UFRJ ie. | DIP DECARBONIZATION & INDUSTRIAL POLICY

DECARBONIZATION AND INDUSTRIAL POLICY: CHALLENGES FOR BRAZIL

Working Paper DIP-BR 06/2025

Decarbonization in the steel value chain: Global and the Brazilian experiences

Germano Mendes de Paula

DECARBONIZATION AND INDUSTRIAL POLICY: CHALLENGES FOR BRAZIL

About the Project DIP-BR

"Decarbonization and Industrial Policy: Challenges for Brazil" (DIP-BR) is a policy-oriented research-action project aimed at influencing public debate on industrial, innovation, and trade policies in Brazil and selected Latin American countries that promote decarbonization and energy transition in the region. The initiative seeks to inform and induce efficacy, efficiency, effectiveness, and innovativeness in policy design and implementation. The methodology encompasses critical benchmarking analyses of past and present policy experiences from an international comparative perspective, regional trade studies, and economic analyses of productive sectors and chains, combining structural analysis of traditional production, employment, and trade statistics and simulation models of sectoral impacts using input-output approach.

Funded by the Open Society Foundations (OSF), Project DIP-BR is executed by the Research Group of Industry and Competitiveness at the Institute of Economics, Federal University of Rio de Janeiro (GIC/IE-UFRJ, **https://www.ie.ufrj.br/gic**) and is currently managed through José Bonifácio University Foundation (**https://www.fujb.ufrj.br/**).

Project DIP-BR Team

HEAD INVESTIGATOR

Carlos Frederico Leão Rocha (IE-UFRJ)

MAIN RESEARCH TEAM

João Carlos Ferraz (IE-UFRJ)
Marta Castilho (IE-UFRJ)
Fabio Freitas (IE-UFRJ)
Kaio Vital (IE-UFRJ)
Julia Torracca (IE-UFRJ)
Wilson Peres (IE-UFRJ)

CONSULTING TEAM

Agrifood Industry
John Wilkinson (UFRRJ)

Cement Industry
Lucas Rosse Caldas (FAU-UFRJ)
Thaís Pinto Lôbo Siqueira (COPPE-UFRJ)
Lívia Corrêa Silva (COPPE-UFRJ)
Romildo Dias Toledo Filho (COPPE-UFRJ)

Steel Industry
Germano Mendes de Paula (IERI-UFU)

Oil Industry
Marcelo Colomer (IE-UFRJ)
Sofia Kelly (IE-UFRJ)

RESEARCH ASSISTANTS

Bruna Ribeiro (IE-UFRJ)
Gabriel Pessanha (IE-UFRJ)
Tatiana Fleming (IE-UFRJ)
Nilo Bezerra Neto (IE-UFRJ)

PROJECT MANAGER

Carolina Dias (IE-UFRJ)

GRAPHIC DESIGNER

Galadriel Design

COMMUNICATION

Carolina Eloy

DECARBONIZATION AND INDUSTRIAL POLICY: CHALLENGES FOR BRAZIL

Working Paper DIP-BR 06/2025

Decarbonization in the steel value chain: Global and the Brazilian experiences

Germano Mendes de Paula [a]

[a] Full Professor of Economics, Institute of Economics and International Relations, Federal University of Uberlândia. Uberlândia, Brazil. ORCID: https://orcid.org/0000-0002-4072-6362. E-mail: germano@ufu.br.

DECARBONIZATION IN THE STEEL VALUE CHAIN: GLOBAL AND THE BRAZILIAN EXPERIENCES

ABSTRACT

The steel industry has long been integral to global industrial development, yet its significance comes at an environmental cost, as it remains one of the largest industrial sources of carbon dioxide (CO_2) emissions. With global production reaching 1.9 billion metric tons of crude steel in 2023, this sector alone accounted for approximately 26% of total industrial CO_2 emissions. The urgent need for decarbonization within the steel value chain is now a key focus for governments, industries, and environmental organizations. This paper examines the decarbonization efforts across the steel value chain, covering technological, economic, and policy aspects shaping the industry's future, including key stakeholders, current and emerging technological trends, and essential corporate decarbonization initiatives within the global steel sector. The paper also evaluates the current and future state of decarbonization efforts among Brazilian steel companies and delves into public policy initiatives designed to foster decarbonization in the steel industry in Brazil and across European Union-27, US, Canada, Mexico, Japan, China, and India. As a conclusion, it suggests that available resources and the timing of measures are currently insufficient to tackle the associated challenges effectively.

KEYWORDS

Decarbonization. Global steel industry. Brazilian steel industry. Industrial policy.

DESCARBONIZAÇÃO NA CADEIA DE VALOR DO AÇO: EXPERIÊNCIAS GLOBAIS E BRASILEIRAS

RESUMO

A indústria siderúrgica tem sido parte integrante do desenvolvimento industrial global há muito tempo, mas sua importância tem um custo ambiental, pois continua sendo uma das maiores fontes industriais de emissões de dióxido de carbono (CO_2). Com a produção global atingindo 1,9 bilhão de toneladas métricas de aço bruto em 2023, esse setor sozinho foi responsável por aproximadamente 26% do total das emissões industriais de CO_2. A necessidade urgente de descarbonização na cadeia de valor do aço é agora um foco importante para governos, indústrias e organizações ambientais. Este artigo examina os esforços de descarbonização em toda a cadeia de valor do aço, abrangendo aspectos tecnológicos, econômicos e políticos que moldam o futuro da indústria, incluindo principais partes interessadas, tendências tecnológicas atuais e emergentes, iniciativas corporativas essenciais de descarbonização no setor siderúrgico global. O artigo também avalia o estado atual e futuro dos esforços de descarbonização entre as empresas siderúrgicas brasileiras e se aprofunda em iniciativas de políticas públicas elaboradas para promover a descarbonização na indústria siderúrgica no Brasil e na União Europeia-27, Estados Unidos, Canadá, México, Japão, China e Índia. Como conclusão, sugere que os recursos disponíveis e a temporalidade das medidas são atualmente insuficientes para enfrentar os desafios associados de forma eficaz.

