energy transition

Scoping Paper on the Brazilian DECARBONIZATION

STEEL INDUSTRY

DECARBONIZATION · BRAZILIAN INDUSTRY ·

CO_2

energy transition

Scoping Paper on the
Brazilian DECARBONIZATION

STEEL INDUSTRY

STUDY BY

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ACRONYMS AND DEFINITIONS

ABRAFE	*Associação Brasileira dos Produtores de Ferroligas e Silício Metálico* / Brazilian Association of Ferroalloys and Metallic Silicon Producers
AMIF	*Associação Mineira da Indústria Florestal* / Forest Industry Association of Minas Gerais
APP	Area of Permanent Preservation
BEN	*Balanço Energético Nacional* / Brazilian Energy Balance
BNDES	*Banco Nacional de Desenvolvimento Econômico e Social* / Brazilian Development Bank
BF-BOF	Blast furnace-blast oxygen furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital expenditure
CDM	Clean Development Mechanism
CGEE	*Centro de Gestão e Estudos Estratégicos* / Center of Management and Strategic Studies
CBAM	Carbon Border Adjustment Mechanism
CCfDs	Carbon Contracts for Differences
CDF	Contract for Difference
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CDRI	Cooled direct reduced iron
CO2	Carbon dioxide
COPAM	*Conselho Estadual de Política Ambiental de Minas Gerais* / State Council for Environmental Policy of Minas Gerais
CSN	Companhia Siderúrgica Nacional
DR	Direct reduction
DRI	Direct reduced iron
DPC	Drying, Pyrolisis, Cooling
EAF	Electric arc furnace
EOF	Energy Optimising Furnace
EPE	*Empresa de Pesquisa Energética*/ Energy Research Office
ETS	Emissions Trading System
EW	Electrowinning
FBMC	*Fórum Brasileiro de Mudanças do Clima*/ Brazilian Forum on Climate Change
FISET	*Fundo de Investimentos Setoriais* / Sector Investment Fund
FSC	Forest Stewardship Council

GEF	Global Environment Facility
GHG	Greenhouse gases
GPP	Green Public Procurement
LR	Legal Reserve
H2	Hydrogen
HBI	Hot Briquetted Iron
H-DR	Hydrogen Direct Reduction
H-DRI	Hydrogen Direct Reduced Iron
IEA	International Energy Agency
IPPU	Industrial process and product use
IABR	*Instituto Aço Brasil* / Brazil Steel Institute
IBÁ	*Indústria Brasileira de Árvores* / Brazilian Tree Industry
IBDF	*Instituto Brasileiro de Desenvolvimento Florestal* / Brazilian Institute of Forestry Development
IEF	Instituto Estadual de Florestas / State Forestry Institute
IPCC	Intergovernmental Panel on Climate Change
IPEF	*Instituto de Pesquisas e Estudos Florestais* / Institute of Forestry Research and Studies
MAPA	*Ministério da Agricultura, Pecuária e Abastecimento* / Ministry of Agriculture, Livestock and Supply
MCTI/MCTIC	*Ministério da Ciência, Tecnologia e Inovações* / Ministry of Science, Technology and Innovations
ME	*Ministério da Economia*/ Ministry of Economy
MEO	Molten Electrolysis Oxide
MMA	*Ministério do Meio Ambiente* / Ministry of the Environment
NDC	Nationally Determined Contribution
NG	Natural Gas
NG-DRI	Natural Gas-Direct Reduced Iron
NGO	Non-governmental organization
ONU	*Organização das Nações Unidas* / United Nations
OPEX	Operational Expenditure
PNH2	*Programa Nacional do Hidrogênio* / National Program of Hydrogen
PNMC	*Política Nacional de Mudanças Climáticas* / National Policy on Climate Change
PDP	*Política de Desenvolvimento Produtivo* / Productive Development Policy

PEFC	Programme for the Endorsement of Forest Certification
R&D	Research and Development
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
SR	Smelting Reduction
SIF	*Sociedade de Investigações Florestais* / Forest Research Society
SINDIFER	*Sindicato da Indústria do Ferro no Estado de Minas Gerais* / Union of the Iron Industry in the State of Minas Gerais
UNDP	United Nations Development Programme
USP	*Universidade de São Paulo* / University of Sao Paulo
RCF	Rima Container Furnace
RDI	Research, Development and Innovation
RPPN	*Reserva Particular do Patrimônio Natural* / Private Natural Heritage Reserve
ROW	Rest of the World
TGRBF	Top Gas Recovery Blast Furnace
TRL	Technology Readiness Level
TIMO	Timber Investment Management Organization

UNITS

ha: Hectare

Gt_{CO2eq}: billion tons of CO_2 equivalent

M_t: Millions of tons

t_{CV}: ton of charcoal

t_{CO2eq}: ton of CO_2 equivalent

t_{steel}: ton of steel

KEY POINTS

In order to contribute to the discussion on opportunities in the decarbonization of the steel industry in Brazil, this study presents a systemic and conceptual review of traditional steel production routes, with a particular interest in low carbon trajectories. In addition, the role of the leading technologies in the Brazilian steel industry and the country's competitive advantages are discussed in light of the perspectives and projections of emissions in this sector.

In this sense, this work explores the paths for the decarbonization of the Brazilian steel industry through a scoping paper. From the outline of the general context of the steel industry in Brazil and worldwide, its objective is to identify the main conditions to support its transition towards a low carbon industry. In turn, this analysis can help stakeholders recognize opportunities, advantages, and challenges for the development of a low carbon steel sector in Brazil.

The key points of the study are:

1. **The Iron and Steel sector is the largest industrial source of greenhouse gas (GHG) emissions globally.** For this reason, governments and global corporations are focusing on their rapid decarbonization. Therefore, it creates a unique opportunity for Brazil, which has the strategic resources (iron ore, expertise in the use of charcoal, and high potential for renewable energy) necessary for transforming the global steel industry associated with climate neutrality.

2. **Hydrogen-based steel and sponge iron (DRI) production is seen as a great opportunity on the horizon until 2050.** A possible path to the decarbonization of the sector is the replacement of coal with natural gas to serve as a bridge to hydrogen technologies. In the future. Brazil has abundant potential for producing renewable hydrogen, with prospects of becoming a significant producer and exporter of hot briquetted iron (HBI) and green steel.

3. **Charcoal is a strategic raw material used by Brazil to produce low-carbon steel.** To position itself for this opportunity, Brazil needs to invest in the expansion of forests, sustainable charcoal production, hydrogen production, and new facilities and technologies to produce low carbon steel.

4. **The transition to net-zero emissions (net-zero GHG emissions) has been adopted by large producers in the Brazilian steel sector.** Still, there is no detailed description of how targets/goals will be achieved. Thus, it requires a combination of technologies and initiatives geared towards the specificities of the regions in which the industries are located.

5. **New policies and instruments for the transition to a net-zero emission economy are essential to achieve emission reduction targets.** In addition, government and industry must work together to enable the diffusion of less carbon-intensive technologies and processes.

INTRODUCTION

The transformation of sectors that consume fossil energy sources to clean and renewable energy sources is one of the main challenges and opportunities of the Brazilian energy transition.

The transformation of sectors that consume fossil energy sources to clean and renewable energy sources is one of the main challenges and opportunities of the Brazilian energy transition. In addition to its importance for the decarbonization of the Brazilian economy, the industrial sector's energy transition is an opportunity to support Brazil's economic recovery and socio-economic development. The country can take advantage of its potential for generating clean and renewable energy at a low cost to increase its productivity and competitiveness and play a leading role in meeting the growing global demand for low-carbon products.

According to the International Energy Agency (IEA, 2020a) the global steel industry has a roughly 8% share of global final energy demand. It is a prominent industrial source of GHG emissions, corresponding to 7% of global energy-related CO_2 emissions. Because of the progress made in developing of renewable hydrogen and clean steel-making technologies, the steel and iron ore industry is increasingly gaining significant attention, with decarbonization projects being developed in Europe, Asia, the Middle East, and even Latin America.

Brazil has significant international competitive advantages when it comes to building a low carbon steel sector.

Brazil has significant international competitive advantages when it comes to building a low carbon steel sector. First, the country is well-endowed with substantial iron ore reserves, which positions Brazil as the world's second-largest iron ore exporter. Second, the abundance of renewable energy sources, biomass, and water allows the country to produce low carbon or climate-neutral steel at significantly lower costs (Chapter 2.5) than in other regions. Such a transformation would add value to the Brazilian economy since the country can switch from exporting iron ore to more valuable ore based iron products and green steel. Also, the transformation reduces costs and GHG emissions of transport, which are one of the most critical comparative disadvantages of the Brazilian mining industry.

This work explores the constraints that lead Brazil to have a unique opportunity to transform its iron/mining industry and pig iron and steel production to meet the growing global demand for low carbon steel products. First, we analyze the profile of the worldwide steel industry and the different processes and mitigation technologies that are being developed and implemented. Next, we examine the Brazilian steel industry, its characteristics, climate change policies, and firm commitments. Lastly, we present information to support the transition to a low-carbon industry. We show the perspectives on steel emissions in Brazil and the role of the leading mitigation technologies in domestic production.

With our study we illustrate that Brazil has a unique opportunity to transform its industry for iron or mining and the production of pig iron and steel to supply an increasing global demand for low carbon steel products. As a result, this will reduce related GHG emissions and make the country one of the most promising investment destinations for decarbonization in the steel industry worldwide.

We hope that this analysis can help stakeholders recognize opportunities, advantages, and challenges for developing a low carbon steel sector in Brazil and make the country one of the most promising investment destinations for the decarbonization of the steel industry worldwide.

DECARBONIZATION BRAZILIAN INDUSTRY

1

GENERAL OUTLOOK ON INTERNATIONAL PROSPECTS

Steel is indispensable to modern society and is one of the materials with the broadest range of applications: buildings, infrastructure, transport, household products, etc. The sector contributes to the global economy with over 2.5 trillion USD in revenue and about 6 million people employed globally (World Steel Association, 2021a; IEA, 2020a).

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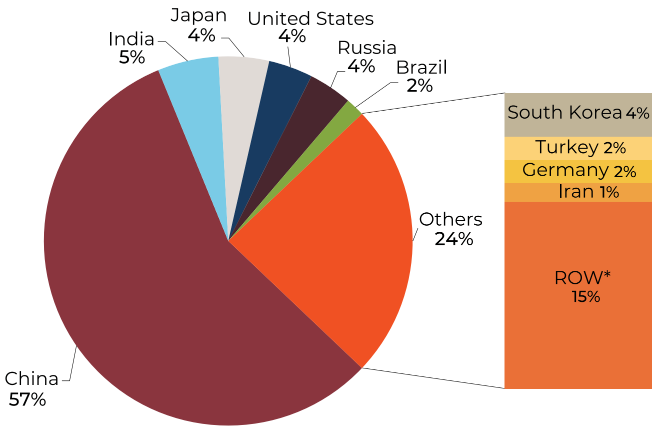
China concentrates most of the sector's production. For instance, this country holds 56.7% of the share of global output in 2020 (1,065 Mt), and is followed by India, Japan, the United States, and Russia, holding a smaller percentage of the production (Figure 1). The amount of steel produced by the top 10 countries accounts for 84.8% of the world production. Thus, the continents that hold the largest share of production are Asia (76.4%), Europe (14.9%), and North America (5.4%). Regarding global trade, China is also the largest importer and exporter of steel (World Steel Association, 2021b).

FIGURE 1 → **Steel production by countries in 2020**



Source: Adapted from World Steel Association, 2021b

When looking at the top 10 steel producers individually, seven of them are Chinese (Table 1). In 2020, China Baowu Group became the largest producer in the world, surpassing ArcelorMittal from Luxembourg (World Steel Association, 2021b). The top ten producers account for approximately one quarter of the total global output. At the same time, the top 25 and top 50 producers account for 42.7% and 58.1% of total production, respectively, illustrating how competitive the sector is (World Steel Association, 2021b).

TABLE 1 → **Steel production by companies in 2020**

Rank	Company	Production (Mt)	Share
1	China Baowu	115.3	6.1%
2	ArcelorMittal	78.5	4.2%
3	HBIS Group	43.8	2.3%
4	Shagang Group	41.6	2.2%
5	Nippon Steel	41.6	2.2%
6	POSCO	40.6	2.2%
7	Ansteel	38.2	2.0%
8	Jianlong	36.5	1.9%
9	Shougang	34.0	1.8%
10	Shandong	31.1	1.7%
ROW	-	**1,376.5**	**73.3%**
Total	-	**1,877.5**	**100.0%**

Source: Adapted from World Steel Association, 2021b

1.1

Traditional Steel Production Routes

Blast Furnace and Basic Oxygen Furnace

This technological route accounts for 70% of all steel produced (Fan and Friedmann, 2021). Considering the top country producers, this process consumes about 20-25 GJ and emits 1.5 to 2.5 tCO_2 per tonne of steel produced (Hasanbeigi and Springer, 2019).

The main production route of steel uses iron ore, coal, and limestone as feedstock. First, the coal passes through coke making, where the coal is heated, removing its impurities, and producing coke. Iron ore and limestone are prepared in the sinter or pellet plants. The next step is the reduction of the iron ore in the Blast Furnace (BF), producing pig iron. During this process, CO_2 is emitted as the result of the chemical reduction reaction. Finally, the pig iron goes into the Basic Oxygen Furnace (BOF), where oxygen is blown, reducing the carbon content of the iron, producing steel. Later, the steel passes through finishing processes to become the final product.

Electric Arc Furnace

Electric Arc Furnace (EAF) is the second largest steel production route, accounting for 25 to 30% of all steel produced in the world (Fan and Friedmann, 2021). In this production route, the main inputs are scrap and electricity. When using only scrap, the product is called secondary steel, in opposition to primary steel when using iron ore (BF-BOF). The process has lower energy and emission intensity when compared to the previous route (BF-BOF) production. The average top producer's energy consumption for producing one tonne of steel using EAF is less than half of the energy of the BF-BOF process. Accordingly, EAF production also emits half of the CO2 (0.4 to 1.6 tCO2/t steel) compared to BF-BOF (Hasanbeigi and Springer, 2019).

