the emission of CO_2 by avoiding the use of fossil fuels. Their only emissions are indirect and come from the generation, which can and should be tackled as well.

The application of the best available technology (BAT) across the world would also drastically reduce the industry's average energy and CO_2 intensities and therefore must be made a priority. In the scenarios projected their application led to a reduction of the energy and CO_2 intensities of nearly 40 and 17 per cent, respectively. Today's average energy and CO_2 intensities of the main steelmaking routes are well above the best available technologies, which proves there is still a big room for improvement. This is of added importance since the leading countries in steel production have been emerging countries where steel production is less efficient and more carbon intensive. They have been the ones pushing the world steel production up and, considering India's expected populational growth and economic development, are likely to strengthen their position, thus reducing the efficiency and carbon intensity gaps between them and the developed countries would impact today's and future's averages greatly.

These can be further reduced by increasing the share of EAF and shifting towards a recycling-based production, maximizing the benefits of its low energy consumption and CO_2 emissions. This is, however, limited by the scrap availability and its ratio to steel demand, which makes the continuous increase in steel demand a big obstacle, especially as there is a significant delay between the steel being produced and originating end-of-life scrap. Since steel products have and average lifespan of 40 years the current availability of scrap is influenced by the steel production levels of the early 1980's, thus nowhere near enough to cover today's demand. Furthermore, China's exponential growth of the early 2000's is only expected to impact scrap availability in the 2040 decade.

An increase of the EAF's production share would make improving the efficiency and carbon intensity of electricity generation extremely important, as its consumption in steel production would definitely increase. Even though the current dominance of the coal-based BF-BOF steelmaking route has been keeping the share of electricity in final energy consumption still under 20 per cent, thus diminishing any improvements made to its generation, this would still be a valuable contribution in reducing the energy and CO_2 intensities of today and would maximize emission reduction potential of future technological breakthroughs.

The combination of these strategies would lead to a CO_2 intensity of 0.96 tonnes of CO_2 per tonne of steel in 2050. This shows that despite the application of these strategies being able to reduce both the energy and CO_2 intensities in almost 50 per cent it would still not be enough for the iron and steel industry to achieve net zero emissions by 2050 nor would put it in track to do it in 2070. This is especially alarming considering that the scenarios drawn were based in rather optimistic steel production forecasts that predict its rapid growth of the last decades will slow down. If those predictions are proven to be unrealistic, like most have been, the situation will get even more complicated. Furthermore, it was considered that every integrated steel plant past their lifespan would be replaced either by a state-of-the-art version of the same steelmaking process or by an alternative method equipped "CO_2 direct avoidance" technologies. Due to the high costs associated those renovations and steel's competitive industry this will only be possible if governments implement incentive policies to lower those cost and limit and tax the industry's CO_2 emissions. The latter, however, would require a joint action from governments all around the world to ensure that there would be a level playing field and steel companies would not be benefited nor harmed due to their location.

The negative forecast must be a wake-up call to governments and companies and push them to double down on their efforts to decarbonise the iron and steel industry and to do it together. In 25 to 30 years the vast majority of the world's DRI and blast furnaces will need to be replaced and the production boom of the beginning of the century will finally make itself noted in scrap availability. The combination of these two situations presents a tremendous opportunity to effectively restructure the industry and reduce its environmental impacts. It is then mandatory that steel producers invest heavily in the research and development of new technologies to tackle these issues as soon as possible and make the most of that opportunity.

5.2. Conclusions

The breakdown of the evolution of steel production and the forecast of its energy and CO_2 intensities scenarios allowed to better understand the dynamics of the industry, highlight its main challenges and disclose some of the strategies that must be followed to overcome them. It was also possible to analyse the impact these strategies can have and realise the importance of their application and complementary use. The need to decarbonise steel production is undeniable and there is a lot of ground to cover in an ever shorter amount of time, hence the necessity of a concerted and dedicated effort by governments and steel producers.

The scenarios projected showed that even with the implementation of multiple energy saving and emission reduction strategies is very unlikely to achieve any of the IPCC net zero emissions goals. Their combination resulted in a 49 per cent reduction of energy intensity and a 48 per cent reduction of CO_2 intensity by 2050, with the latter leading to an average CO_2 intensity of 0.96 tonnes of CO_2 per tonne of steel (in 2050).

There were obstacles along the way that limited this work and forced to change some of the initial goals. The most notable one was the data from the IEA World Energy Balance being incomplete. This made it impossible to compare the evolution of energy efficiency and carbon emissions between different stages of steel production and analyse whether their variation over the years has been mostly caused by improvements in the steelmaking process or in the production of the energy source used. It also forced the utilisation of data from different sources to cover the evolution since 1970, which proved to be difficult due to them often using different boundaries to define the system and referring to a very specific group of plants that is not representative of the steel production around the world.

In future works it would be interesting to do a separate analysis for the main emerging countries and draw global scenarios by putting together their evolution with the evolution of the developed countries. Looking at the world's average energy and CO_2 intensities can be misleading.

There are many dynamics that offset others, which makes us unaware of their existence or even leads us to wrongly assume they did not happen in the first place. Therefore, breaking down the analysis by regions with similar evolution patterns and dynamics – economical, cultural, etc. – would reduce the margin of error of the scenarios drawn and result in takeaways that are more likely to reality.

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Appendix A

Category	Fuel	NCV (MJ/kg)	Carbon content (tC/t)
Primary energy sources	Hard coal (if no detail)	26,7	0,72
	Brown coal (if no detail)	11,9	0,33
	Anthracite	26,7	0,72
	Coking coal	28,2	0,73
	Other bituminous coal	25,8	0,67
	Sub-bituminous coal	18,9	0,5
	Lignite	11,9	0,33
	Peat	9,76	0,28
	Natural gas	48	0,73
	Natural gas liquids	44,2	0,77
	Crude oil	42,3	0,85
	Primary solid biofuels	11,6	0,32
	Biogases	50,4	0,75
	Biogasoline	27	0,52
	Biodiesels	27	0,52
	Other liquid biofuels	27,4	0,59
	Non-specified primary biofuels and waste	11,6	0,32
	Industrial waste	-	-
	Municipal waste (non-renewable)	10	0,25
Secondary energy sources	Refinery gas	49,5	0,78
	Liquefied petroleum gases (LPG)	47,3	0,81
	Motor gasoline excl. biofuels	44,3	0,84
	Other kerosene	43,8	0,86
	Gas/diesel oil excl. biofuels	43	0,87
	Fuel oil (residual)	40,4	0,85
	Naphtha	44,5	0,89
	White spirit & SBP	40,2	0,8
	Lubricants	40,2	0,8
	Bitumen	40,2	0,88
	Petroleum coke	32,5	0,86
	Other oil products	40,2	0,8
	BKB	20,7	0,55
	Peat products	20,7	0,55
	Patent fuel	20,7	0,55
	Charcoal	29,5	0,9
Final energy produced and consumed in the iron and steel industry	Coke oven coke	28,2	0,82
	Coke oven gas	38,7	0,47
	Coal tar	28	0,62
	Blast furnace gas	2,47	0,17
	Other recovered gases	2,47	0,17
	Gas coke	28,2	0,82
	Gas works gas	38,7	0,47

Table A. 1 – Net calorific value (NCV) and carbon content of the fuels used in steel production.