PALAVRAS-CHAVE

Descarbonização. Indústria siderúrgica global. Indústria siderúrgica brasileira.
Política industrial.

Table of Contents

Introduction

This paper examines the decarbonization of the steel industry by analyzing the entire value chain. Globally, the steel industry is well-established, characterized by significant economies of scale and high levels of energy consumption and carbon dioxide (CO_2) emissions. While technological breakthroughs have been infrequent, the industry has experienced numerous incremental innovations since mid-2000s. However, the push toward decarbonization now requires the steel industry to undertake significant efforts to adapt to this new paradigm.

The decarbonization of the steel industry is clearly a global issue with numerous practical implications. Firstly, the industry is characterized by high production volumes. Along with cement, steel is one of the few materials produced in billions of tons annually. According to the World Steel Association (WSA, 2024a), global crude steel production reached 1.9 billion metric tons (Bt) in 2023. Steel has been a crucial component of the global economy for several centuries. In 1709, Abraham Darby introduced the coke-fired blast furnace (BF) for producing cast iron, and since then, the BF has remained a key element for the primary technological route for steel production. Looking ahead, steel is likely to remain essential for decades, especially in developing countries, where it plays a critical role in infrastructure development, including housing.

Secondly, the steel industry is both energy and raw material intensive. According to the IEA (2020), iron and steel production is one of the most energy-intensive industrial activities, comprising 20% of global industrial final energy consumption and roughly 8% of total final energy demand. Therefore, improvements in energy efficiency within the steel industry can provide significant positive environmental impacts. Additionally, the steel industry has had the largest share of total direct industrial CO_2 emissions, accounting for 26% in 2019 and contributing approximately 7%-9% of global CO_2 emissions.

Thirdly, steel is a relatively cheap material, which helps explain its vast production volume. It comes in a wide range of products, with reinforcing bars (rebars, a long steel product), primarily used in construction, and hot rolled coil (HRC, a flat steel product), used extensively across the metal-mechanical value chain, being the most significant. As of mid-October 2024, the free on board (FOB) export price for Turkish rebar was US$ 620/t, and for Chinese HRC, it was US$ 530/t (Metal Expert, 2024a). In comparison, at the same time, the aluminum price at the London Metal Exchange (LME) was approximately US$ 2,566/t. Although aluminum is a strong substitute for steel in some applications, especially in packaging, construction, and automotive sectors, global aluminum production reached approximately 70 million metric tons (Mt) in 2023, which was only about 3.7% of the crude steel output.

Fourthly, decarbonization will lead to higher operational (opex) and capital expenditures (capex) compared to the current situation. According to McKinsey Global Institute (2022), steel production costs could rise by 30% by 2050 relative to today's costs, although ongoing innovation may reduce this percentage. Meanwhile, JP Morgan (2021) suggests that adopting a new technological route that uses hydrogen (H_2) will result in a 26% increase in operational costs for steel companies.

Bearing this context in mind, this paper is divided into five sections, in addition to this brief introduction. Section one examines the global steel chain focusing on key stakeholders, current and future technological trends, and crucial corporate decarbonization initiatives. The section offers a concise investigation into the corporate dimension of decarbonization in the global steel industry.

Section two discusses the Brazilian steel chain, emphasizing current and future technological trends, environmental and innovation practices, carbon intensity indicators and the influence of various sectors on carbon emissions, corporate decarbonization initiatives, and technological threats and opportunities. This section aims to scrutinize the current and prospective situation of Brazilian steel companies regarding decarbonization.

Section three addresses the public policy dimension, on a global level, focusing on the most relevant public initiatives and their respective policy instruments aimed at promoting decarbonization in the steel industry. In the following section, it is discussed whether the financial and institutional resources available to Brazilian steelmakers are sufficient to tackle the challenges of decarbonization. Section five concludes and summarizes the main findings of the study.

1. Global steel value chain and decarbonization

1.1. Steel products and consumption by sector

Often thought of as a uniform commodity, steel encompasses a wide range of products with numerous applications. According to WSA (2024a), global finished steel product consumption in 2023 reached 1.76 Bt. Usage is divided among various sectors: building and infrastructure (52%), mechanical equipment (16%), automotive (12%), metal products (10%), other transportation like ships and railways (5%), electrical equipment (3%), and domestic appliances (2%). It should be noted that the transformation of crude steel into finished (or rolled) steel products involves a loss of material. Steel typically functions as an intermediate product supporting various manufacturing industries and construction. In developing countries, the market share for building and infrastructure is generally higher than the global average. Conversely, in developed ones, the demand for steel in metal-mechanical products is habitually above the world average.