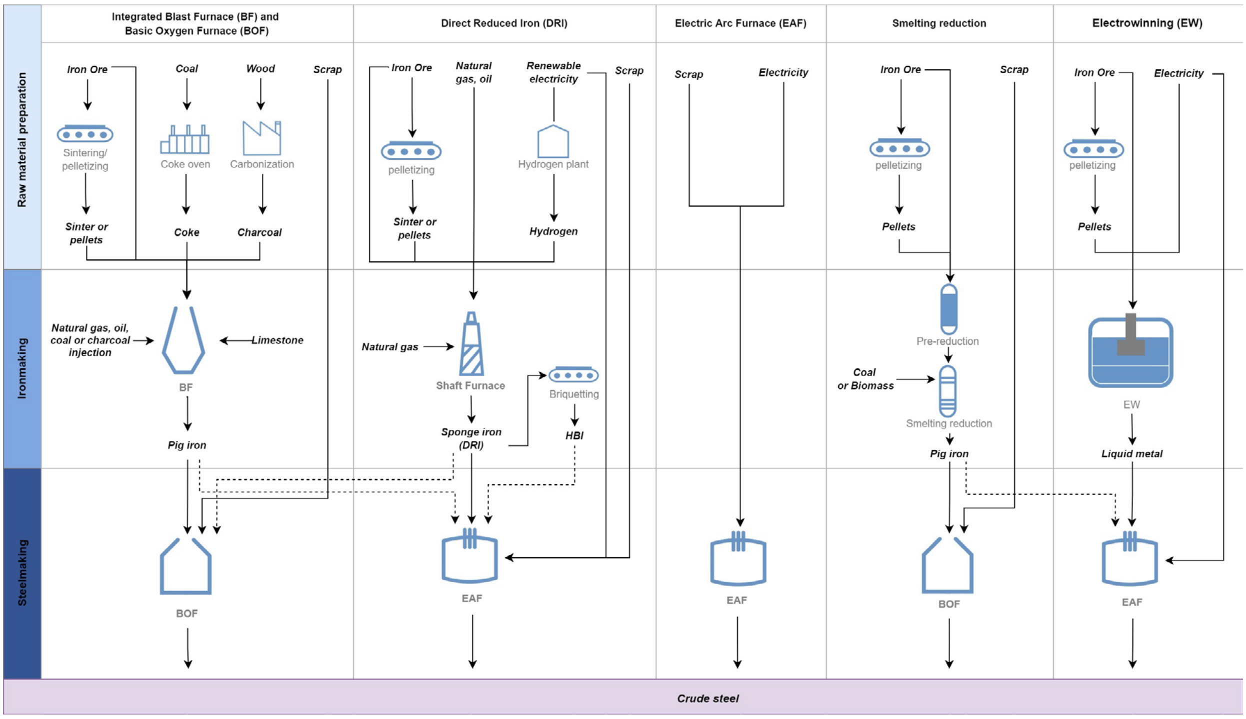
1.2

Low carbon Steel Production Routes

Mitigating the emission in the steel sector is crucial to meet the Paris Agreement (ETC, 2018). Three main mitigation options can be used to reduce emissions in steel production: **(i) Energy efficiency; (ii) Fuel/reducing agent replacement; and (iii) Carbon capture and storage (CCS)** (Arens et al., 2017; Eurofer, 2013; Griffin and Hammond, 2019a; IEA, 2020a, 2020b). Energy efficiency considers all mitigation measures that can be implemented into the current production to reduce energy consumption. The second option considers changing the way steel is made by considering technological routes that use less carbon-intensive fuels and reduction agents (e.g., Natural Gas, hydrogen, and electricity). Lastly, CCS technologies help to reach the goals in carbon intensive steel-making processes.

The next sections present the leading low-carbon steel production technologies that could help the sector in the decarbonization pathway. All routes for steel production are illustrated in Figure 2.

FIGURE 2 → **Flow Diagram of Steel Production: traditional and alternative technologies**



Adapted from World Steel Association, 2021b; Eurofer, 2013; MCTIC & ONU Meio ambiente, 2017

1.2.1

Energy Efficiency

Steel production can reduce its emissions by implementing measures that can decrease the amount of energy consumed. In the traditional production route, BF-BOF, energy efficiency improvements can reduce its emissions by 20% (IEA, 2020a). For example, **(i) the injection of pulverized coal or natural gas into the BF can reduce 0.36 to 0.77 GJ/t pig iron; (ii) Coke Dry Quenching has a potential for reducing 1.41 GJ/t coke in the coke making process; (iii) the recovery of BOF gas reduces the energy consumption by 0.73 GJ/t steel** (Hasanbeigi et al. 2013).

1.2.2

Direct Reduction

The Direct Reduction (DR) process can use a reducing gas (carbon monoxide and hydrogen) obtained from the natural gas reforming (Eurofer, 2013; Fischedick et al., 2014; Griffin and Hammond, 2019b). The reducing gas reacts with the iron ore, without melting it, producing the Direct Reduced Iron (DRI). In other words, the product of this process is solid DRI pellets instead of the hot liquid metal that is produced from a blast furnace. Due to the low-temperature requirements, it reduces the process energy consumption (Fischedick et al., 2014). The DRI can be transferred to an EAF to produce steel, it can be cooled (CDRI) to ease the transport to adjacent plants or compressed to become Hot Briquetted Iron

(HBI), the best form to transport DRI as an intermediate product (Toktarova et al., 2020, Tenova HYL, 2019). HBI has lower porosity, reducing its inflammability and oxidation, and becoming a more secure and stable product for transportation (Toktarova et al., 2020).

There are two key direct reduction technologies in the steel production: MIDREX and HYL-Energiron[1]. Together they account for 80% of the DRI produced in the world (65% MIDREX and 15% HYL/Energiron) (World Direct Reduction Statistics, 2019). Overall, the process has an energy consumption of 9.6 GJ/t DRI and is 20% less carbon-intensive than the BF route (Eurofer, 2013). Therefore, in countries with cheap natural gas, it can be an essential and competitive instrument to reduce emissions in steel production.

Another advantage of this technology is the possibility of partial or total substitution by hydrogen without significant modification of the reactor. Using renewable hydrogen instead of natural gas as a reducing agent in DR can further minimize emissions. Renewable hydrogen can be produced from water electrolysis, with oxygen as a coproduct. Providing the electricity used for this process has been generated from renewable sources, such as hydro, wind and solar generation, and the resulting hydrogen is carbon neutral. (Eurofer, 2013). This approach has a disadvantage in terms of cost and the infrastructure requirements. Electricity costs can have an enormous impact on production costs. Vogl et al. (2018) show the energy costs accounts for 32% to 47% of total production cost, depending on the price of electricity. For hydrogen based steelmaking in Germany, where electricity prices are comparably high, Agora Industry has calculated that hydrogen based steelmaking is competitive with the conventional production in blast furnaces at a carbon price of 208 €/ tCO_2 (Agora Energiewende, 2021).

Since 2021, the carbon price in the European market was higher than 30 euros per ton, reaching 96 euros in 2022[2] (Sandbag, 2022). In order to cover the remaining gap between the carbon price and the effective cost of producing low carbon steel, the European Union and its member states such as Germany and France are discussing the implementation of carbon contracts for difference as a policy incentive to build the first hydrogen-based steel making plants.

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DRI is one of the key mitigation strategies for decarbonizing steel (Bataille et al., 2021; IEA, 2020a). The projections of IEA (2020a) assume a high insertion of this technology until 2070. Furthermore, several companies are emphasizing this technology as part of their decarbonization strategies. Over 50% of the low-carbon technologies investment announced is DR (Agora 2021a, Agora 2021b).

1 Countries such as Iran, Canada, Argentina, Russia, Saudi Arabia, India, Oman, Egypt are using these technologies (see World Direct Reduction Statistics, 2019).

2 One of the main reasons for the increase of the price is the increase of NG prices that shifts the power generators toward coal, increasing both emissions and demand for emissions permits (Reuters, 2022).

1.2.3

Smelting Reduction

Another option to produce low-carbon steel is Smelting Reduction (SR). Unlike traditional methods, this process does not require coke production. Overall, smelting reduction splits the BF into two steps: first, coal pre-heating and iron ore pre-reduction. This process consumes 20% less energy than the BF-BOF technology (IEA, 2020a). However, some technologies, such as HIsarna, COREX, FINEX, and Tecnored, are projected to produce a CO_2-rich gas to be coupled into a CCS system, reducing the emissions of the process to near zero (IEA, 2020a). Another benefit of this technology is the potential to use biomass as an energy source and reducing agent (IEA, 2020a; Tecnored, 2021). According to the International Energy Agency, a demonstrative plant should start production between 2023 and 2027 in India with a capacity production of 0.5Mt/year and an industrial plant in the Netherlands around 1.5Mt/year in 2030 (IEA, 2020a).

1.2.4

Blast Furnace with Biomass

Biomass can also be used into blast-furnace to produce pig iron. Approximately, 10% of the Brazilian steel are produced using charcoal as reducing agent (IABr, 2021a). Its energy consumption is about the same as BF-BOF (21 GJ/t steel) (Hasanbeigi and Springer, 2019). However, because of the use of renewable sources, its emission intensity is ten times lower (0.25 tCO_2/t steel) (Pinto et al., 2018). One drawback of using charcoal in BF-BOF is the productivity and competitiveness. Charcoal can only be used in small BF; besides, the production is limited by the supply of charcoal next to the facilities and problems of a lack of carbonization technologies, i.e., GHG emissions related to charcoal production (see section 2.3.8) (MCTIC and ONU Meio Ambiente, 2017).

1.2.5

Electrowinning

There are innovative technologies that can reduce iron ore using electricity. The iron ore reduction happens in an electrolytic cube (Eurofer, 2013). For example, we can cite the technologies of Molten Oxide Electrolysis (MOE) by Boston Metal and ULCOLYSIS/ULCOWIN by Ulcos. According to Boston Metal (2021), 1 tonne of steel requires 5.5 MWh (19.8 GJ) of energy, which might be reduced to 4.0 MWh (14.4 GJ). Regarding costs, the process is competitive, if electricity costs are between 15 USD and 35 USD (Rauwerdink, 2019). Currently, pilot plants are in development. If clean electricity is used in this process, the emissions can be null. ULCOS and Boston Metal are working to develop pilot plants in the next few years (IEA, 2020a).

1.2.6

Carbon Capture and Storage

Carbon Capture and Storage (CCS) is another option highlighted as a key mitigation measure for the sector. It can help to reduce end-of-pipe emissions in fossil-fuel-based production processes or achieve negative emissions in those that use biomass (Griffin and Hammond, 2019a). The main disadvantages of this technology are its high cost and the need for large-scale infrastructure. It is important to notice that some of the smelting reduction processes produces a concentrated CO_2, facilitating its capture (EUROFER, 2013).

1.2.7

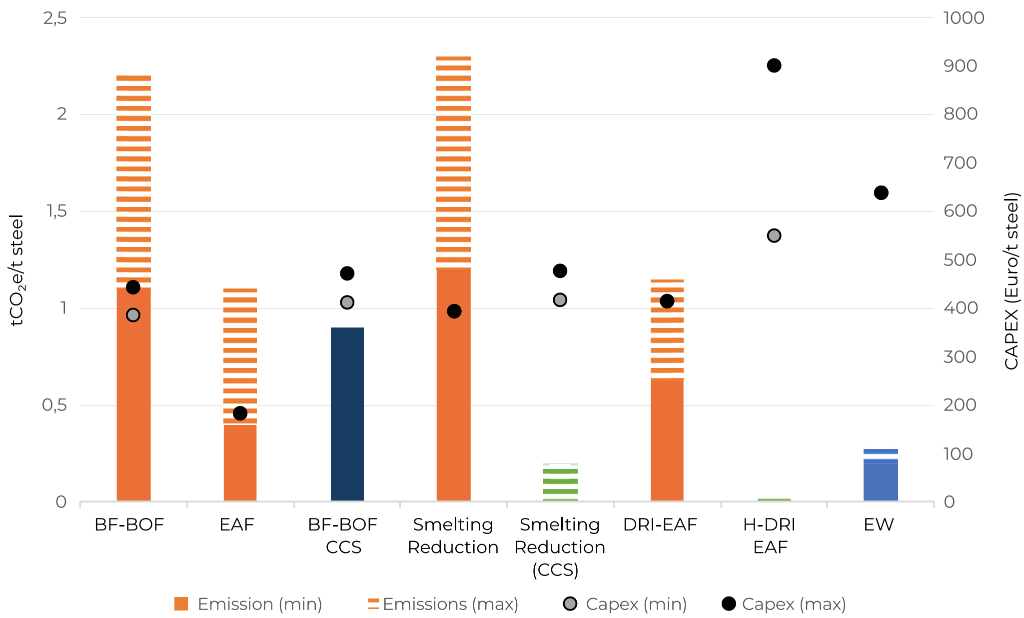
Technologies overview

Figure 3 outlines the technologies that can be used during steel production, considering its approximate emission intensity, and capital expenditure (CAPEX) and TRL Status[3]. It is a complex task to define the best technology option for producing steel in a decarbonization pathway. The best option to fit may differ depending on the emission goal of each country or steel producer, the specific national advantages, and their barriers. For example, EAF production has an inferior emission intensity and CAPEX, but it is constrained by scrap availability. Both Hydrogen Direct Reduced Iron (H-DRI) and Electric arc furnace (EAF) have a high electricity intensity. To become competitive, the country needs a low cost and clean electricity production. The use of biomass in the form of charcoal or charcoal fines can also play different roles in the process. Providing charcoal is sourced from sustainable agricultural and forest management practices, it can provide an alternative for the climate-neutral production of pig iron or steel. Moreover, it can be an essential complement for the hydrogen-based production route as a minimum share of carbon is needed due to metallurgical aspects of steelmaking.

The following section depicts the steel industry's prospects, highlighting companies' outlooks over the next 30 years.

3 **APPENDIX I** shows the steel production technologies in terms of emission intensity, CAPEX and TRL status. TRL stands for Technology Readiness Level. It varies from 1 (basic research) to 9 (commercial).

FIGURE 3 → Steel production technologies: emission intensity and CAPEX



Note: Blast Furnace - Basic Oxygen Furnace (BF-BOF), Electric Arc Furnace (EAF), Carbon Capture Storage (CCS), Directed Reduced Iron (DRI), Hydrogen Direct Reduced Iron (H-DRI) and Electrowinning (EW)

Source: Griffin and Hammond, 2019a; IEA, 2020a; Milford et al., 2013

1.3

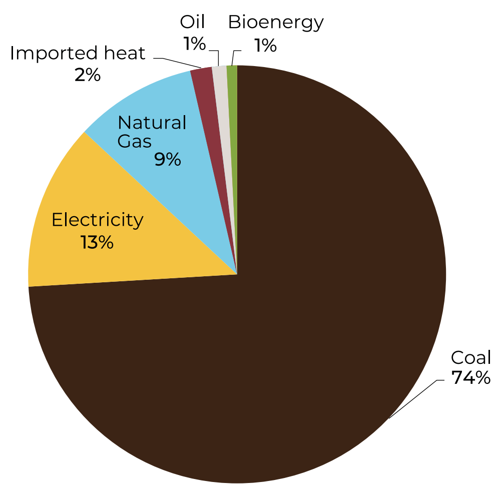
Steel Industry emissions

1.3.1

Energy Consumption and Greenhouse Gases (GHG) Emissions

The steel sector is the largest industrial GHG emitter and second-largest industrial energy consumer. In 2019, its energy consumption was 35 EJ, totaling 20% of the energy use in the industry sector. The most used fuel in the steel sector worldwide is coal, representing 74% of the sector's energy use. Besides coal, electricity, and natural gas account for almost all the sector's remaining energy demand (Figure 4) (IEA, 2020a). Notably, 16% of the global demand for coal is represented by coking coal, an input in steel production, which is also responsible for almost all its global demand (IEA, 2020a).

FIGURE 4 → Global steel industry energy mix in 2018



Source: IEA, 2020b

Because of its intensive energy use, with a high carbon profile, steel production was responsible for 7% of global CO_2 emissions from combustion and 1/4 of the CO_2 industrial (process-related) emissions in 2019. Despite the reduction in emissions due to the development of energy efficiency in the sector, each tonne of steel still emits an average global of 1.4 tCO_2 (IEA, 2020a).

