Evolution of the energy efficiency and CO_2 emissions of the Iron and Steel Industry

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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.

1. Introduction

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.) 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.

2. Overview of the iron and steel industry

2.1. Current structure of the iron and steel industry

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. Today's refining processes occur almost exclusively in basic oxygen

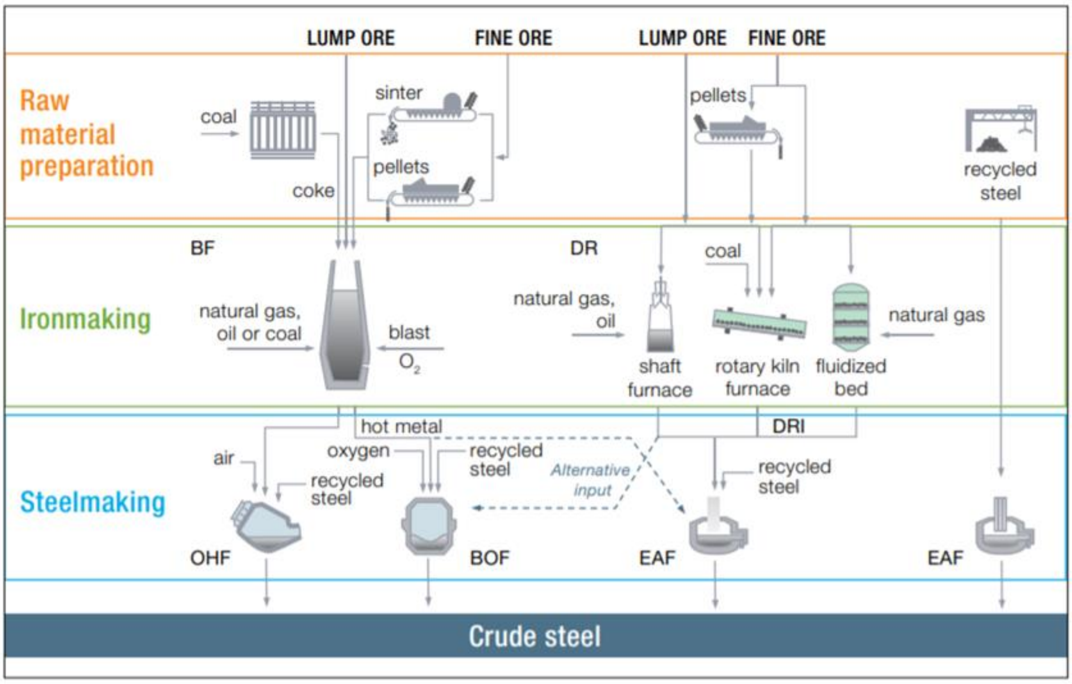

Figure 1 - Steelmaking routes (World Steel Association, 2019).

furnaces (BOF) and electric arc furnaces (EAF), with the first being responsible for 70 to 75 per cent of today's steel production and the remain being produced almost entirely by the latter (Holappa, 2019).

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.

Table 1 and 2 list the energy and CO_2 intensity values for these routes. The combination of those with the production shares of the respective route put the current average energy and CO_2 intensities at 18.6 GJ and 1.83 tonnes of CO_2 per tonne of steel (IEA, 2020; World Steel Association, 2020b). It should be noted that these values do not consider hot rolling or finishing processes.

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 1 - Energy intensities of each steelmaking route in GJ/t. The 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 nor consider electricity production.

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 2 - CO_2 emission factors of the main steelmaking routes.

2.2. Future scenarios and long-term goals

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 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 (International Energy Agency., 2020a).

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 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, 2020a).