Steel is classified into semi-finished or finished (rolled) products. The semi-finished products (slabs, blooms, and billets) are directly consumed by steel companies to fabricate rolled products. Additionally, semi-finished products are also in demand, albeit in a residual proportion, by manufacturers within the metal-mechanical chain. Similarly, rolled products can be directly used by end consumers in various applications. They are divided into four main segments: carbon flat-rolled products, special/alloy flat-rolled products, carbon long-rolled products, and special/alloy long-rolled products (also known as special bar quality, or SBQ). As suggested by their name, long-rolled products are distinguished by their physical shape, with a notable predominance of length over other dimensions such as width and thickness (Pinho, 1993). Seamless tubes are sometimes considered a separate market segment, but they can also be classified as part of the long products category.

In 2023, global production of flat-rolled products reached 933 Mt, making up 50.9% of the total output. Long-rolled products totaled 798 Mt, accounting for 46.2%, while seamless tubes amounted to 54 Mt, representing 2.9% of the total (WSA, 2024c).

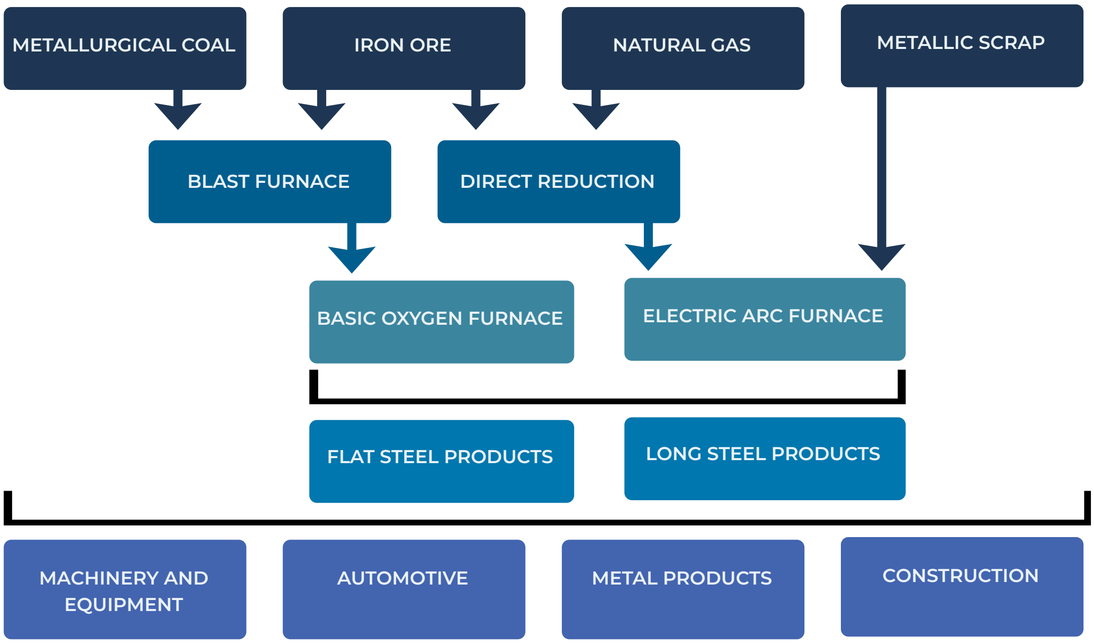
The proportion between flat-rolled and long-rolled products varies according to a country's level of industrialization. In developing countries, with typically less complex industrial bases compared to developed countries, steel consumption and production tend to favor long-rolled products, which is more oriented toward construction. In contrast, flat-rolled products are more intensively used by manufacturing sectors, predominantly the metal-mechanical chain, which includes the fabrication of machinery, equipment, and automobiles, among others.

1.2. Technological routes

To facilitate understanding how the decarbonization paradigm impacts the global steel industry, it is necessary to introduce some key terms related to the production process. The goal here is not to exhaust the topic nor delve into technical details but to provide a schematic view of the main phases in the steel production chain.

Figure 1 shows a simplified view of the stages of the steel production chain. In terms of mining, the two most important inputs are metallurgical (or coking) coal and iron ore. The BF can be fed with three types of iron ore: natural lump ore, sinter, and pellets (obtained through agglomeration processes of iron ore fines). Sinter, produced in sintering plants of the steel mills themselves from sinter feed (fines ranging from 0.15 to 8 mm), is the most consumed form. Lump ore and pellets are produced mainly by mining companies, with pellets being obtained by agglomerating pellet feed (ultrafine particles below 0.15 mm) in pelletizing plants. It should be noted that iron ore mining does not necessarily require pelletizing.

Figure 1 - Simplified view of the steel value chain



Source: own elaboration.

There are two main technological routes for steel production: integrated mills and semi-integrated mills. Integrated mills produce steel from iron ore through one of two methods: BF or Direct Reduction (DR) Modules. BF, the predominant method in the sector, combines iron ore and coke (made from metallurgical coal) to produce pig iron. Generally, such equipment is found in large-scale mills. DR, on the other hand, uses iron ore and natural gas (or non-coking coal) as the main inputs to produce direct reduced iron (DRI) and hot briquetted iron (HBI). This method is widely used in India and the Middle East due to the ample availability of non-metallurgical coal and natural gas, respectively. DR integrated mills are usually of intermediate size. In situations where scrap availability is limited, the use of DRI-HBI becomes essential to ensure specific quality characteristics. HBI, a denser and more processed form of DRI, is designed to improve its handling and transport efficiency. Because it is a less reactive form, its transport is simpler (Fernandes *et al.*, 2024).