Considering that the steel sector is a carbon-intensive industry, several steel producers have adopted emission reduction targets encouraged by several net zero initiatives worldwide as well as targets set by the countries in which they are headquartered. Five of the world's six largest producers (with Shagang being the exception) have already stated net-zero targets for 2050, and three already published reports detailing how they plan to achieve this goal (ArcelorMittal, 2021; HBIS GROUP, 2021; Nippon Steel Corporation, 2021; POSCO, 2020).

1.3.2

Emissions Projections

According to IEA (2020a), the steel industry must reduce its emissions by 50% until 2050 to meet the Paris Agreement Ambitions and to be aligned with net-zero emissions goals by 2070. This challenge is aggravated by the increase in steel demand attached to economic and population growth (IEA, 2020a). IEA analyzes two scenarios for the future of steel production. The Stated Policies Scenario (STEPS), based on the projection of the current pathway, and the Sustainable Development Scenario (SDS), where mitigation measures are taken to reach low emissions goals. Steel production grows from 1.9 Gt in 2019 to over 2.5 Gt in 2050 in the STEPS, an increase of approximately 30%, whereas in the SDS it only rises by 10% higher than in 2019.

The difference between the two IEA scenarios is mostly due to demand-side strategies and better material efficiency, particularly with the adoption of the following measures: **"(i) Extending the lifetime of buildings (6% reduction in demand in 2050); (ii) Direct reuse without remelting (3% reduction); (iii) Improved building design (2.5% reduction); (iv) Improved manufacturing yields (2.5% reduction), minimizing material losses during the process in which steel products are converted to end-use goods; (v) Reduced vehicle sales and use (2% reduction); (vi) Light weighting vehicles (2% reduction); (vii) Improved semi-manufacturing yields (1.5% reduction), minimizing material losses during the process in which crude steel is converted into steel products like bars, sheets, and coils"** (IEA, 2020a).

Scrap can be used as an input for both secondary and primary steel production to reduce iron ore and energy consumption. Despite not reducing total steel demand, scrap-based production reduces energy use and emissions. Therefore, an increase in the scrap collection rate is expected, especially for end uses and regions with current lower collection levels.

By 2050, IEA (2020a) expects an overall collection rate of 88% in STEPS, and just over 90% in SDS. In addition, total scrap availability is expected to increase considerably in both scenarios in 2050 (70% in STEPS and 43% in SDS, i.e., 1480 Mt and 1240 Mt), mainly because of the end-of-life of the steel-containing product. Importantly, despite the increase in total scrap availability, in 2050, scrap still represents only about 45% of total production inputs in both scenarios. According to Wang et al. (2021), the worldwide scrap supply will rise by ~3.5-fold from 2020 to 2050 and developed regions could generate scrap equivalent to their steel demand. The scrap supply depends on "social behavior, governmental regulation, product design, existing facility inertia and scrap quality".

To meet its future demand, the steel sector's geopolitics are based on two dynamics for the distribution of world production capacity. The first one is the stagnation or slight reduction in production in advanced economies (US, EU, Japan, and Korea). The second factor is the growth in many emerging economies, especially India. These countries would offset the decline in production in China, which is shifting its industrial structure to less energy-intensive activities. Until 2050, China's share of global production is expected to decrease from 53% in 2019 to 35% in 2050. In contrast, India's share of production is expected to increase from 6% to 17% in the same period.

It is also necessary to consider the potential to expand import/export to take advantage of the existing potential in regions with low renewable energy costs. For example, Australia and Brazil could become more prominent iron and steel producers, given their renewable energy potential and their iron ore reserve (IEA, 2020a; Wang et al., 2021, Wood Mackenzie 2021). Agora describes Sweden, Australia, South Africa and Brazil as Green Steel Opportunity Countries (Agora, 2021b).

Regarding emissions of the global steel sector, they are expected to increase, reaching 2.7 Gt CO_2 per year in 2050 (7% more emissions than in 2019) if no measures are adopted to reduce demand and improve the production process (IEA, 2020a). Implementing mitigation measures, like energy efficiency, EAF, H-DR, and CCUS at SDS led to a 54% reduction in emissions between 2019 and 2050 (1.2 Gt CO_2) (IEA, 2020a). Wood Mackenzie (2021) set a reduction goal of 75% in 2050 compared to today's levels to limit global warming up to 2°C. To achieve this reduction, it must "(1) doubling scrap use in steel making; (2) tripling direct reduced iron (DRI) production and use; (3) reducing global average electric arc furnace (EAF) emissions intensity by 70%; (4) reducing blast furnace – basic oxygen furnace (BF-BOF) emissions intensity by 30%, close to its theoretical minimum; and (5) capturing and storing 45% of the residual carbon emissions (around 500 Mt per annum)".

For net-zero emissions, Bataille et al. (2021) consider an increase in EAF production, Direct Reduction (Hydrogen and NG), and CCUS.

It is also necessary to consider the potential to expand import/export to take advantage of the existing potential in regions with low renewable energy costs.

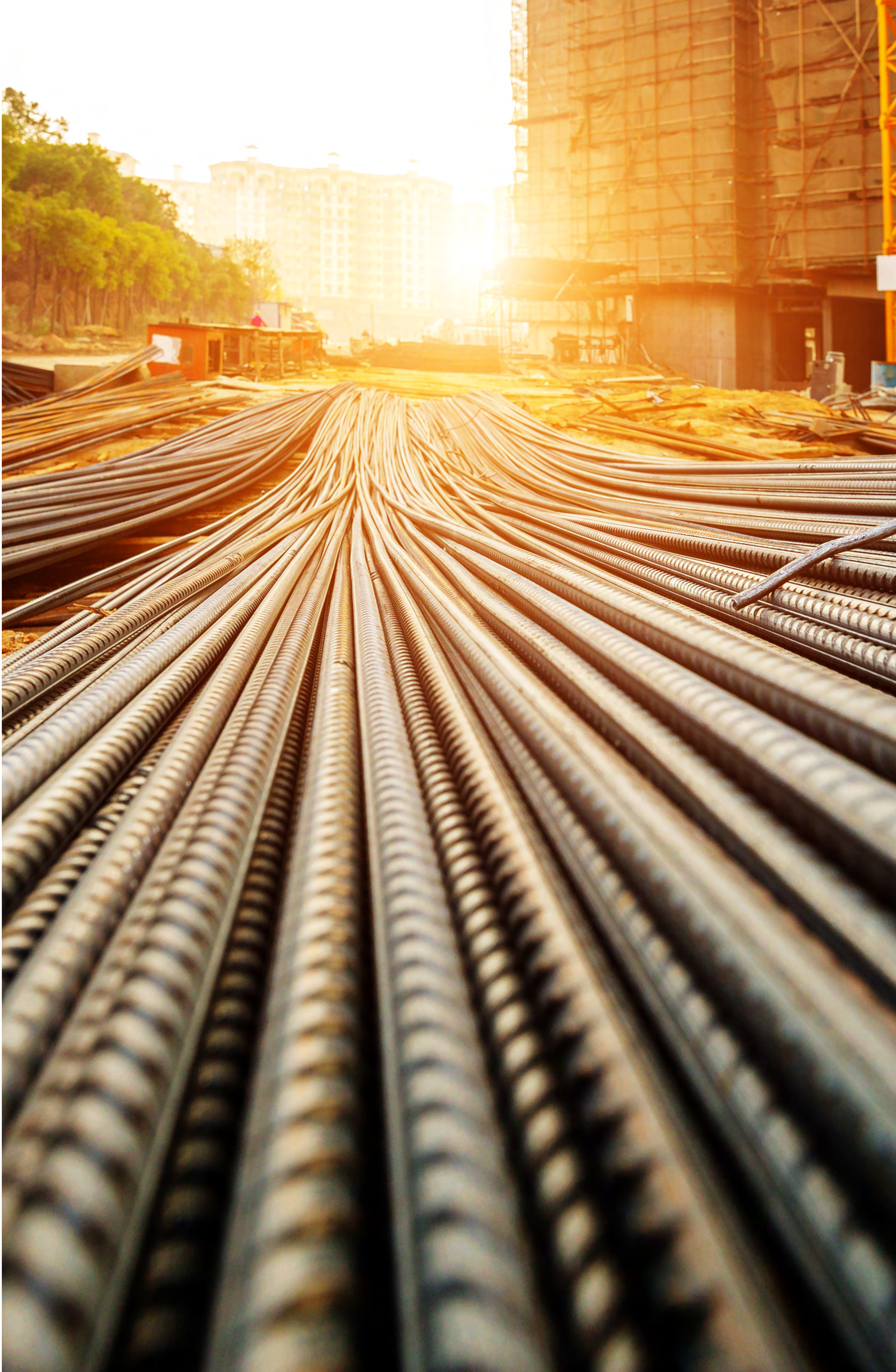
This will require implementing low-carbon technologies and policies and adapting to a less carbon-intensive society (IEA, 2020a; ArcelorMittal, 2021; Wang et al., 2021).

For achieving emission reduction goals, new policies and instruments for net-zero transition are essential. Government and industry must work together to enable the diffusion of less carbon intensive technologies and processes (ArcelorMittal, 2021; Hoffmann et al., 2020). As an example, a global carbon pricing[4] covering every region could be one of the most effective mechanisms to achieve emission goals. However, what has been happening are separate actions rather than a unified action (ArcelorMittal, 2021)[5].For more details regarding instruments, see **Appendix II**.

According to ArcelorMittal (2021) it is essential to deliver five market conditions to achieve climate goals: **"(i) Measures to incentivize the transition to low and zero carbon-emissions steelmaking; (ii) A fair competitive landscape that accounts for the global nature of the steel market, ensuring domestic production, import and exports are subject to equivalent GHG reduction regulations; (iii) Financial support to innovate and make long-term investments and neutralize the higher operating costs of low and zero carbon-emissions steelmaking; (iv) Access to sufficient clean energies at affordable price level; (v) Incentives to encourage the consumption of low and zero carbon-emissions**

4 There are two main types of carbon pricing: (i) a Carbon Tax and (ii) an Emissions Trade System. For more information regarding carbon pricing in Brazil see Wills et al (2021)

5 Van Ruijven et al. (2016) estimate a carbon tax of $100/t_{CO2}$ starting in 2020 and increasing 4% per year to reduce emissions by 80-90% in 2050 compared to 2010 level. Vercoulen et al. (2018) shows that a carbon tax of $200/t_{CO2}$ by 2050 will lead to a reduction of 75% emission in China, Japan, Korea, and Taiwan. Morfeldt et al. (2015) estimate a carbon tax ranging from 25 to $120/t_{CO2}$ to achieve a pathway in which production using CCS becomes cost efficient.



steel over higher carbon-emissions steel". ArcelorMittal also highlights the importance of the given instruments to enable this transition: ***"Emissions Trading System (ETS); Indirect compensation; Public funding via innovation awards, grants, loan; Carbon Border Adjustment Mechanism (CBAM); Carbon Contracts for Differences (CCfDs); Consumer carbon charge; Clean energy policies; and Green Public Procurement (GPP)".***

Considering the countries that contribute the most to the steel sector's emissions, there are different positions regarding the adoption of policies to achieve net zero. Some have already declared their goal in law, such as Germany, which plans to achieve carbon neutrality by 2045 (Agora, 2021c); and Japan and South Korea, which plan to achieve carbon neutrality by 2050. Besides these, some countries have an in-policy document, such as China, which plans to achieve carbon neutrality by 2060; and the United States and Brazil, which plan to achieve carbon neutrality by 2050. Finally, some countries do not have any carbon neutrality plan, such as India, Russia, Turkey, and Iran (Climate Watch, 2021; Energy & Climate Intelligence Unit, 2021; United Nations, 2021).

To achieve neutrality, most of these companies plan to adhere to the following measures: Smartization; Steelmaking transformation (footprint change, energy efficiency, pellets); Energy transformation (CCUS, DRI-Natural Gas, DRI-Hydrogen, Bioenergy); Increased use of scrap; Sourcing clean electricity; and Offsetting residual emissions. Among the main Brazilian steel companies (section 2.2.3, Company level), zero-carbon targets have not yet been defined. However, Gerdau and Usiminas declared they are carrying out studies to determine long-term emission targets soon (Gerdau, 2020; Usiminas, 2020). A synthesis of the company's emissions goals and key mitigation measures are given in Table 2.

TABLE 2 → **Companies emissions goals and key mitigation measures**

Company	2030 goal	2050 goal	Key mitigation measures
China Baowu	30% of emissions reduction in 2035	Carbon neutrality	Focus on Direct Reduction (Natural Gas and Hydrogen)
ArcelorMittal	25% reduction of its emissions across their global steel and mining operations, and 35% of its European emissions compared to 2018	Carbon neutrality	Steelmaking transformation (footprint change, energy efficiency, pellets); Energy transformation (CCUS, DRI-Natural Gas, DRI-Hydrogen, bioenergy); Increased use of scrap; Sourcing clean electricity; and Offsetting residual emissions.
HBIS Group	Reduce carbon emissions by 30% or more compared to carbon peaking	Carbon neutrality	Investing in studies to develop CCUS and Hydrogen technologies
Nippon Steel	Reduce 30% of its emissions compared to 2013	Carbon neutrality	Actual implementation of the COURSE50[6] in the existing BF and BOF process; Reduction of CO_2 emissions in existing processes; Establishment of an efficient production framework; Mass-production of high-grade steel in large size EAFs; Hydrogen reduction steelmaking (by Super-COURSE50 use of BFs; Direct reduction of 100% hydrogen; multi-aspect approach, including CCUS and other carbon offset measures).
POSCO	20% of emissions reduction compared to average emissions from 2017 to 2019	Carbon neutrality	Smartization; Partial H_2 reduction; Scrap; CCUS Net Zero; Hydrogen- based Steelmaking
VALE	Reduce 33% of its emissions and 15% of the emissions of its chain value (Scope 3)	Carbon neutrality	Energy efficiency, electrification, Tecnored

Source: ArcelorMittal, 2021; China Baowu Group, 2021; Gerdau, 2020; HBIS GROUP, 2021; Nippon Steel Corporation, 2021; Usiminas, 2020; Vale, 2021b

6 COURSE50 and Super-COURSE50 (Ultimate Reduction System for Cool Earth 50) are a Japanese Innovative Technology Development scheme, supported by the New Energy and Industrial Technology Development Organization (NEDO). Its goal is to achieve practical industrial implementation by around 2030, with the final goal of widespread transfer of the technologies by 2050.

2

DECARBONIZATION PATHWAYS IN THE BRAZILIAN STEEL INDUSTRY

Many decarbonization scenarios can be elaborated for the charcoal/steel industry. This section is not intended to determine the best path for Brazilian steel production, but rather to provide information that will assist stakeholders in recognizing opportunities, advantages, and challenges. To do so, we present future projections of the Brazilian charcoal/steel industry and potential GHG mitigation options.