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 consumed will account for 50 per cent of the annual crude steel production, instead of the current 33 per cent (Çiftçi, 2018). This increase is largely due to the expected scrap availability resulting from China's production increase over the last decades (World Steel Association, 2021c). 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

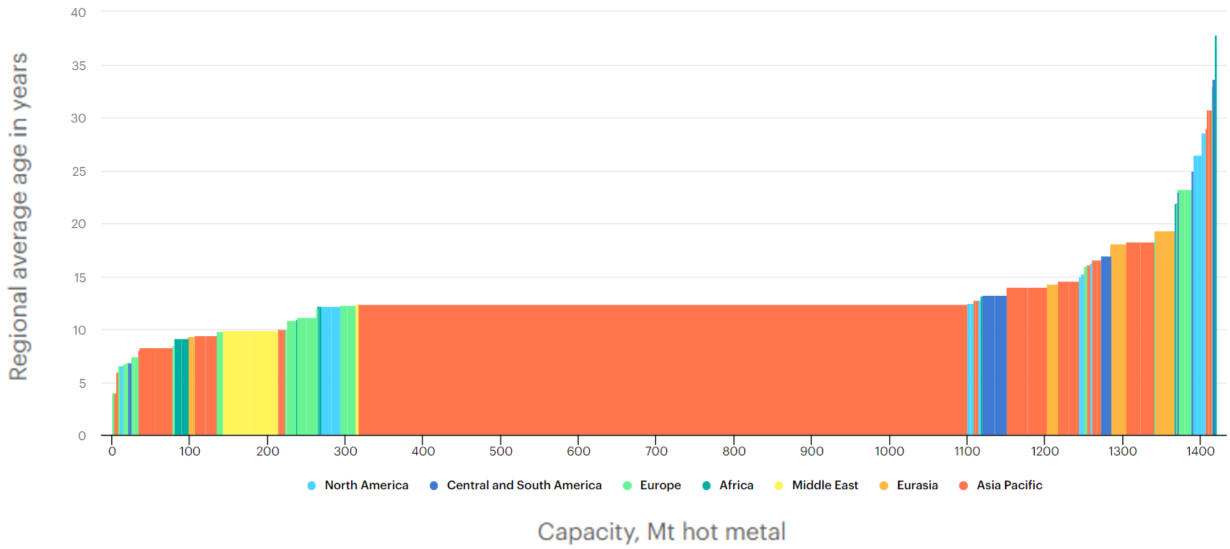

Figure 2 - Age profile of global production capacity for the steel sector (blast furnaces and DRI furnaces) (modified from IEA, 2020a).

mini mills or other alternative and more environmental-friendly routes. Figure 2 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).

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).

2.3. Carbon reducing 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).

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. The share of electricity use would increase likewise and so would the demand for **electricity decarbonization**.

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.

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, 2020).

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, 2021a). 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, 2021b).

3. Method

3.1. 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 were 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 3 - 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. 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 2.1 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.

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 2.1. 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.

4. Results

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

By isolating the efficiency improvements in each route from the change in their shares of production it is possible to conclude that both factors have equally contributed to the decrease of the industry's average energy intensity. Figure 3 shows that multiplying each route's share