In 2023, global pig iron production totaled 1.3 Bt, significantly surpassing the 137 Mt produced of DRI/HBI. Semi-integrated mills, on the other hand, manufactures steel from ferrous scrap. This process starts in the steel shop, eliminating the need for iron making. Due to their more compact technology, such mills are often referred to as mini-mills. This does not necessarily imply that the plants are small, though in practice, the average size of semi-integrated mills is considerably smaller than that of coke-integrated ones. Semi-integrated plants are more flexible both operationally (production variation is less costly than for coke-integrated mills) and economically (due to lower capital intensity).

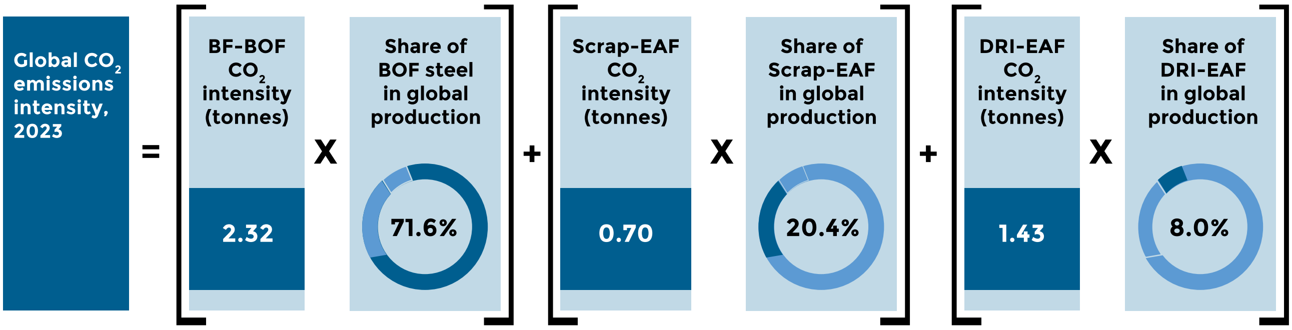
Coke integrated mills have a basic oxygen furnaces (BOFs), while DR integrated and semi-integrated ones are based on electric arc furnaces (EAFs). In 2023, 71.1% of global crude steel production came from BOFs, 28.6% from EAFs, and 0.3% from other processes (notably, the technologically outdated Siemens-Martin process). Once steel is produced, it is cast (cooled) and transformed into slabs (for flat-rolled products) or blooms and billets (for long-rolled products). In 2023, 96.7% of the global steel industry applied continuous casting technology, while 3.3% used conventional casting, which is a less efficient technology (WSA, 2024a).

Predominantly, flat-rolled products are manufactured in integrated plants (mainly coke-based), although semi-integrated plants have gradually gained ground in this segment, particularly in the US. For long-rolled products, semi-integrated mills dominate. In the rolling phase, steels are transformed into final products. This paper focuses more on ironmaking (BF and DR) and steelmaking, as these activities account for the bulk of energy consumption and CO_2 emissions in the analyzed sector. Additionally, rolling mills experience large variety of processes and energy and environmental performances.

1.3. CO_2 emissions

Figure 2 demonstrates that in 2023, the BF-BOF mill's share in the global steel production reached 71.6%, followed by mini-mills (scrap-EAF, with 20.4%) and DRI-EAF ones (with 8.0%). Furthermore, the CO_2 specific emissions (t CO_2/t crude steel) were equivalent to: BF-BOF mills (2.32), DRI-EAF mills (1.43), semi-integrated mills (0.70) and the three combined (1.92). These data refer mainly to scopes 1 (direct emissions from sources owned or controlled by a company) and 2 (indirect emissions from purchased energy).

Figure 2 - CO_2 specific emissions in the global steel industry, 2023 (in t CO_2 equivalent/t crude steel)



Source: WSA (2024b).

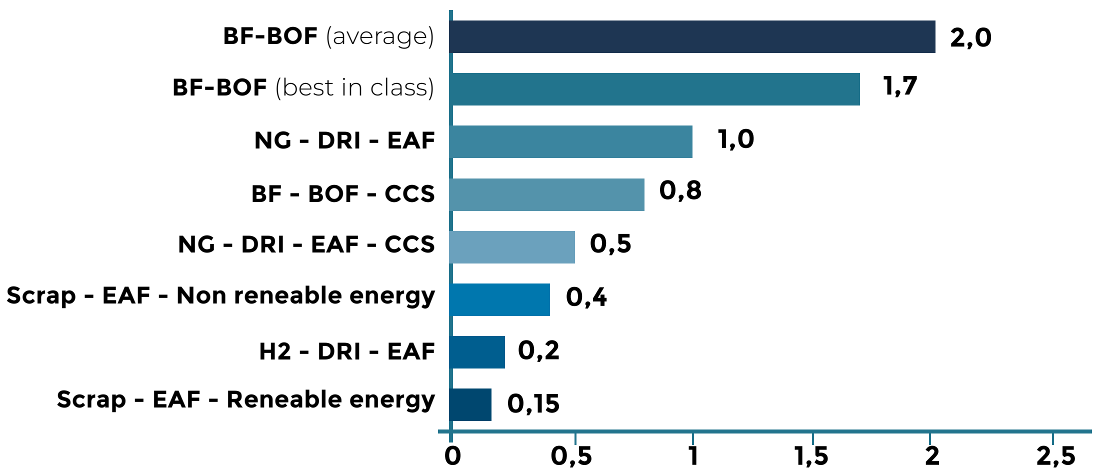
According to IEA (2020), when considering direct CO_2 emissions from the steel industry, BFs and DRs are the main emitting equipment. Furthermore, they are among the longest-lived and most capital-intensive assets within a steel mill. The average lifetime of these assets is typically around 40 years. However, after approximately 25 years of near-continuous operation, a BF will need to have its internal refractory lining replaced. At that time, the weighted global average age was about 13 years for BFs and 14 years for DRs. It can be concluded that these assets had roughly half of their useful life remaining. The Brazilian average for BFs was similar to global average as of 2019, but the DR modules were disabled.