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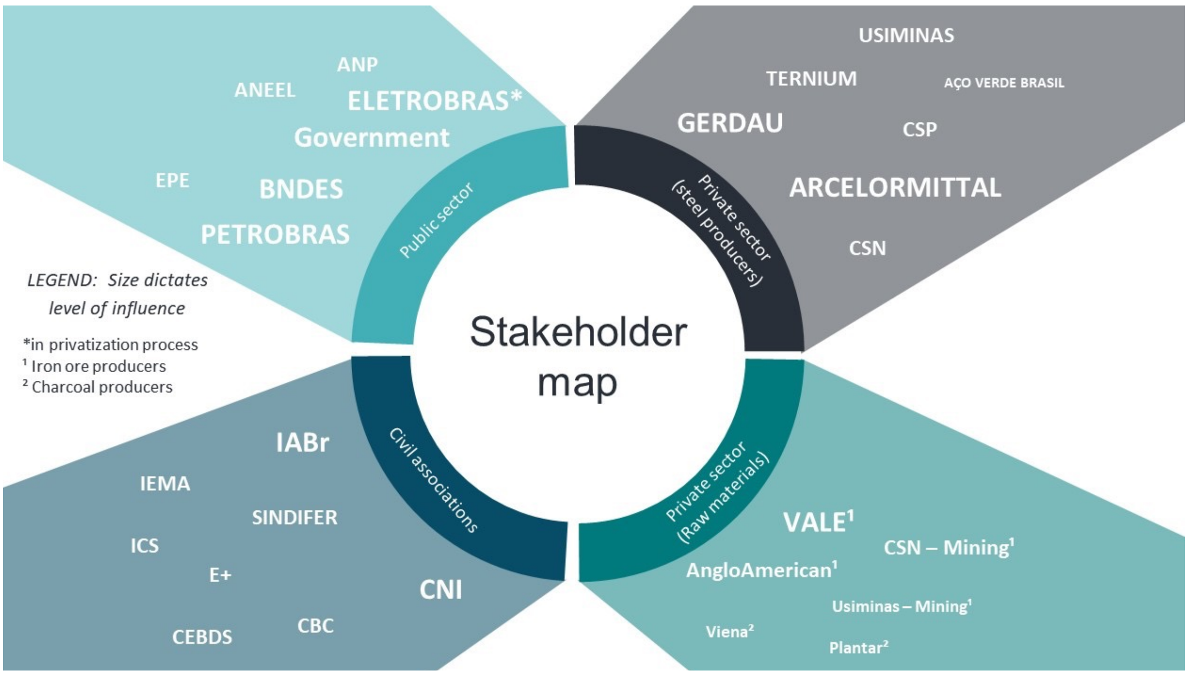
2.1

Outlook/Overview of the Brazilian steel industry

Brazil is the ninth-largest steel producing country globally and the largest in Latin America. Production is distributed in 10 states but concentrates mainly in Minas Gerais (31%), Rio de Janeiro (29%), and Espírito Santo (17%), in the southeast region (IABr, 2021a, 2021b). There are 12 business groups in the country, but 90% of the production comes from 6 companies: ArcelorMittal, Gerdau, Ternium, CSN, Usiminas, and CSP. Figure 5 shows the stakeholder map of the Brazilian steel and iron industry.

FIGURE 5 → **Stakeholder map**



Source: Self-elaboration

For instance, the iron and steel industry is the largest CO_2 emitter in the Brazilian industrial sector. The production of one tonne of steel emits 1.5 tCO_2, less than the average of the significant country producers (2.0 tCO_2/t steel). However, the Brazilian steel sector still needs to reduce its emissions to compete in the decarbonized global market (Centro Clima, 2020; Hasanbeigi and Springer, 2019).

Brazil can benefit from using iron ore reserves strategically. Its expertise in using charcoal and biomass in production processes, its natural gas reserves, and its renewable electricity potential. Brazil can become a Direct Reduced Iron (DRI) exporter, an intermediate product of low carbon steel production, contributing to the decarbonization of other countries. Regarding the technologies, replacing coal with natural gas in DRI can act as a bridge to hydrogen use. On the other hand, GHG mitigation policies has been focused on the use of charcoal in blast furnaces. Nonetheless, due to the drawbacks of charcoal production (see Section 2.2.2), policies were implemented to combat the use of unsustainable charcoal in the steel industry, curbing illegal practices.

Below, the main groups of stakeholders in the charcoal production chain in Brazil are presented.

2.1.1

Producers

The major steel producers are ArcellorMittal and Gerdau, accounting for almost 50% of the steel production (Figure 6). Followed by CSN, Ternium, CSP, Usiminas. We considered Aço Verde Brasil as an important player due to its vanguard position as the first carbon-neutral steel company. Regarding forestry and carbonization processes, a large part of the production of eucalyptus forests and the production of charcoal (which uses the carbonization process) is verticalized, that is, produced by the steel companies themselves. However, in recent years there has been an increase in the participation of independent wood producers, including funds (TIMOs) and, to a lesser extent, an increase in the participation of independent charcoal producers.

The main pressure points for the primary steel producers are related to the decarbonization of the world steel industry and its consequences in Brazil. Hence, the risks for the transition regard on are: Fuel prices for the energy transition (NG, charcoal, electricity, hydrogen); Low carbon fuel availability (NG and charcoal); Infrastructure for natural gas and hydrogen; Scrap availability.

In the case of charcoal producers, inspection and legality in the production of charcoal, product certification, in particular, restricting the use of charcoal from native forests, and air quality around the production ovens[7].

FIGURE 6 → **Steel Producers**

ARCELORMITTAL	GERDAU	TERNIUM/CSN/CSP/ USIMINAS	AÇO VERDE BRASIL (AVB)
Holds 28% of the National production Production based on coal, charcoal and electricity Worldwide: the company is investing in low carbon technologies (e.g., DRI) Pressure points: Charcoal availability; electricity prices; scrap availability	Holds 20% of the National production Production based on coal, charcoal and electricity Low carbon steel (0.93 tCO_2/t steel - global) Pressure points: Charcoal availability; electricity prices; scrap availability	Around 10% of the national production each Coal based production Ternium: Ternium and Vale signed an agreement focusing on technologies for iron reduction (e.g., Tecnored, HYL) Pressure points: hard to abate emission; Fossil fuel prices	Aço Verde Brasil 1,7% of national production First steel producer in the world with carbon neutral production

Source: Self-elaboration

7 Other command and control instruments have been used, focusing on the adequacy and legitimacy of the entire charcoal production chain. An example is the recently launched project by the State Forestry Institute (IEF), in Minas Gerais, which seeks to work throughout the charcoal chain, from the plantation to the industrial consumption, with blockchain technology. It is expected that the system will ensure the traceability of the product, from the forest of origin to the final product, avoiding fraud, accelerating the process, and bringing greater reliability in the use of charcoal by the steel industry (IEF, 2020).

Vale is the major iron ore producer in Brazil and one of the world's largest producers (Figure 7). The iron ore industry's pressure points rely on the environmental impacts, land conflict with indigenous people, and regulation. Those aspects may restrict the expansion of iron ore production.

FIGURE 7 → **Iron ore**

VALE	CSN Mining/AngloAmerican/Usiminas
Largest iron ore producer in Brazil (ANM, 2020) and one of the largest in the world 72% of the iron ore production in Brazil Exporter of minerals Possibilities as DRI producer (exports) (ABIFA, 2019) Ternium and Vale signed an agreement focusing on technologies for iron reduction (e.g., Tecnored, HYL) Pressure points: Environmental impacts and regulation	Together, They account for 20% of the iron ore production in Brazil Pressure points: Environmental impacts and regulation

Source: Self-elaboration

2.1.2

Producer associations

Regarding the industrial processes, the following associations should be highlighted:

(i) the Brazil Steel Institute (IABr), which represents steel producers in the country. Its mission is to "defend and represent the Brazilian steel industry, working to improve competitiveness and sustainable development."

(ii) the Brazilian Association of Ferroalloys and Metallic Silicon Producers (ABRAFE), which brings together producers of ferroalloys.

(iii) the Union of the Iron Industry in the State of Minas Gerais (Sindifer), which represents independent pig iron producers at the national level, whose production is entirely based on charcoal (Sindifer, 2021).

(iv) the Forest Industry Association of Minas Gerais (AMIF) which represents the base of planted forests associated with charcoal and aims to "contribute to the sustained growth and ordering" of the industry[8].

(v) the National Confederation of Industry (CNI) is the "main representative of Brazilian industry in the defense and promotion of public policies that favor entrepreneurship and industrial production".

8 However, it should be noted that all companies that produce steel based on charcoal and are affiliated with IABr are also members of AMIF, as are most of those associated with ABRAFE and, to a lesser extent, some associated with it Sindifer. In addition, there are also independent producers of planted forests located outside the State of Minas Gerais, related to other state entities, and with Ibá (Brazilian Tree Industry). This entity has AMIF itself as an affiliate.

2.1.3

Public Sector: Governmental and regulatory level

The major players in the public sector include the Executive Government (and its ministries); the Brazilian Development Bank (BNDES); public energy companies such as Petrobras and Eletrobras (in the privatization process); regulatory agencies (ANEEL and ANP); and the Energy Research Company. A synthesis of the main characteristics of these key players is given in Figure 8.

FIGURE 8 → **Public sector players**

Government	Eletrobras	Petrobras
The government has the power to create carbon pricing, set its price or emission permits; Ministry of Science and Technology has among its competences the implementation of national policies for scientific and technological research and the encouragement of innovation (MME, GIZ e Procobre, 2019); Ministry of Environment, Ministry of Economy; Ministry of Agriculture, Ministry of Mining and Energy can create policies regarding mineral and energy resources (MME, GIZ e Procobre, 2019).	A publicly traded company in privatization process; The largest Brazilian electric energy generation company, (1/3 of the country's total installed capacity); Over 90% of the installed capacity comes from sources with low greenhouse gas emissions (Eletrobras, 2021); It can be an important player with the increased use of electricity in steel production and in green hydrogen production; Pressure points: Climate change (hydropower generation).	One of the largest producers of oil and gas in the world (Petrobras, 2021); There is an economic and environmental opportunity to use NG in the steel sector, as around 1/3 of the associated gas produced in the pre-salt is re-injected into the wells (Barroso et al., 2020); Pressure point: Natural gas infrastructure; Environmental regulation.

BNDES	The Energy Research Office (EPE)	ANP/ANEEL
One of the largest development banks in the world; Main instrument of the Federal Government for long-term financing and investment in all segments of the Brazilian economy (BNDES, 2021).	Provides services to the Ministry of Mines and Energy (MME) in studies and research designed to support the planning of the energy sector (MME, GIZ & Procobre, 2019).	ANP: Provides the regulation, contracting and inspection of economic activities that are part of the oil industry. ANEEL: Regulatory agency for the electricity sector.

Source: Self-elaboration

2.1.4

Civil society organizations

A paradoxical context also marks the sector's relationship with non-profit civil society organizations. On the one hand, there is support and recognition regarding the potential to contribute to the sector's sustainable development. Yet, on the other hand, there has always been activism against unsustainable and illegal practices, especially those associated with deforestation, management of water resources, and working conditions in carbonization processes (Figure 9).

FIGURE 9 → **Civil society players**

Civil Associations (E+ Institute/iCS/CBC/IEMA/CEBDS)
Associations that provide knowledge helping the transition for a low carbon economy;
iCS is a philanthropic organization that provides grants for development of projects focusing on climate change solutions;
E+ Energy Transition Institute is a think tank that guides the energy transition agenda in Brazil;
CBC is a think tank that promotes knowledge for decarbonizing the Brazilian economy;
IEMA creates knowledge supporting public policies on energy and environment;
CEBDS promotes the sustainable development through the dialogue between civil society and the government.

Source: Self-elaboration

Many decarbonization scenarios can be elaborated for the charcoal/steel industry. This section is not intended to determine the best path for Brazilian steel production, but rather to provide information that will assist stakeholders in recognizing opportunities, advantages, and challenges. To do so, we present future projections of the Brazilian charcoal/steel industry and potential GHG mitigation options. In addition, we discuss the keys stakeholders, national characteristics, cost estimates, and total GHG emissions.

2.2

Charcoal in the steel industry in Brazil

Brazilian industry has always relied heavily on renewable energy, mainly charcoal and other biomass sources (EPE, 2021). As a result of steel production, the country has become the largest producer and consumer of charcoal globally (IBÁ, 2021a). Therefore, it is often cited as an example of renewable energy use, with charcoal accounting for 18% of the total energy mix.

The charcoal-based steel production chain can be characterized by three general processes (Figure 10):

(i) the production of renewable biomass, especially eucalyptus planted forests,

(ii) the transformation of biomass into renewable charcoal, through carbonization processes in different types of furnaces, and

(iii) the use of charcoal as a reducing or thermo-reducing agent in the process of manufacturing pig iron, ferroalloys or steel, in its many forms.

FIGURE 10 → **Process flowchart**

Source: The author

Regarding planted eucalyptus forests, in addition to the favorable soil and climate conditions, it is worth mentioning the intense effort of research, development and innovation (RDI) for the development of cutting-edge technologies for cloning using genetic improvements. To exemplify this, between 1970 and 2015, the average Brazilian forest productivity increased fourfold, mainly based on the production of high-productivity cloned trees (Binkley et al., 2017).

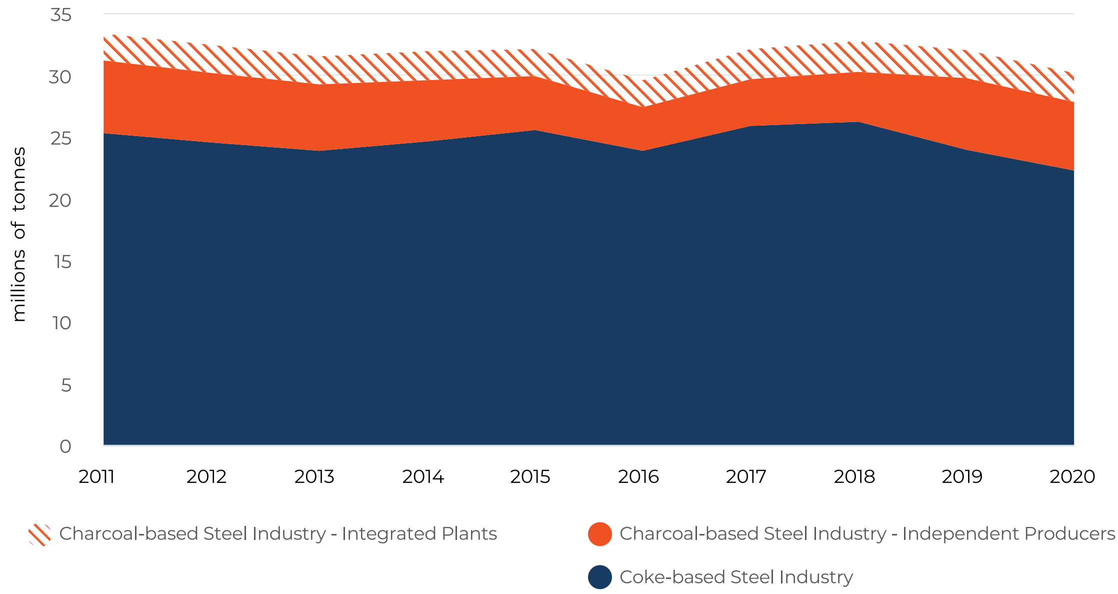
Concerning carbonization processes, the RDI effort is relatively more recent and less developed compared to the planted forest. For many years, charcoal production was based on rudimentary ovens, with low productivity, determined by the rate of conversion of wood into charcoal. The focus was maximizing wood production in a given area and not so much on the process of converting wood into charcoal. In recent years, especially in the last decade, there has been a substantial increase in RDI initiatives in the sector, aimed at improving carbonization processes. This includes the construction of larger-scale furnaces, with more mechanized operations and using more sophisticated structures, including better management of stonework and other structures.