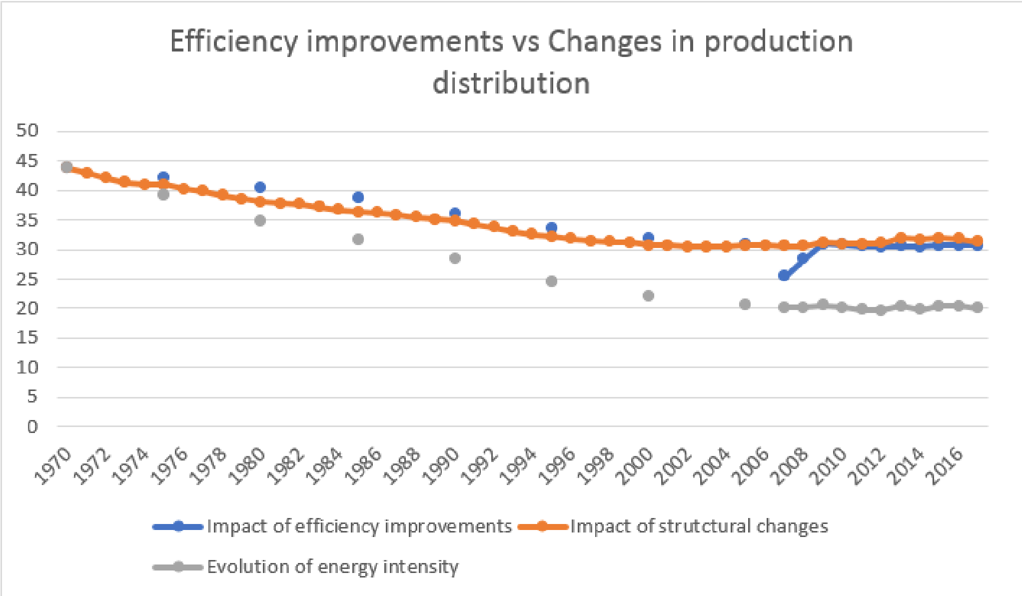

Figure 3 - Comparison of the effect of efficiency improvements in steelmaking routes and the variation of their production shares on the reduction of energy intensity.

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.

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.

4.2. Energy and CO_2 intensity long-term scenarios

The combination of these strategies is expected to be able to reduce the energy intensity by 49 per cent and reduce CO_2 intensity by 48 per cent 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).

This would not still be enough to reach the CO_2 emissions reduction targets set by the IPCC. This comparison is shown in figure 4, where their projected reductions until 2050 are plotted side by side with the reductions that are required to limit global warming to 1.5 and 2°C. 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

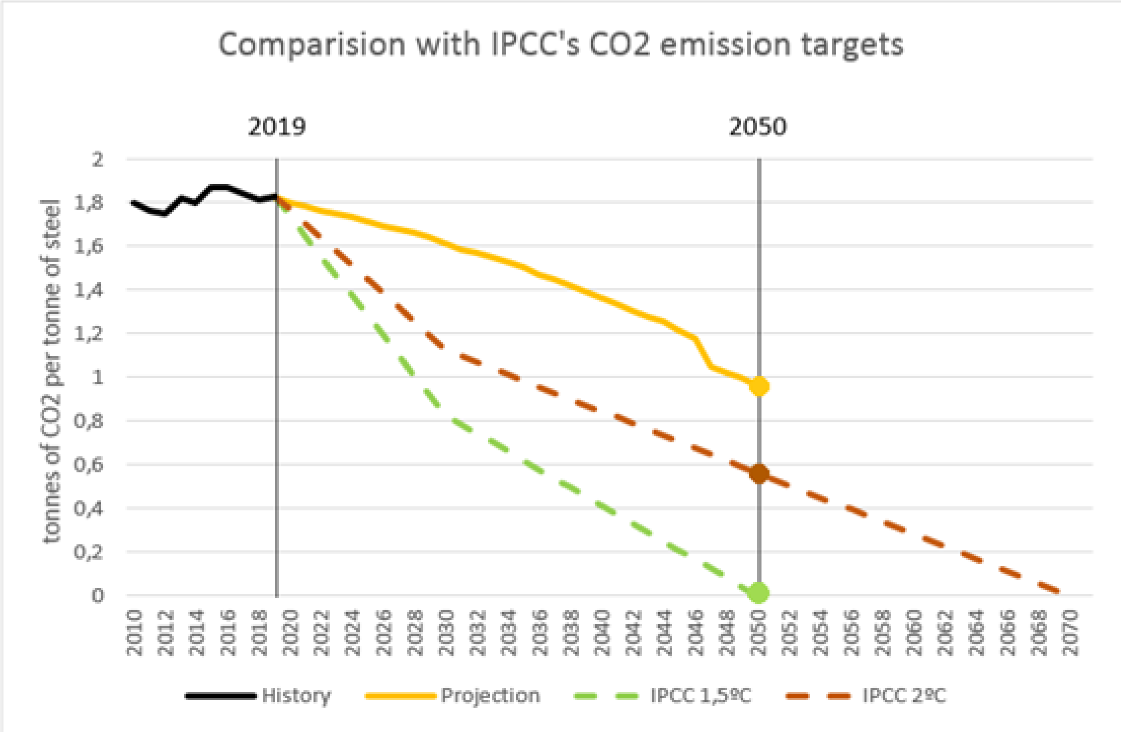

Figure 4 - Comparison between the CO_2 intensity reduction projected with those required to limit global warming to 1.5 and 2º C.

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. Conclusions

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).

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.

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