IEA (2020) also reports that the initial installation cost of a BF is around US$ 200-300 million per metric ton (M/Mt) of capacity, while the relining cost is typically around half of this figure. As many BFs are able to produce annually 3 Mt-4 Mt, the required capex to construct a new one reaches US$ 750 million-1.0 billion. Thus, a considerable barrier to decarbonize the steel industry refers to the sunk costs of the existing BFs.

Decarbonization requires improvements in the BF-BOF route, but mainly a higher diffusion of alternative technologies. Graph 1 shows the estimation of specific CO_2 emissions by routes in the coming years, according to the consultant firm CRU. For instance, on average, the best BF-BOF will generate 1.7 t CO_2/t crude steel. With the addition of carbon capture and storage (CCS), this level can be reduced to 0.8. The respective figure for DRI-EAF, based on natural gas (NG), which is a well-established technology, is 1.0. In the case of H_2 as a reductant, this ratio will drop to 0.2, because oxygen combines with H_2 to produce water, instead of reacting with carbon to produce CO_2. The best performance will be achieved by using 100% ferrous scrap, in EAF, consuming renewable energy, with an index of 0.15.

Bearing these possibilities in mind, the most effective way to decarbonize the steel industry is to improve the diffusion of EAF, converting ferrous scrap into steel, and being supplied by renewable energy. However, there is a strong shortage of obsolete scrap, particularly in emerging countries, because its reservoir is generated by steel consumption many years ago. Not surprisingly, in 2021, at least 42 countries, including China, India, Russia, South Africa, Argentina, and Colombia, adopted some restriction on ferrous scrap exports (OECD, 2022a). In January 2025, Argentina lifted restrictions on scrap exports that were originally imposed in January 2009 and has been recurrently renewed since then (Kallanish, 2025). This move is part of a broader trade liberalization effort under Javier Milei's administration, and it is goes against the trend observed in the global steel industry.

Graph 1 - Global steel's specific emissions of CO_2 equivalent, scopes 1 and 2 (in t CO_2/t crude steel)



Source: CRU (2024).

Another important opportunity to decarbonize the steel industry is through the adoption of DRs, consuming natural gas, sometimes substituting BFs. This strategy is most prominent in Europe, and to a lesser extent in the US and Canada, as it will be explained further in this text. In fact, this is medium-term solution, as the second step will involve the consumption of H_2 once it becomes available at reasonable costs. In the particular experience of the US, which it is a net exporter of ferrous scrap and where the diffusion of EAF is comparatively high, industry leaders are investing heavily in renewable sources of energy, such as wind and solar.

It is worth noting that the substitution of BF-BOF for DRI-EAF will imply a considerable demand of electricity. According to McKinsey (2024b), the annual production of 2 Mt via BF-BOF requires the consumption of 1.2 Mt of coking coal as an energy source, with limited or no external energy purchase. For the DRI-EAF route, there is a need of approximately 1.2-1.6 terawatt hours of electricity. Moreover, it requires 5 terawatt hours of electricity to produce H_2. McKinsey (2024b) estimates that electricity (including for H_2 production) accounts for 40%-50% of production costs for green steel.

Another possibility to decarbonize the steel industry is the diffusion of carbon capture utilization and storage (CCUS) technology. Nevertheless, this is a relatively controversial issue. On the one hand, International Energy Agency (IEA) has a track record of reliance on CCUS for decarbonization in its scenarios, including for the steel industry. The IEA estimates that the share of CCUS will reach a diffusion rate of 3% of the global steel production by 2030, 10% by 2035, and even 37% by 2050 (IEA, 2023). One the other hand, the Institute of Energy Economics and Financial Analysis (IEEFA) argues that CCUS will not be relevant in the steel business (IEEFA, 2024). It claims that CCS has been around for decades, but currently only 41 commercial-scale projects are in operation globally and 351 are under development. Of the 392 combined projects, only four are in the steel industry. The Al Reyadah CCUS facility by Emirates Steel Arkan (in the United Arab Emirates) is the first and only commercial-scale plant in the steel sector. It came into operation in 2016, with a capacity of 0.8 Mt/year. Emirates Steel Arkan is a DR integrated mill, comprising a 4.2 Mt/year DR, 3.6 Mt/year EAF, 3.5 Mt/year long and flat rolling mills. Nonetheless, the percentage of overall scope 1 and 2 emissions captured in 2022 was only 26%. More importantly, the captured CO_2 is used for enhanced oil recovery (EOR), enabling more fossil fuel extraction and therefore more carbon emissions (IEEFA, 2024). Bearing in mind this global scenario, the next section will focus on the Brazilian steel industry.