As an example, we can mention the large rectangular masonry kilns that allow the mechanization of both the infilling of the kilns with wood and coal; the metallic cylindrical furnaces (Rima Container Furnace (RCF) technology, Bricarbras furnaces and continuous wood carbonization retort), which allow the achievement of a charcoal with higher gravimetric yield; the Drying, Pyrolysis, Cooling (DPC) technology, which consists of rectangular metallic ovens, which in addition to using drying, pyrolysis and cooling stages, reuses the gases from the pyrolysis process, resulting in a high gravimetric yield charcoal with a more homogeneous composition and, finally; the Ondatec technology, which is carried out in horizontal metallic ovens that uses microwaves as a source of energy, with this process being controlled by a supervisory system (CGEE, 2015).

In terms of industrial use, a large part of the charcoal-fired steel production is concentrated in the pig iron and ferroalloys segments, whose production is not vertical, that is, it is not physically integrated with steel production and is generally based on smaller-scale furnaces compared to the coal-based steel industry. However, a relevant fraction of the steel production takes place in integrated or semi-integrated plants, which produce pig iron as a feedstock for steel production in vertical processes.

In general, the use of charcoal never exceeded the proportion of 25% of the total production capacity of pig iron in Brazil *(32 million tonnes in 2020)*. However, during the economic recession of 2015-2018, the overall share of charcoal has decreased to 20% of the total pig iron production. In the most recent "post-pandemic" period, the recovery of the production chain has been observed, related to the general recovery of the steel sector, which was driven by segments such as civil construction, the automotive industry, and others (Fig. 11).

FIGURE 11 → **Total pig iron production in Brazil**



Source: Adapted from Sindifer (2021)

In the ferroalloys sector, according to the National Energy Balance (BEN, 2021), it can be noted growth in charcoal and firewood use, reaching 40% of total energy use in 2020. In this year, the highest participation of charcoal and firewood in the last 10 years was observed, as given in Table 3.

TABLE 3 → **Percentage of energy sources in the Ferroalloys sector (%)**

Sources	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Natural Gas	0.2	0.2	1.5	1.4	0.5	0.0	0.0	0.2	0.2	0.2
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
City Gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal Coke	6.2	6.0	5.6	5.5	5.8	5.7	6.1	5.8	5.9	6.2
Electricity	43.6	42.5	41.6	40.7	43.4	42.6	41.6	40.1	40.5	42.8
Charcoal and Firewood	38.0	37.0	36.2	35.4	37.8	36.3	39.0	37.5	38.0	40.1
Others not specified	12.0	14.3	15.2	17.1	12.5	15.4	13.4	16.3	15.4	10.7

Source: Sindifer (2021) and EPE (2021).

Regarding the geographical distribution of the sector, there is a clear predominance of the State of Minas Gerais (77.7% of production in 2020) followed by the States of Pará (10.1%), Mato Grosso do Sul (7.2%) and Espírito Santo (5%) (Sindifer, 2021). The predominance of Minas Gerais is due to the historical abundance of iron ore and the availability of forests, although important changes have recently been observed in the quality of iron ore extracted in the Minas Gerais compared to the Pará, which may eventually contribute to gradual changes in this distribution. According to Vale, Carajás ore is considered the best quality iron ore in the world, as the rocks contain, on average, about 67% iron content (Vale, 2021c). Being the State with the longest history of mineral extraction in the country, Minas

Gerais observes the scarcity of higher grades iron ore reserves, such as hematite reserves, which has contributed to research technologies for the use of lower grade iron ores, such as itabirite ores (Carvalho, 2012).

The participation of the sector in the Brazilian foreign trade stands out, with a relevant contribution to the country's exports. There are historical oscillations between the proportion of production absorbed by the domestic market and the international market, according to the dynamics of external markets and exchange rate volatility. However, export levels are always maintained at relevant levels, varying in a range of 46.5% in 2018 and 74.4% in 2020. In the last 10 years, the record of exported values was in 2011, reaching approximately US$1.6 billion with the export of 3,230,012 tonnes of steel abroad. Finally, another relevant data refers to the generation of direct and indirect jobs, which reached 112,653 jobs in 2020, considering the industrial and forestry components (Sindifer, 2021).

2.2.1

Other aspects of sustainable development

In the past, mainly through illegal practices, activities related to charcoal production have exerted pressure for the deforestation of native forests, resulting in loss of native forest, loss of biodiversity, and water resources. Added to this is the social effect of illegality, reflected in terrible working conditions in clandestine charcoal kilns (Pereira, 2007).

Even with the presence of companies that operate within the laws, inadequate past practices ended up contaminating the sector's image. Moreover, from a practical point of view, these inappropriate actions also generate an economic "dumping" effect, since organizations that used charcoal from unsustainable sources did not have to bear the costs of planting eucalyptus or the high financial impact related to an investment that takes at least 7 years to generate revenue *(historical average of eucalyptus rotation).* Thus, less investment is made in planting wood, which tends to the pressure to clear native forests[9].

Currently, it can be said that, from the institutional point of view, there has been a significant evolution, whether at the regulatory and governmental level or in the relationship with organized civil society. Nevertheless, there are already public (e.g., Forest Code) and private (e.g., a more important requirement for traceability on renewable inputs or forest certification systems) governance instruments that constitute solid starting points for risk management.

In general, with the evolution of forest management and the current regulatory frameworks, it is known that eucalyptus plantations are the activity of the agricultural sector that most contributes to environmental conservation in Brazil.

> In Brazil, for each hectare of eucalyptus or pine planted forest, there is an average of 0.65 hectare of native forests conserved by the companies.

On the other hand, there is still a lack of public policies focused on charcoal in the steelmaking process since the most significant evolutions occurred in a "middle component" of the production chain. For example, the wood

9 Although smaller, the "dumping" effect remains a problem, especially when the steel market has a high demand and there is not enough planted wood available.

carbonization process, which is also relevant but does not reflect most of the sector's mitigation potential.

Regarding biodiversity, in addition to reducing the pressure on the deforestation of native forests, eucalyptus forests can contribute to the maintenance of several species of fauna and flora in conservation areas, in legal reserves and permanent preservation, often interspersed with eucalyptus plantations generating habitat corridors.

In Brazil, for each hectare of eucalyptus or pine planted forest, there is an average of 0.65 hectare of native forests conserved by the companies. In 2019, the planted forest sector accounted for a total of 5.9 million hectares of APPs, RL and Private Natural Heritage Reserves (RPPN), a size larger than the area of the State of Rio de Janeiro (IBÁ, 2021b).

Likewise, as long as they are well managed, these eucalyptus crops can contribute to the conservation of water resources, soil conservation (less intensive and long-term culture), among other positive aspects (Daniel, 2014). There is still room to increase these and other improvements in the charcoal production chain, which is not only made up of large companies.

From a social point of view, the potential for contribution is also relevant. Based on the fundamental condition of respect for regulations of work quality, including aspects of health and safety in charcoal production, the sector has a good capacity to generate jobs on a large scale in rural areas, often in less developed regions (for example, Northern Minas Gerais and Northern Brazil), connected to the industrial environment.

Therefore, within the current management conditions and regulatory frameworks, it can be said that the sector has a high potential to contribute to a sustainable development. However, in addition to the continuous improvement of all the practices exemplified above, some special attention should be paid to the challenge of communicating with the society as a whole and the "dumping" effect in the case of organizations that act outside the law and harm the structure of the sector under the economic and institutional point of view.

2.2.2

Main barriers to increasing the use of charcoal

There are technological limits and several barriers to the expansion of the charcoal-based steel industry. In relation to steel production, the lower mechanical strength of charcoal compared to coal coke makes it unfeasible to use in part of the large blast furnaces. Among other factors, this makes it impossible to replace the use of coke in all existing plants.

However, this difficulty could be partially overcome through fines injection technology (*pulverized coal/charcoal injection* – PCI). However, even if the industrial challenge is overcome, the acquisition of charcoal fines must become economically viable, which basically depends on the availability and the logistics of the feedstocks, like the proximity between the blast furnace and the production centers for planted forests and charcoal[10].

Regarding possible capacity expansions, there is more room for expanding the use of charcoal from a technological point of view since the industrial process can be planned in a compatible manner in steel production. For example, it is possible to use a set of relatively

10 Despite these difficulties, it is worth mentioning that some technologies have been developed, such as Tecnored, which reduces iron ore inside a self-reducing agglomerate, composed of iron and coal fines (which can be charcoal). With this technology, the reduction of emissions from the steelmaking process is expected (Tecnored, 2022).

smaller but still relevant-scale ovens instead of a single very large-scale oven. Companies such as Arcelor Mittal, Aperam, Gerdau, and Vallourec already have extensive experience in the production of charcoal-based steel with medium/large scale blast furnaces.

The issue of land use and availability for plantations is also relevant, but it is not an impediment, even though it is always challenging to find adequate and cost-effective land. In general, two factors help to understand the reality: ***(i) there are available areas already anthropized in Brazil on a relevant scale, including in areas that do not compete with traditional agriculture (Sparovek et al., 2016), (ii) there is no expectation of expansion in the total scale of steel production in Brazil, which can also use other sources such as scrap and new technologies for production processes.*** The charcoal-based steel industry can be seen as a high potential alternative, especially for Brazil, which is part of a portfolio of solutions at a global level.

In fact, the barriers to expansion go beyond the issue of land availability and the technical barrier in the industrial component, even for the independent production of pig iron and ferroalloys, which is already based on charcoal. In general, the main challenge of expanding the use of charcoal refers to the long cycle of the production chain compared to other inputs or investments. On average, the eucalyptus cycle in Brazil lasts 7 years. Thus, it is necessary to invest high amounts in the acquisition or lease of land, in the execution and management of plantations and all aspects associated with land use, including long environmental licensing processes, so that from the 7th year onwards the area can be harvested and charcoal produced up to the 14th year, when the last planting is amortized (carried out in year 7, if a company plants constant amounts). A company could choose to buy wood on the market and not have to internalize the entire process. However, although an independent wood market has advanced in Brazil in recent years, there is still no availability of forests for complete outsourcing, in addition to challenges related to predictability and stability of supply, even though there is still good availability of areas across the country.

When this logic is compared to the use of coal coke, for example, the difference becomes evident. Coal is one of the most available fossil sources in the world. Although Brazil is not a major producer of coal, the input can be easily imported from countries such as China, Australia and South Africa. Often, when importing, companies can make an advance on an exchange contract, which allows payment for the input after the production and sale of the final steel product, that is, a temporal logic inverse to that of charcoal.

Although there may be variations in prices, exchange rates, interest, and other financial parameters that routinely affect the economic attractiveness of coke and charcoal in the short term, the transaction costs associated with charcoal and, especially, the need for high immobilization of capital over long periods make investment decisions relatively more complex and riskier compared to using coke.

> The charcoal-based steel industry can be seen as a high potential alternative, especially for Brazil, which is part of a portfolio of solutions at a global level.

Therefore, although there are differences in the market dynamics of pig iron, ferroalloys, and steel, in all of them the investors are faced with the challenge of dealing with the volatility of several economic variables in a hiatus that lasts at least from 7 to 14 years, from the time the initial costs are invested and the determination of the price of the final product. Therefore, the opportunity cost of investing in the charcoal-based steel industry is always subject to comparisons with alternative sources used in the sector itself or even in comparison with other types of investments that shareholders may be willing to make.

In addition to this structural challenge, a series of other barriers need to be addressed to increase the share of charcoal in Brazilian steel production. Among which we can mention the lack of availability for financing, with a grace period and interest and guarantee policies suitable for the eucalyptus cycle, which ranges from 7 to 14 years; the need for infrastructure and logistics improvements that allow improving the reach of forest development poles; longer terms of environmental licensing related to land use; investments to improve the use of wood carbonization processes and exploitation of by-products, including cogeneration of energy and bio-oils; greater engagement within the forestry production chain, which can optimize the availability of wood and the cost of capital involved in the use of land; the need for improved communication on data and the possible benefits generated by the sector and; finally, the creation of a price premium for final products as the carbon footprint lowers, which could play a relevant role in the opportunity cost of the necessary investments. In this context, carbon market and green finance instruments may be of increasing importance for the expansion of the charcoal-based steel industry, given their high potential for mitigation and the various global and national commitments to achieve a carbon neutral economy by 2050.

To have an order of magnitude of possible impacts, if the carbon removals generated by the implantation of a planted eucalyptus forest are priced at approximately USD5/t_{CO2e}, the added value would cover about 50% of the cost of forest implantation[11]. The emissions avoided in the thermo-reduction process are added to this, conservatively estimated at 1.5t_{CO2e}/ton of hot metal, which could also be priced. In the European Union emissions trading system, the current carbon price is in the range of USD80/t_{CO2e} (EURACTIV, 2021).

Even though there is no automatic fungibility between the European market and projects in Brazil, even a possible official Brazilian carbon market is still under discussion in the National Congress. Nevertheless, these numbers give an order of magnitude of the impact that the recognition of the value carbon could generate in new investments.

2.2.3

The mitigation potential

The sector's mitigation potential is distributed along the three processes of the production chain, with emphasis on the forestry and industrial stages. According to the main regulatory frameworks already consolidated, such as the Brazilian Forest Code (Law No. 12.651/2012) and the Minas Gerais Forest Law (Law No. 20.922/2013), the fundamental assumption is that reforestation activities are implemented in areas already anthropized, for example degraded areas, pastures or other crops, and not in areas where suppression of native forests would be necessary[12]. Therefore, there are relevant possibilities of land use already anthropized, for the implementation of different cultures, especially forestry, without the need to suppress native forests.

Regarding the forestry stage, climate benefits refer to the removal of CO_2 provided by reforestation activities, based on eucalyptus, for production purposes. It also considers the

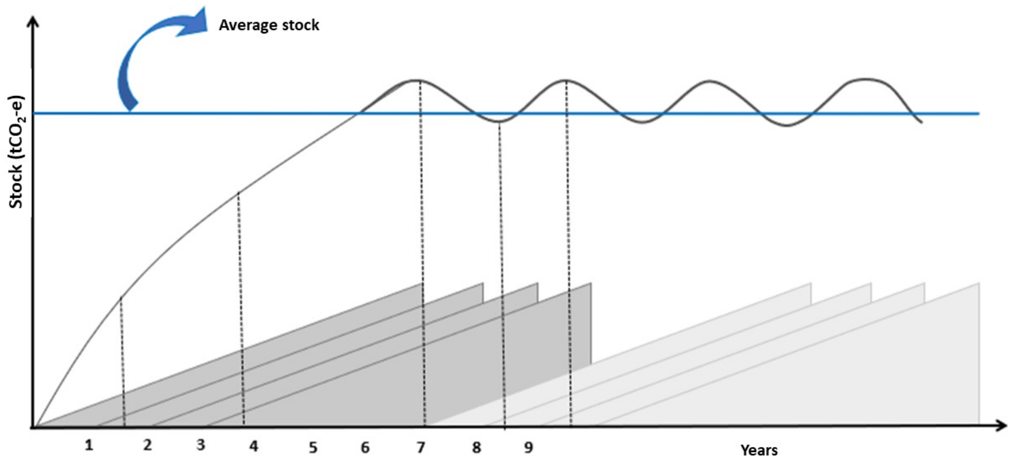
11 Estimates considering an exchange rate of R$5/USD and an average cost of forestry implementation could achieve R$7,000.00, approximately (not considering the cost of land).

12 According to Brazilian Agricultural Research Corporation (Embrapa, 2021), there are about 200 million hectares of pastures in Brazil, which is equivalent to approximately 23.5% of the national territory. It is estimated that about 130 million hectares of these pastures, or 65% of its total, are degraded.

restoration or conservation activities of native forest species in areas of permanent preservation (APPs), legal reserves (LR) and other areas. Although the production areas are subject to the dynamics of harvesting and planting, there is still the climatic benefit of removals. During the 7-year cycle of wood growth, while 1/7 of the area is in a constant process of planting and harvesting each year, the other 6/7 remains stored in different stages of growth. This means that there is an average carbon stock while forestry activity exists. It is estimated that each hectare of planted eucalyptus forests stocks approximately 177 t/ha.

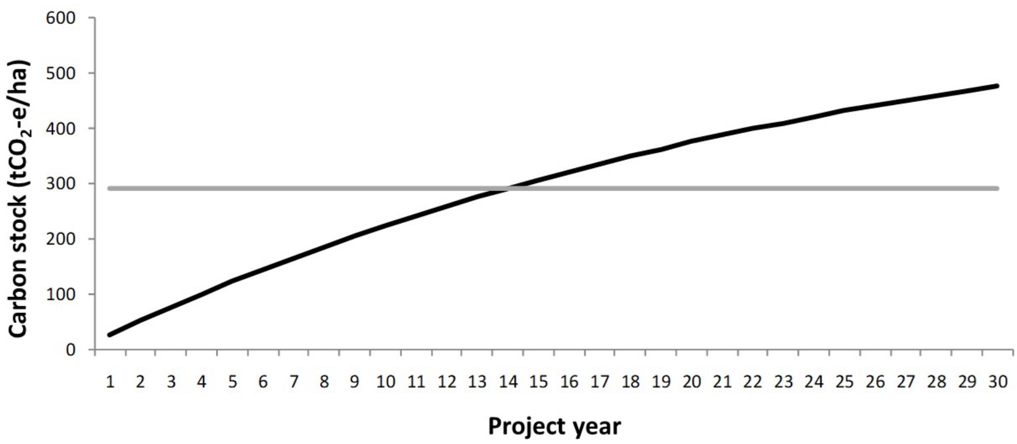
The effect of carbon removals and stocks in conservation areas is simpler, since there is generally no stock management, but rather the accumulation of carbon at a lower and constant rate until the period of stability or "steady state", analogous to saturation. Figure 12 and Figure 13 illustrate the dynamics of carbon removals and stocks in production and conservation areas[13].

FIGURE 12 → Schematic representation of the increase in carbon stocks (removals) in a reforestation activity.



Source: Adapted from Plantar Carbon (2022).

FIGURE 13 → Schematic representation of the increase in carbon stocks (removals) in a restoration area.



Source: Adapted from Plantar Carbon (2022).

In the wood carbonization process, CO_2 emission is neutral, as the carbon emitted comes from planted wood that previously removed CO_2 from the atmosphere, but there are also methane (CH_4) emissions. However, in recent years the sector has contributed to the reduction of these emissions through improvements in technologies and processes in two main aspects:

13 For a more detailed explanation of the logic and potential of removals and other climate benefits from the production chain, see Marques (2019).

(i) Improvement of gravimetric yield, which began through the methodology and CDM project approved in this sectorial scope and, later, disseminated in the sector, including through the Sustainable Steel Program that made use of the CDM methodology. Despite relevant advances, there is still room for further improvements that can generate additional emission reductions.

(ii) Burning and/or energy use of methane: some companies in the sector have developed pilot plants, on a smaller scale and at initial operation level, integrated with CH_4 burners, enabling relevant mitigation. In other cases, there are studies for the use of gases for energy cogeneration.

It is important to note that, although this component of the production chain generates methane emissions, these emissions are proportionately small in relation to the climate benefits generated in forestry and industrial processes. Recent estimates by AMIF indicate that, in general, methane emissions, even if eventually not mitigated, would not represent more than 27% of total emissions in the production chain.

In the carbonization process, there is still a theoretical potential that could be better explored in the future, related to the use of potential derivatives and co-products of the charcoal production process, such as, for example, tar (which is, in practice, a bio-oil). However, the full potential of using carbochemistry and its products still requires a series of arrangements that enable technological developments and the necessary scale for relevant mitigation along this and other production chains, such as in the cement industry.

In the industrial process, for each tonne of hot metal (pig iron, ferroalloys, steel) produced with charcoal instead of coal coke, approximately 1.25 t_{CO2eq} is avoided. This is the direct effect of using a renewable reducing agent instead of a fossil source (coal coke), which is the predominant source in the global steel sector (Babich et al., 2018).

Therefore, it is important that an analysis of the mitigation potential of the supply chain considers the three types of climate benefits, which can be cumulative as long as they are properly accounted for[14]. In this context, despite the limitations and barriers, the use of renewable charcoal provides a great mitigation effect. Probably the largest in the respective production chain because, in addition to avoiding the use of fossil or non-renewable sources, it also provides carbon removal and lasting carbon stocks over time (PBMC, 2014).

14 During the steel production process, there are also other important climatic benefits, such as the use of blast furnace gases for cogeneration of electricity, among others. However, as these benefits are common to different routes (i.e., charcoal, coke, scrap metal, etc.), it was decided to focus on the main marginal benefits related to the use of charcoal.

Lastly, climate change is another relevant factor that may have an impact on biomass production. Temperature increase can reduce crop productivity and increase pest proliferation, while modifying precipitation patterns can destroy crops in the short term and reduce productivity in the long term (Nelson et al., 2009). Eucalyptus is the most common species employed in Brazil's forest plantations for industrial purposes (Mota, 2013). According to Elli et al. (2020), climate change can affect eucalyptus productivity, with temperature increases having a negative impact and CO_2 levels in the atmosphere having a favorable effect. These impacts will vary by region, with planted areas in the South and Southeast regions predicted to increase productivity. In contrast, those in the Center-North region will decrease.

2.3

Decarbonization policies for the Brazilian steel sector

2.3.1

National level

To reduce GHG emissions, Brazil ratified the Paris Agreement in 2016 and submitted a Nationally Determined Contribution (NDC) with reduction targets of 37% by 2025 and 43% by 2030 in comparison to 2005 levels (UNFCCC, 2016). Although there was no specific mention of the steel sector in the Brazilian NDC, it mentioned the adoption of mitigation measures for the industrial sector as a whole: development of low carbon infrastructure, new standards of clean technology, and energy efficiency improvements.

The federal government has taken some initiatives to minimize GHG emissions in the steel sector, focusing primarily on increasing charcoal use.

In 2020, Brazil presented an updated NDC that maintained the percentage of emission reductions. Following the NDC update, in 2021, the country also established the commitment to achieve climate neutrality by 2050 (WRI, 2021). However, none of these publications mentioned specific mitigation measures for the steel sector.

The federal government has taken some initiatives to minimize GHG emissions in the steel sector, focusing primarily on increasing charcoal use. For example, the National Plan on Climate Change was released in 2008. The goal was to increase the use "of sustainable charcoal to replace coal in steel plants, mainly through the encouragement of forestation in degraded areas" (Government of Brazil, 2017).

In 2012, the Industry Plan for Mitigation and Adaptation to Climate Change was published within the National Policy on Climate Change (PNMC). The PNMC also elaborated a Sectoral Plan for the Reduction of Emissions from the Steel Industry, which was never made public (Paula et al., 2020).

In 2014, the Sustainable Steel Project was approved, aiming to reduce GHG emissions in the State of Minas Gerais (pilot State) through the production of steel using charcoal at a competitive cost and establishing a legal framework (PNUD, 2021).

In 2018, the Climate Change and Brazilian Industry report was published, and it analyzed the steel sector and recommended several measures, including replacing coal with charcoal, increasing energy efficiency, expanding scrap utilization, and adopting disruptive technological innovations (CNI, 2018).

2.3.2

Sub-national level

In terms of state-level decarbonization, the states of Minas Gerais, Rio de Janeiro, Espírito Santo, São Paulo, Pará, Maranhão, Pernambuco, Paraná, and Mato Grosso do Sul[7] have joined the United Nations campaign entitled *"Race to Zero"*. The campaign aims to achieve GHG emissions neutrality by 2050 and encompasses several other regions in the world (FIEMG, 2021; GOV MS, 2021; GOV PR, 2021; Governo ES, 2021; The Climate Group, 2021). It is noteworthy that, considering the steel-producing states, only Ceará and the Rio Grande do Sul have yet to join the campaign.

The States' participation in the campaign is encouraging because it constitutes a step toward climate neutrality, even with slower actions at the federal level (The Climate Group, 2021).

2.3.3

Company level

The Brazilian steel industry has been gradually adopting more sustainable measures in its production, driven by global decarbonization trend, multinationals efforts in Brazilian territory and the influence of industry associations. Between 2018 and 2020, the Brazilian steel industry invested roughly R$2.6 billion in measures aimed at reducing GHG emissions and sustainability (IABr, 2021a) [15].

The Brazilian steel industry has been gradually adopting more sustainable measures in its production, driven by global decarbonization trend.

In Brazil, ArcelorMittal has committed to a 10% reduction in emissions by 2030 to reach the company's global climate neutrality target by 2050. The following measures are planned as a strategy to achieve this reduction: expanding the scrap utilization; increasing the use of natural gas; and optimizing the use of charcoal in units that already use this fuel (ArcelorMittal, 2021).

Gerdau, Brazil's second-largest steel producer, has not yet set reduction targets for the medium-and long-term, but it has a low intensity of CO_2 emission per produced steel (0.93 t_{CO2}/t steel) when compared to the global average. This is mainly because of the use of scrap (73% of the steel produced by the company worldwide uses scrap in the process), charcoal, and the energy efficiency (Gerdau, 2020).

15 1 USD = 4.25 Reais, considering the average commercial exchange rate from 2018 to 2020 (IPEA, 2021).

Ternium has set a decarbonization target for 2030: a 20% decrease in emissions per tonne of steel produced, using 2018 as the baseline. The following activities will be developed to achieve this goal: increase scrap use and participation of renewable energy sources in the production process, partial replacement of coal with charcoal, increase in energy efficiency, adoption of cleaner technologies, and collaboration with raw material suppliers to reduce process emissions (Ternium, 2021a). In addition, in 2021, the companies Ternium and Vale signed an agreement to carry out economic feasibility studies as part of their emission reduction strategy. These studies focus on technologies for iron reduction (e.g., Tecnored, HYL) (Ternium, 2021b).

Another highlight is Aço Verde Brasil, the first steel producer in the world with carbon neutral production[16]. Neutrality was achieved using charcoal reforested by the company, the use of process gases and the reuse of solid waste (IABr, 2021a).

Regarding iron ore production, Vale company plans to reduce 33% of Scope 1 and 2 net emissions (direct and indirect emissions) by 2030, 15% of Scope 3 net emissions by 2035 (value chain emissions) and achieve climate neutrality by 2050. In addition, they intend to consume 100% of electricity from renewable sources by 2025 in Brazil (Vale, 2020). In this direction, Vale and Jiangsu Shagang signed a Memorandum of Understanding where both companies agreed to look for ways to reduce emissions in steel production. This initiative intends to develop studies regarding the Tecnored technology and for using less carbon intensive products (Vale, 2021a). The company plans to invest 6 billion USD to achieve these goals. One of its strategies includes a carbon shadow price in the investment planning process: 50 USD per tonne of CO_2 in new projects and investments, and 10 USD per tonne of CO_2 for carbon sequestration in forest restoration projects. Aside from low-carbon technology investments to minimize scopes 1 and 2 emissions, the company also has a portfolio of solutions for consumers and suppliers (scope 3) (Vale, 2020).

16 Société Générale de Surveillance verified the GHG emissions inventory of Aço Verde Brasil between 2018 and 2020 and granted its certification to the company. The methodology used followed ISO 14064 and the Brazilian GHG Protocol Program.

2.4

The role of key technologies in the Brazilian steel industry and the country's competitive advantages

In terms of energy and emissions efficiency, the Brazilian steel industry is one step ahead of the leading producers. However, to meet the Paris Agreement target, the sector will require more effort.

This section presents mitigation measures analyzed from a national perspective. The questions that lead this part are: ***'Which technologies are more likely to be implemented Worldwide?'*** and ***'What are the national competitive advantages?'***

The technologies considered herein are those that are often mentioned in decarbonization pathways (Eurofer, 2013; IEA, 2020a). First, we analyze mitigation measures that can be applied in conventional technologies such as energy efficiency, the use of charcoal as a reducing agent, and EAF. Then, the alternative technologies are analyzed from a national standpoint. It is important to mention a lack of studies regarding the impact of alternative technologies in the Brazilian steel industry decarbonization.

2.4.1

Energy efficiency

Energy efficiency refers to a range of measures for lowering the energy consumption in steel production. The Brazilian energy intensity is 20.9 GJ/t steel, about 10% higher than the world average (18.6 GJ/t steel) (IEA, 2020a). The national production using BF-BOF has an energy intensity of 18.6 GJ/t steel when considering the production with coal and 23.4 GJ/t steel when using charcoal (EPE, 2018a). Regarding the second major route, EAF, Brazil has the second lowest energy intensity among the top steel producers (Hasanbeigi and Springer, 2019).

Some studies investigated the possibility of reducing energy consumption and emissions by considering energy efficiency measures. EPE (2018a) shows a potential of 23% energy consumption reduction for producing pig iron and 10% potential in steel production. According to Pinto et al. (2018), energy efficiency measures can cut 16% of the Brazilian steel emissions projected by 2050. In its cost analysis, about 75% of the emissions mitigated have a marginal abatement cost less than 50 USD/tCO_2 and require 3.8 trillion dollars in investments. Because of its low cost and potential, energy efficiency can be one of the critical options to reduce emissions in the sector in the short term.

2.4.2

Electric Arc Furnace

In the short term, increasing scrap production for EAF applications can be quite beneficial. Energy intensity in this technology is considerably inferior to BF-BOF, such as its emission intensity (0.7 vs 2.3 tCO_2/t steel) (IEA, 2020a). About 25% of the steel production in Brazil comes from scrap, when countries like the USA, India and Mexico have shares superior to 50%. Brazil has the potential to increase its steel production by EAF, this measure would help cut emissions from the industry around 36% by 2050 (de Souza and Pacca, 2021).