2. Brazilian Steel Value Chain and Decarbonization

2.1. Steel products and consumption by sector

In 2023, the sectoral distribution of steel consumption in Brazil was led by the construction sector (38.9%), followed by automotive (23.4%), capital goods (20.3%), household and commercial utilities (5.8%), small diameter welded pipes (4.7%), packaging (3.2%), and other sectors (3.8%), according to Aço Brasil (2024b). This represents a relatively sophisticated composition for an emerging country, as in other nations such as China and India, the relative importance of the construction industry exceeds 50%.

In terms of the distribution of steel products, in 2023, Brazilian flat products accounted for 55.9% of the total, while long products represented 41.5% and seamless pipes, 2.6% (Aço Brasil, 2024a). These values are similar to the global average, with respective figures of 52.5%, 45.1%, and 2.4% in 2022. Conversely, the country's steel industry has the peculiarity that semi-finished products (especially slabs) correspond to a significant share of the total volume, about 30.6% in 2023. The semi-finished products, aimed mainly at export, are used by other steel mills for transformation into rolled products.

It is worth mentioning that rolling activities are of little relevance in terms of CO_2 emissions. Furthermore, considering the different types of rolling, the specific CO_2 emission indices released by both the WSA (2024b) and Aço Brasil (see Yuan, 2024) include up to the steelmaking process and, therefore, do not account for the rolling activities.

2.2. Technological routes

From the perspective of the production structure, Brazil stands out with the technological route known as charcoal integrated mill, which only exists in the country. This process uses charcoal as a reductant (instead of coke) for producing pig iron, which then feeds into a BOF or even an EAF. The latter case it is often referred to as hybrid route, but for simplification, it will also be treated as a charcoal integrated mill in this paper. According to BNDES (Fernandes *et al.*, 2024), the use of charcoal faces technical limitations in replacing coke in traditional BF processes, because of its lower mechanical resistance compared to metallurgical coal coke. In BFs, charcoal tends to disintegrate, as these devices are designed to operate on a large scale, with larger volumes of materials and intense operating conditions.

The large physical dimensions of BFs increase the pressure and weight of materials on the charcoal, exacerbating its tendency to disintegrate. When charcoal is fragmented, it results in greater generation of fines, which can obstruct the flow of gases essential for efficient combustion and reduction of iron ore, compromising operational efficiency. Additionally, charcoal has a lower energy density, so that larger quantities are needed to generate the same level of heat as coke, overloading the BF capacity and making it difficult to maintain ideal temperatures and precisely control the process. Furthermore, on average, coke-fired BFs have an internal volume of 3,000 to 6,000 m^3 and are 30 to 40 meters high, whereas charcoal-fired BFs have an internal volume of 200 to 600 m^3 and are 10 to 20 meters high.

Given the low availability of obsolete scrap in the country, Brazilian steel mills have developed and optimized the use of solid pig iron in the metallic charge (around 30%) in EAFs. This corresponds to a high proportion compared to that practiced in developed countries, which usually have greater availability of ferrous scrap (De Paula, 2010). In 2023, Brazilian steel mills produced 26.0 Mt of pig iron, of which 23.8 Mt based on coke and 2.3 Mt based on charcoal (Sindifer, 2024).

Also in 2023, independent pig iron producers (commonly referred to as *guseiros*) produced 5.3 Mt of pig iron based on charcoal (Sindifer, 2024). These companies are non-vertically integrated and sell solid pig iron to be consumed by steel mills. Of the total produced by *guseiros* in 2023, 72.3% were exported, primarily to the US. Until 2022, all charcoal-based production from *guseiros* worldwide was concentrated in Brazil. However, in 2023, a charcoal-based BF from Companhia Siderúrgica do Cuchi in Angola began operations, with an annual capacity of 96 thousand tons (kt) (Steel Orbis, 2023). Additionally, a charcoal-based BF from Fermosa Biosiderúrgica is currently under construction in Argentina, with an annual capacity of 144 kt (Gobierno de la Provincia de Formosa, 2024). Overall, these two ventures are not expected to substantially change the fact that charcoal-based ironmaking is predominantly a Brazilian characteristic. It is important to note that the pig iron output from guseiros is not accounted for by either WSA or Aço Brasil. Although they are part of the value chain, they are not considered as steel companies properly since they do not produce steel.

The share of the BF-BOF route in the Brazilian steel industry was 73.3% in 2023, followed by the semi-integrated route (with 14.8%) and the charcoal-based route (11.9%), according to Aço Brasil (2024a). On one hand, the relevance of the BF-BOF process is marginally higher than the global average (71.6%). On the other hand, the relevance of the semi-integrated route is significantly lower than the global standard (20.4%), due to the scarcity of obsolete scrap. Meanwhile, only Brazil operates with the charcoal-based integrated route in practice and it does not have any DRI-EAF plants currently.

The ferrous scrap reservoir in the country is relatively low, mainly due to four factors: i) Brazil has been a significant exporter of steel since the 1980s, thereby generating ferrous scrap in the importing countries; ii) a significant part of Brazilian steel consumption is directed toward the construction sector, which has a lower scrap recycling rate and a longer recovery time compared to the automotive industry; iii) the average age of the vehicle fleet is higher than in developed countries, which 'delays' the generation of obsolete scrap; iv) the scrap generated in the country is of lower quality compared to developed countries. In 2023, Brazil's ferrous scrap net exports totaled 782 kt, which represented a minimal fraction of the country's iron ore net exports (353 Mt) (Aço Brasil, 2024a). Therefore, there are considerable limitations preventing an exponential growth in the diffusion of EAFs in Brazil.