By 2030, 13.4% of the emissions could be reduced and by 2050, 20.2%. Regarding the abatement cost, increasing the use of scrap has high uncertainty, ranging from -54 USD/tCO_2 to 32 USD/tCO_2.

Steel production using EAF is one of the most cost-effective options available. Metal supplies account for 70% of the total cost of EAF production. As the Brazilian industry has the third-lowest metal supplies cost, Brazil has the fourth-smallest production cost of long steel compared to the major steel producers (Carvalho et al., 2015). There are two major concerns regarding this production: *the cost of electricity and scrap availability* (de Souza and Pacca, 2021).

2.4.3

Natural gas and Direct Reduction Technologies

One of the most promising technologies regarding the steel industry transition is the direct reduction using natural gas (NG). Its application in the Brazilian steel industry can play an important role until 2050. NG can be injected into a blast furnace, decreasing the energy consumption of the BF-BOF process (Pinto et al., 2018), and as a reducing agent in the DRI process. The Iron and Steel Technological Roadmap and company's roadmaps highlight this technology (IEA, 2020a). In Brazil, there are no published studies concerning its mitigation potential and costs. The DRI technology, on the other hand, is already available and used in many countries. The IEA projects that by 2050, the global share of DRI in steel production will have increased from 5% to 20-25% (IEA, 2020a).

One of the main reasons why natural gas could be a good option for reducing emissions in the Brazilian steel industry is that its supply is expected to increase in the next years, mainly due to the production associated with the pre-salt[17]. Besides the increase of the NG supply, in 2020, a regulation promoting the competitiveness of the NG market was approved by the Congress (BNDES, 2021b). The new Natural Gas Law aims to improve the natural gas market's efficiency, competitiveness, and transportation network, while also lowering prices. This combination can create fertile ground for projects using natural gas. These characteristics puts DR-NG as an option for reducing the emissions in the steel industry. Later, natural gas can be replaced with hydrogen, achieving greater emission reduction.

One of the major concerns of producing steel by DR technologies is the cost of natural gas. Brazil has one of the highest prices in the world. Among 30 countries analyzed, Brazil has the third highest price (10.5 USD/BTU), after Finland (13.6 USD/BTU) and Sweden (11.3 USD/BTU). This can be explained in part by the high cost of extraction and in part by the

17 According to EPE (EPE, 2018b) the production of NG should increase from 119 million m^3/day in 2015 to 205 million m^3/day in 2030 and between 340 and 450 million m^3/day in 2050 (186% to 278% increase when compared to 2015).

high taxes charged by the fuel. Brazil has the second highest natural-gas taxes, about 24% of the price paid by consumers (Joísa Dutra; Mirella Rodrigues, 2019; MME and EPE, 2019). According to the National Energy Plan 2050, natural gas prices are expected to fall in the coming years, reaching more competitive levels (4 USD/BTU) if the new Natural Gas law succeeds in increasing the number of agents in the market (EPE, 2018b).

It is important to note that biogas and biomethane can be used to replace natural gas in the production process. This change helps in reducing the emission intensity of the process. As an example, Ternium replaced 30% of the natural gas consumption with biomethane in 2019. However, expanding the share of biogas and biomethane may be hampered by a lack of supply of these gases (Ternium, 2021b).

2.4.4

Hydrogen and Direct Reduction Technology

Hydrogen can be a reducing agent in Direct Reduction, as a partial substitution or 100% of the feedstock in some technologies (Eurofer, 2013; IEA, 2020b). Because no specific study on hydrogen's use by Brazilian industry exists, we cannot provide its mitigation potential and costs from the national perspective. However, the role that hydrogen can play in the Brazilian steel industry can be understood by looking at the advantages and necessities of the country.

Competitive advantages

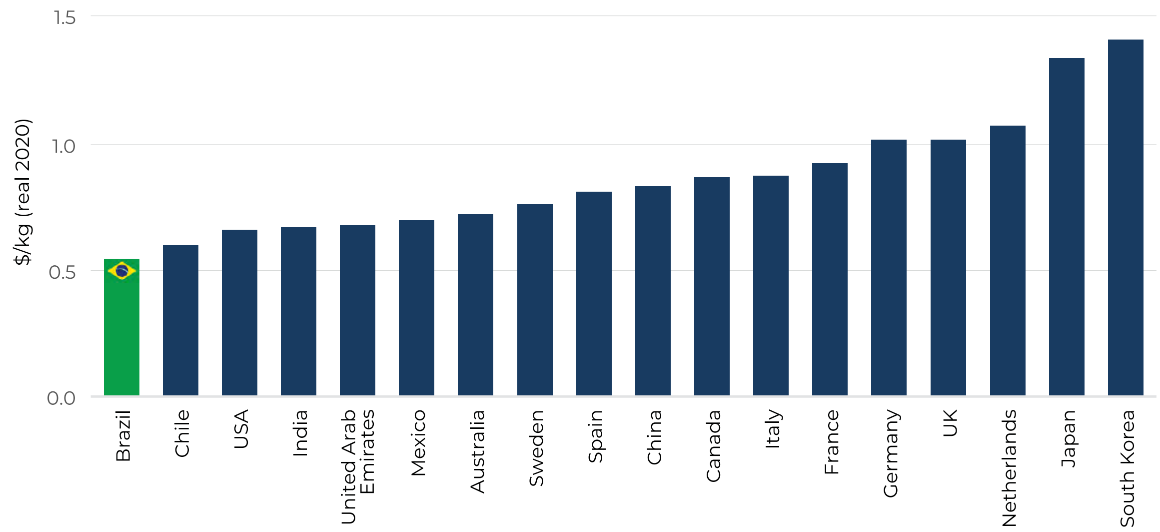
It is important to provide electricity from cleaner sources to produce clean hydrogen, *e.g.,* hydropower or wind power. Brazilian electricity generation is one of the cleanest in the world. 83% of the electricity generation came from renewable sources (65% hydropower and 8% wind power). This results in one-fifth of the average emission intensity of G20 countries (about 100 gCO_2/kWh vs 500 gCO_2/kWh) (Climate Transparency, 2016). Besides, Brazil has the possibility of producing hydrogen using biofuels (e.g., ethanol and biogas) and transport it through the existing natural gas infrastructure, mentioned in the National Program of Hydrogen (PNH2) (MME, 2021).

Another important natural resource for hydrogen production is water. Producing one kg of hydrogen consumes between 9-15 liters of water. If Brazil produces all the hydrogen needed to meet the Germany demand in 2030, it will only consume 0.02% of the current water consumption. Although Brazil occupies the 116 position between the countries with water stress risk[18] (E+ INSTITUTE, 2021; WRI, 2022).

Brazil may have one of the lowest costs for hydrogen production (Agora, 2021b; McKinsey & Company, 2021). In the study published by (McKinsey & Company, 2021), the Levelized Cost of hydrogen production in 2030 is about 1.50 USD/kgH_2, lower than USA, China and Germany. BloombergNEF estimates that Brazil has the lowest cost of production in 2050, about 0.5 USD/kgH_2 (BloombergNEF, 2021a, 2021b) as given in Figure 14.

18 There are specific regions in Brazil with high water stress risk, e.g., Bahia, Ceara and Rio Grande do Norte. Their level is like Middle East countries (E+ INSTITUTE, 2021; WRI, 2022).

FIGURE 14 → **Global average levelised cost of hydrogen production by renewable source in 2050**



Source: BloombergNEF (2021b)

Brazil has the possibility of producing hydrogen using biofuels (e.g., ethanol and biogas) and transport it through the existing natural gas infrastructure, mentioned in the National Program of Hydrogen (PNH2) (MME, 2021).

Challenges and risks

The main challenges for the hydrogen production in Brazil are related to the infrastructure need for transportation and storage. Due to its low energy density, the transportation through long distances may increase its costs. It will be required a high level of investments for enabling the hydrogen industry (McKinsey & Company, 2021; MME and EPE, 2020). The costs associated with this investment can make unfeasible the hydrogen production when compared to other renewable sources. At least, uncertainties regarding the future demand increase the risk of this source and it can keep away the investment in large projects.

Another important challenge is to develop the regulation regarding the use of hydrogen (McKinsey & Company, 2021; MME and EPE, 2020). It will be required new and specific regulation for transport, storage, and use. Developing policies and regulations is fundamental for enabling a hydrogen industry in Brazil.

The participation of this technology in the decarbonization pathway of the steel industry relies on certain conditions. As a first step, DRI plants must be built for the initial use of natural gas but ready for adaptation and operation with increasing hydrogen shares. Then, such plants are ready for deployment. In parallel, electrolysis and the infrastructure for the production and supply of renewable hydrogen must be developed with the objective to gradually reducing the cost of the technology and the resulting hydrogen. The second challenge is the green hydrogen production cost that must fall considerably to become competitive (from three up to five times) (ArcelorMittal, 2021).

2.4.5

Carbon Capture and Storage

CCS is a key technology to achieve net zero emissions (ArcelorMittal, 2021; Rochedo et al., 2016; Toktarova et al., 2020). Rochedo et al. (2016) analyzed the carbon capture potential and costs in Brazil, considering the current production structure. Using the Top Gas Recovery Blast Furnace (TGRBF) associated with carbon capture, the steel sector can decrease 54% of its emissions at a cost of 112 USD/tCO_2. Furthermore, the potential can be increased up to 80% when considering the cogeneration units associated with steel plants with a capture cost of 116 USD/tCO_2.

Using the Top Gas Recovery Blast Furnace (TGRBF) associated with carbon capture, the steel sector can decrease 54% of its emissions at a cost of 112 USD/tCO_2.

Alternative production routes can benefit from CCS as well. Smelting Reduction (SR) technologies produce a gas-rich in CO_2, facilitating its capture and decreasing the abatement cost (Eurofer, 2013; IEA, 2020b; IRENA, 2020). When used in conjunction with coal, it has the potential to reduce emissions by up to 80%. When used with charcoal, emissions can be negative (Griffin and Hammond, 2019b). However, SR technologies should not be available until 2030. Direct Reduction using natural gas can improve its emission reduction when using CCS (Toktarova et al., 2020). This could cut the emission intensity of NG-DRI to levels lower than H-DRI at lower costs (IEA, 2020b).

It is important to mention that there is no study regarding CCS associated with innovative technologies from a Brazilian perspective. Despite the importance of this mitigation measure for decarbonizing steel production, a number of prerequisites, such as infrastructure development, must be met before carbon capture can be considered a viable alternative for the industry.

2.4.6

GHG Emissions Insetting/Offsetting

The amount of investment required to achieve zero emissions during the steel production process may rise production costs, resulting in carbon leakage, i.e., firms relocating production to other countries. Steel emissions can be offset through planted forests outside production sites or within its own value chain[19]. Offsetting GHG emissions can be a helpful instrument to achieve net-zero emissions in the Brazilian economy, as there is significant potential in Brazil, which would alleviate pressure on steel producers to achieve near-zero emissions intensity.

In the Brazil Zero Carbon 2060, the Brazilian Forum on Climate Change (FBMC) examined the prospects for reaching net-zero emissions in 2060 (FBMC, 2018). Restoration of native forest, as well as planted forest, can mitigate over 1,000 MtCO2-eq, five times higher than the projected emissions for all the industry in the same year. ArcelorMittal considers that 5%

19. According to Priory Direct, (2020), the term carbon insetting describes the development of activities that reduce GHG emissions or that generate CO_2-Sinks in the value chain of a company. Such activities allow reducing scope 3 emissions and thus contribute to the overall GHG footprint of the company, its suppliers, and clients.

of its emissions to be mitigated by high-quality offsets or carbon credits (ArcelorMittal, 2021).

On the other hand, the investment needed to achieve net-zero emissions in the steel production process can increase production costs, resulting in carbon leakage. Hence, companies that migrate their operations to other countries.

2.4.7

Steel production by electrolysis

The clean electricity generation in Brazil is a clear advantage for using Molten Oxide Electrolysis. However, the technology is still in its infancy. The uncertainty regarding its potential and costs is high. Therefore, it is unlikely that this technology will have a significant impact by 2050.

2.5

Production Costs

Low-carbon steel production technologies, such as H-DRI, Smelting Reduction, and CCS have higher investment costs than the traditional production BF-BOF method. Furthermore, their emission intensity reduction can increase the production costs up to twice the typical BF-BOF production cost (Fan & Friedmann, 2021). This may have a negative impact on the industry, as the steel producers have low profitability and operate in extremely competitive markets (Bataille, 2019). As a result, the increase of production costs may lead to a reduced market share. Another risk regarding the increase of production costs is carbon leakage (IABr, 2017).

The most significant part of OPEX in steel production is the energy cost, which represents about 60-80% (IEA, 2020a). Major technologies for reducing emissions focus on natural gas, hydrogen, and biomass. Overall, there are a few risks related to these energy sources. Renewable Hydrogen - DRI is one of the most expensive technologies, but it has one of the highest mitigation potentials. Electricity prices also may impact the steel decarbonization. Electricity is used in two important production technologies: EAF and H-DRI. As previously mentioned, electricity prices must be low for H-DRI to become competitive.

Climate change and deforestation are two issues that may have an impact on electricity costs. As roughly 85% of the generation comes from renewable sources, the Brazilian electricity generating system is vulnerable to these changes (IX Estudos e Projetos, 2018, EPE, 2021). De Jong et al. (2019) identified that climate change is expected to increase the wind power potential across most of Brazil and that in the Northeast and Southeast regions, solar power potential could increase modestly. According to Arias et al. (2020), climate change might reduce dry season hydropower potential, while the combined effects of deforestation could increase interannual variability in the hydropower generation (Vogl et al., 2018).

Finally, additional investment is needed to reduce the carbon intensity of electricity generation. Electricity prices may also rise because of this action (Wills, 2017). **Appendix I** provides an overview of steel production technologies costs and emission intensity.

2.6

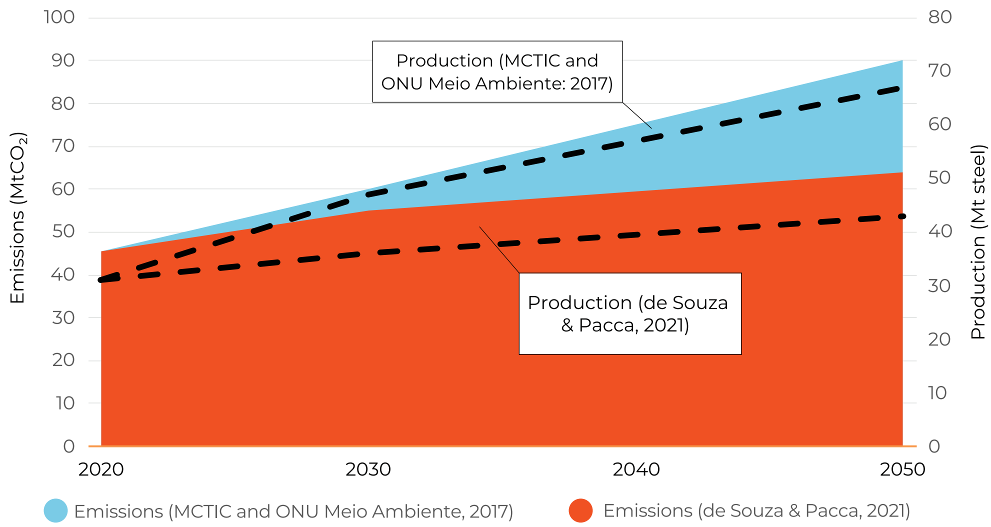
Perspectives on the Brazilian Steel Industry Emissions

Industrial emissions can be separated into two primary sources: industrial process and product use (IPPU) emissions and energy emissions. The iron and steel industry are the largest CO_2 emitter in the Brazilian industrial sector, accounting for 30% of the total sector emissions (Centro Clima, 2020). Iron and Steel is the most emitting industry (44%) considering IPPU emissions, and the third (11%) considering energy emissions in the industry sector (SEEG, 2021). The iron and steel industry corresponds to 6% of the national energy consumption (EPE, 2019).