Brazil has had three DRI-EAF mills: Gerdau Cosigua, Piratini, and Usina Siderúrgica da Bahia (Usiba). Gerdau Cosigua's DR was commissioned in 1977, with a 350 kt annual capacity. This plant was designed to operate with naphtha gas, but due to the oil shock, it became unfeasible. In the absence of naphtha gas, the solution was to partially oxidize the fuel gas, but the module could not operate with satisfactory results. Thus, due to technical infeasibility, the DR was discontinued in 1979 (De Paula, 1998).

Like Usiba, Piratini was originally a state-owned enterprise (SOE) controlled by the Ministry of Mines and Energy. Its main purpose was to consume the non-coking coal abundant in the Southern region. It began operations in 1973. Piratini was the second plant in the world to use SL/RN technology with a rotary kiln, but the DR was deactivated in 1990, two years before its privatization (De Paula, 1998). Since then, the plant has operated as a semi-integrated mill.

Usina Siderúrgica da Bahia (Usiba) was founded in 1963 under the control of the Superintendência de Desenvolvimento do Nordeste (Sudene) as an attempt to diversify the sector's energy matrix by using natural gas (De Paula, 1998). The plant started operations in 1973, while rolling only began in 1977. In 1989, the plant was privatized and acquired by Gerdau, which maintained its focus on producing carbon long products. However, the DR module had its activities interrupted in 2009, transforming the plant into a semi-integrated mill. A few years later, in 2014, the plant was temporarily halted and then permanently deactivated in 2020. Thus, although DRI-EAF is a well proven technology, it has not performed satisfactory in the Brazil, although only one was based on NG, which is the predominant reductant worldwide.

2.3. CO_2 emissions

Yuan (2024) reported the specific CO_2 emissions of the Brazilian steelmakers by technological routes: BF-BOF (2.2 tCO_2/t crude steel), charcoal integrated ones (0.7) and semi-integrated ones (0.4). This data refers only to Brazil Steel Institute's associates, which accounted for 88% of the country's crude steel output in 2023. The Brazilian performance of the BF-BOF is marginally better than the global average (2.32), which can be explained by several factors: i) Brazil has a large availability of high iron content, being the second-largest iron ore exporter globally in 2023, surpassed only by Australia; ii) the average age of BF is similar to the global industry; iii) the scale of the BF is comparable to international counterparts, and the management capability is often recognized as a positive aspect of the Brazilian industry.

The comparative performance of the Brazilian semi-integrated mills (0.4) is much better than that of international peers. This outcome is mainly due to the renewable energy sector (comprised by hydro, solar, and wind power) accounting for 88% of the country's electricity matrix in 2022, while the global average was 29.1%, according to IRENA (2024). It should be highlighted that the indirect emission CO_2 intensity of power generation for electricity imported from the grid takes into consideration the national factor. However, the poorer quality of ferrous scrap, with a lower amount of industrial-origin scrap and higher proportion of obsolete scrap without pre-treatment, hinders the energy performance of Brazilian semi-integrated mills compared to other countries, especially those where the manufacturing industry has a greater relevance in GDP. According to Carvalho, Mesquita, and Araújo (2015), in a sample of eight major steel-producing countries, Brazil ranked fifth in electricity consumption in steel production via EAF. It is reasonable to conclude that this result is somewhat associated with the low quality of ferrous scrap, which is the main input in the metallic charge in semi-integrated mills. In other words, the superior environmental performance obtained by Brazilian mini-mills could be even better with higher quality ferrous scrap.

Regarding technological strategies towards decarbonization, the most prominent efforts have been focusing on reducing greenhouse gas (GHG) emission from scope 2, mainly through investments in wind and solar energies. For instance, In April 2023, ArcelorMittal unveiled the establishment of a joint venture with Casa dos Ventos to construct a 554 megawatt (MW) wind power project in Brazil. ArcelorMittal Brasil would hold a 55% of the venture, with Casa dos Ventos holding the remaining 45%. The total investment would be equivalent to US$ 800 million, while the ArcelorMittal's total equity investment would be equivalent to US$ 150 million. This project is estimated to provide 38% of ArcelorMittal Brasil's total electricity needs in 2030. The company's current electricity consumption is 500 MW, half of which is generated by its own hydroelectric plant and by recovered BF gases from the Tubarão steel mill, among others. Due to the expansion of the industrial facilities underway, its consumption is expected to jump to 750 MW by 2026 (De Paula, 2023a).

The so-called "Babilonia project" will be in the central region of Bahia, northeast Brazil. The site was selected due to several competitive advantages, including high-capacity forecast load factors (exceeding 50%) and a short distance (23 km) to connect to the national electricity grid. There is also the potential to expand the project's capacity by adding a further 100 MW of solar power. The project is expected to be operational by January 2026. ArcelorMittal Brasil will enter a 20-year power purchase agreement with the joint venture for the supply of electricity, to purchase up to 92% of its output. Babilônia's output will avoid the emission of 208 kt/year of CO_2 (De Paula, 2023a).