To compare how cleaner the sector is in terms of greenhouse gases, one of the best indicators is the emission intensity. The Brazilian steel production emits 1.5 t_{CO2}/t steel (Centro Clima, 2020). This value is lower than the average of the major country producers, 2.0 t_{CO2}/t steel (Hasanbeigi and Springer, 2019). Despite outperforming major steel producers such as China and India, the Brazilian steel industry must act. The future of the sector will require low carbon steel to compete in the decarbonized global market.

MCTIC and ONU Meio Ambiente (2017) project an increase in steel production from 34 Mt in 2015 to 67 Mt in 2050. In the business-as-usual scenario, emissions increased from approximately 45 Mt_{CO2} in 2015 to almost 90 Mt_{CO2} in 2050. De Souza and Pacca (2021) forecast more modest growth in steel production, with 43 Mt (median) of steel in 2050. Without changes in the production process, emissions could rise by twice the value in 2015, 64 Mt_{CO2} (median) in 2050. Few studies have analyzed the projections of the steel emissions in Brazil and their mitigation potential. Their paths are summarized in Figure 15.

FIGURE 15 → **Emissions and Production projection in Brazil between 2020 and 2050**



Source: de Souza and Pacca, 2021; MCTIC & Onu Meio Ambiente, 2017

CONCLUSIONS

With a significant share of industrial emissions globally, rapid decarbonization efforts are needed in the steel sector. Steel plants have 20-30 years of lifetime (IEA, 2020a), which indicates that plants in operation today will be decommissioned in the coming decades.

With a significant share of industrial emissions globally, rapid decarbonization efforts are needed in the steel sector. Steel plants have 20-30 years of lifetime (IEA, 2020a), which indicates that plants in operation today will be decommissioned in the coming decades. As a result, the steel sector needs significant investments in the next 10 to15 years for low-carbon technologies to be ready to replace the current production line. Government, companies, and society should work together to propose a strong financial and regulatory framework to achieve a common objective: a sustainable development of the iron and steel industry.

The transition to net zero is already a commitment of the major producers in the Brazilian steel sector, but there is no precise description of how their goals will be achieved. In fact, there is no single silver bullet for decarbonizing steel, but rather a combination of technologies and initiatives aimed at the specificities of the regions in which the industries are located.

Table 4 depicts the main mitigation measures that can benefit the sector, considering their emission-reducing potential, the relevance of the associated costs, the advantages of Brazil that can leverage their adoption in the country's industries, and the time horizon in which their adoption is more likely.

TABLE 4 → **Technology perspectives for the Brazilian iron and steel production**

Mitigation Measure	Time period[20]	Mitigation potential	Cost	Brazilian advantages
Energy Efficiency	Short term	Low-medium	Low-high	Brazil still has potential for reducing its energy intensity
Scrap and EAF	Short-Medium	Medium	Low-medium	Competitive clean electricity generation; Scrap availability potential
Charcoal - BF-BOF	Short -Medium	Medium	Low	Pioneer in charcoal as energy source in steel production. High supply potential
Direct Reduction - Natural Gas	Medium-long term	Medium	Medium	Supply of Natural Gas is expected to increase. Prices are expected to drop
Charcoal - Smelting reduction	Long term	High	Medium	High supply potential
Direct Reduction – Hydrogen	Long term	High	High	Competitive clean electricity and hydrogen generation
CCUS	Long term	High	High	-
Direct Electrification	Long term	High	High	Competitive clean electricity generation
Insetting/Offsets	Short-long term	Medium-High	Low	Large area for planted forest

Source: Self elaboration and others (ArcelorMittal, 2021; Eurofer, 2013; Fan and Friedmann, 2021; IEA, 2020b)

In the short-term horizon, mature technologies stand out as having both an attractive potential for usage and more affordable costs. Therefore, Brazilian companies should initially invest in energy efficiency measures, increase the use of EAF using scrap and charcoal in BF-BOF.

Improving energy efficiency (understood as all mitigation measures that could currently be implemented to reduce energy consumption) in the traditional production route can lead to a 20% reduction in GHG emissions (IEA, 2020a). The EPE (2018a) shows the potential to reduce the energy consumption by 23% for pig iron production and 10% for steel

20 It was considered that short term is a time period between 0 and 10 years; medium term, between 10 and 20 years, and long term, more than 20 years.

production. Due to its low cost and potential, energy efficiency can be one of the fundamental options to reduce the sector's emissions in the short term.

There is still potential for mature technologies to continue helping the decarbonization process in the medium-term and long-term horizon. Steel production using charcoal and EAF have an enormous potential that will not be totally consumed in the short term.

Charcoal is relevant for the country, being responsible for almost 20% of the total energy mix of the steel sector. This relevance makes Brazil the largest producer and consumer of charcoal globally (IBÁ, 2021). However, due to technical and economic restrictions, charcoal is not an option for the complete replacement of coal coke in existing operations. Thus, charcoal is an essential input for several routes, such as ***i) Small/medium blast furnace, optionally with BECCS; ii) Fines injection in large blast furnaces with metallurgical coke; iii) Direct reduction of Tecnored type self-reducing pellets; iv) Complement for the production of H2-based steel to meet the metallurgical demand for carbon in the steel plant. Charcoal is also relevant in the production of ferroalloys and silicon.*** For charcoal to play this role, Brazil must expand its forest plantations (even enabling carbon removals) and produce charcoal in a sustainable way, adopting technologies such as the use of gases, reuse of co-products, etc.

An increase in scrap collection rate is expected, especially for end uses and in regions with current low collection levels. Having a lower emission intensity due to lower energy expenditure, the production of scrap for EAF applications can be quite beneficial for reducing emissions in the short term. However, the use of scrap in domestic steel production is still relatively low compared to other countries. Therefore, there is great potential for greater use of scrap in the future, contributing to the decarbonization of the national steel sector.

Another technology used in many countries with high mitigation potential is the direct reduction of natural gas. This can be an enormous opportunity for the Brazilian steel industry as the NG price from pré-sal is expected to drop with the increase of supply for the industry to be competitive. NG-DR can also be used as a transition solution to help decrease the use of fossil fuels (coal) when renewables are not a viable option. Using hydrogen in DR can improve the mitigation potential thanks to the clean electricity generation in Brazil. However, its production cost must fall to make it competitive concerning fossil alternatives.

Innovative technologies such as Smelting Reduction with charcoal or other biomass, CCS, and Electrolysis have strong mitigation potential. However, the uncertainty regarding their role in the Brazilian decarbonization pathway in the next 30 years is high. Brazil has a huge competitive advantage in using smelting reduction because of the high charcoal supply potential. Electrolysis technologies are still in their early stages of development and must not be considered in the present analysis. Finally, before CCS can be considered a viable mitigation option, it must overcome its high cost. Offsetting/insetting emissions with planted forest is also an enormous opportunity for the Brazilian economy and it can provide a slack margin to relieve the pressure off the sector in using high-cost technologies.

In general, clean electricity generation, abundant iron ore and biomass reserves, potential for NG supply and low-cost green hydrogen put Brazil in an advantageous position. Moreover, as the world will need low-carbon steel, Brazil can play a significant role in providing green steel and green DRI to meet the demand of China and other nations that have a steel sector with a high intensity of emissions, contributing to the world's decarbonization[21]. Additionally, other opportunities may arise because of the increased share of EAF and Smelting Reduction. Figure 16 depicts a possible pathway for the Brazilian steel industry, considering the potential identified in past research as well as the anticipation of new technologies.

21 Vale announced its intention to use DR to provide low-carbon and high quality DRI (ABIFA, 2019).

However, there are obstacles, such as the high costs of technologies, that can delay the transition. Several financial and regulatory instruments can be applied to help lower costs of disruptive technologies (Table 5).[22]

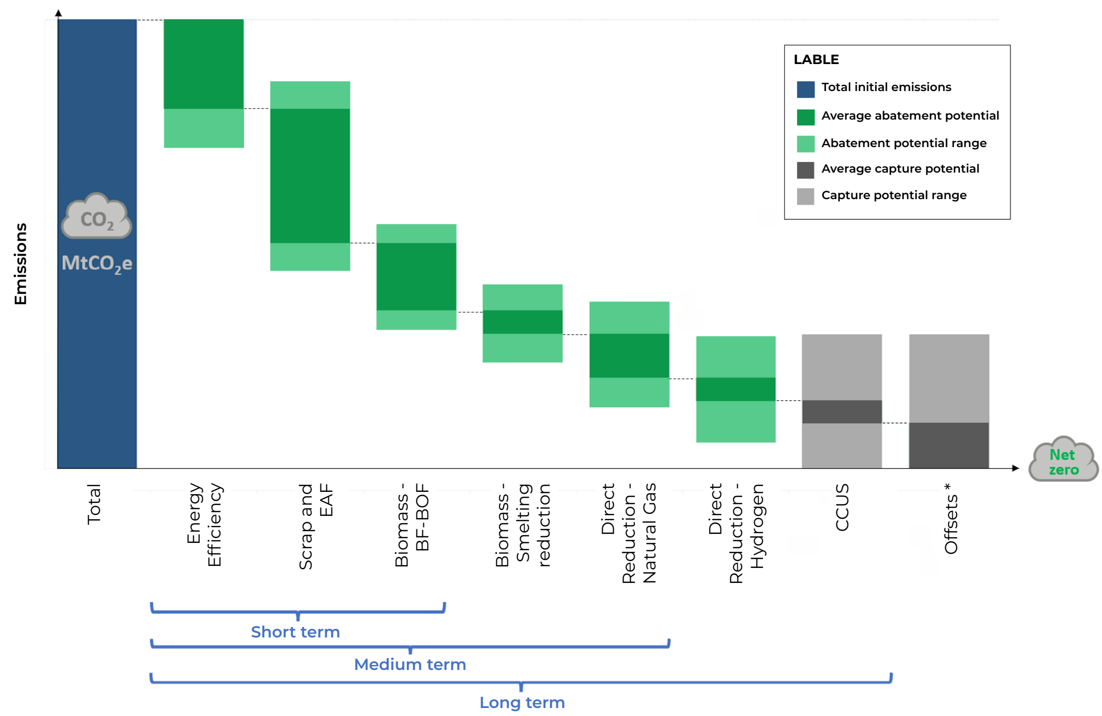
TABLE 5 → **Financial and regulatory instruments suggested to achieve a low-carbon sector**

Instrument	Examples
Financial incentives	Grants, Credit Lines with low interest rates, feed-in tariffs
Carbon Pricing	Cap-and-trade or carbon tax
Increasing Recycling	European Eco-Design Directive
Market Demand	Contract for differences; Preferential buying on public infrastructure projects (Green Public Procurement)
R&D	Public investment

Source: Fan & Friedmann, 2021; IEA, 2020a; Wills et al., 2021; Bataille, 2020; MCTIC & Onu Meio Ambiente, 2017; ArcelorMittal, 2021

Finally, global carbon pricing can be one of the most effective mechanisms for achieving emission targets. Its establishment can generate incentives for companies to accelerate their decarbonization programs toward low-carbon technologies. In particular, in the case of the steel industry, due to its high intensity of GHG emissions and a significant degree of international competition, it is necessary that the conditions between the different companies in the sector are equal and that carbon leakage is avoided.

FIGURE 16 → **Possible pathway for the Brazilian Steel Industry**



Source: Self-elaboration

Note: *Offsets do not consist of a direct reduction of emissions, but an offsetting of the sector's residual emissions, which can be implemented in any time horizon

22 For more details, see **Appendix II**.

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APPENDIX I

Technologies, CAPEX and TRL

Table 6 - Steel production technologies: emission intensity, CAPEX and TRL status

Technology	tCO_2/t steel	CAPEX (Euro/ tonne)	TRL Status
BF-BOF	1.1 - 2.2	386-442	9
EAF	0.4 - 1.1	184	9
BF-BOF CCS	0.9	411-471	5-8
Smelting Reduction	1.2 - 2.3	393	9
Smelting Reduction (CCS)	0.0 - 0.2	418-478	7
DRI-EAF	0.63 - 1.15	414	9
H-DRI EAF	0 - 0.025	550-900	5-7
EW	0.20 - 0.29	639	4-5

Source: Griffin and Hammond, 2019a; IEA, 2020a; Milford et al., 2013

APPENDIX II

Instruments

Financial incentives

A set of incentives can be used for supporting low-carbon technologies, which have higher costs. Some examples of financial incentives are such as Grants, Credit Lines with low interest rates, and feed-in tariffs (Fan & Friedmann, 2021, IEA, 2020a). Public and private financial institutions should work together to develop financial products for low-carbon technologies. This may help to reduce the investment costs of these technologies as well as their risks (IRENA, 2020).

Carbon Pricing

Carbon pricing is one of the key instruments for the decarbonization pathway. It can be a carbon tax or a cap-and-trade system[23]. Implementing carbon pricing increases the competitiveness of low-carbon technologies. Also, the revenue from carbon pricing can be allocated for reducing production costs, as labour tax exemptions (Wills et al., 2021) or as grants for research and development (IEA, 2020a).

Increasing Recycling

Increasing recycling is crucial for decarbonization of the steel industry. A regulatory framework as the European Eco-Design Directive (2005/32/EC, revised in 200915) may contribute to this goal. The framework should promote the enhancement of the design for recycling and marking components to facilitate sorting. Another option for increasing recycling is increasing waste charges for dumping materials that can be recycled (Bataille, 2020).

Market Demand for low-carbon steel

Prioritising the purchase of low-carbon steel by governments contract through procurement and content regulation can help to create a market for this product. Examples of these instruments can be minimum content regulation or preferential buying for infrastructure (Bataille, 2020). Another possibility is the Contract for Difference (CfD), between the government and a producer. In this contract, the government pays a carbon-based premium for the material produced. This helps to reduce the higher operation costs, as well as the risks for producing low-carbon steel (Bataille, 2020).

Investment in R&D

Some of the key technologies for producing green steel are still in the early stages of maturity. Research and development should be one of the main instruments to support the decarbonization pathway. Government should provide incentives, not only for basic research but also to make it commercially available.

23 The industry sector has declared preference for the Cap and Trade system, because a Carbon Tax can increase the production costs (CNI, 2021).

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