Concerning solar energy, in February 2022, the Brazilian steelmaker Usiminas announced a partnership with Canadian Solar regarding photovoltaic (PV) energy. The deal will increase self-production of an average of 30 MW of renewable energy, representing about 12% of the volume of energy consumed by the steel company. Set to being 2024, the construction of the solar park involves investments estimated at US$ 244 million, with Canadian Solar in charge of the capex (De Paula, 2023b). The project is expected to enter commercial operation in January 2025, with a 15-year long-term energy purchase and sale agreement. The energy will be produced in a PV solar park to be installed in Luziânia, located 885 km from Ipatinga, the Usiminas' largest industrial asset.

Also in February 2022, Gerdau and Shell unveiled the formation of a 50:50 joint venture for the development, construction, and operation of a new solar park in Brasilândia de Minas, southeast Brazil. The park's installed capacity will be approximately 260 MW peak (MWp). It will supply 50% of the volume produced for Gerdau's steel operations in the country, in the self-production modality, while the other half will be traded on the free market through Shell Energy Brasil, Shell's energy trader. The agreement was approved by Brazilian antitrust watchdog CADE in July 2022 (De Paula, 2023b).

In November 2022, Gerdau announced the acquisition of one-third of energy generation platform Newave for US$ 284 million. The deal gives Gerdau the right to purchase 30% of the energy generated by power generation projects held directly or indirectly by Newave in the self-production model. In December 2024, Gerdau's shareholding of Newave increased to 40%, which also expanded its long-term energy acquisition commitment from 30% to 40% of the energy generated by Newave. As a result, Gerdau will consume a total of 111 MW average from Newave solar parks, equivalent to approximately 23% of its consumption in Brazil. Using this energy source should generate an estimated emission reduction of 65 kt CO_2e/year (Gerdau, 2024). In addition, in January 2025, Gerdau purchased Garganta da Jararaca and Paranatinga II hydroelectric power plants for about US$ 74 M. Located in State of Mato Grosso, the plants have a power generation capacity of 29 MW each (Steel Orbis, 2025). Their outputs will meet approximately 8% of the energy consumption of Gerdau's steel production units in Brazil.

The investments in wind and solar energies aim to optimize the current production structure, as they not implied the alterations concerning technological routes. However, other initiatives tend to provide more substantial technological changes. Prumo Logística, which owns and operates the Port of Açu, in the State of Rio de Janeiro, is working to develop one or two 2.5 Mt/year DR modules, initially based on NG, to be commissioned from 2027 onwards. DR is a very well-known and mature technology, but its past performance in Brazil has been unsuccessful. According to Prumo Logística, the use of HBI in BF can reduce GHG emissions by approximately 25% (Valor Econômico, 2023a). It should be highlighted that the partial substitution of coke with NG in the BF generates lower CO_2, sulfur, and particle emissions, while resulting in decreased energy consumption, as NG is cleaner compared to coal and coke (Fernandes *et al.*, 2024).

Some steelmakers, especially in Europe, are substituting BF with DRI, initially using NG and then H_2 when the costs drop substantially. In Brazil, Companhia Siderúrgica Nacional (CSN), based on BF-BOF, has engaged in three bets to take part in the green H_2 race. First, in November 2021, CSN announced its investment on the start-up 1s1 Energy. Founded in December 2019 in San Francisco, California, the start-up raised US$ 1 million in this 2021 round from all investors, but CSN's participation was not disclosed. 1s1 Energy has developed a solution to manufacture green H_2 on a large scale at a highly competitive cost by redesigning the essential components for a Proton Exchange Membrane (PEM) electrolysis process. The company expects to achieve a cost of less than US$ 1.5/kg, while the currently average market cost is US$ 5/kg, making the input attractive both environmentally and economically (De Paula, 2022).

Second, in January 2022, CSN announced it was acquiring a minority stake in Israeli start-up H2Pro. The company has developed a technology that promises to cheapen large-scale production of green H_2. At that time, H2Pro raised US$ 75 million via a venture capital round leaded by Temasek (a Singaporean state holding) and that included other investors such as ArcelorMittal (a competitor to CSN) and Breakthrough Energy Ventures (established by Bill Gates) (De Paula, 2022).

Third, in April 2022, CSN announced a pilot project to employ green H_2 in the production process of specific areas of the mill located in Volta Redonda, Brazil. The technology will be supplied by Portuguese company UTIS, which was established in 2018 as a joint venture between Ultimate Cell and the Secil group (cement) and gained Sempai group as its shareholder at the end of 2021. The technology developed by UTIS has already shown results in cement plants, solid waste combustion, and biomass, but will be employed by a steel mill for the first time in CSN's pilot project. CSN has employed UTIS technology for cement production since 2020, first at the integrated plant of Arcos, Brazil, where it obtained a reduction of 12 $kgCO_2$/t of cement. This new technology also allows higher productivity of the clinker kiln and lower power consumption. In 2022, the company began to use it in its Alhandra plant, northeast Brazil. For the cement plant project, CSN obtained financing from Finep (the Brazilian federal agency that funds innovation), but this option was not available for the steel project. Summing up, CSN has become shareholder in two start-ups focused on breakthroughs for producing green H_2 (using different technical methods and being in diverse stages of development) and it has also engaged in employing new but already proven technology in installed equipment. Therefore, to mitigate the risks associated with such technical challenges, CSN opted to navigate with three different approaches, akin to a venture capital strategy (De Paula, 2022). More recently, CSN announced that employing UTIS' technology in the cement plant generated US$ 5 million gains, including higher productivity. The steel mill pilot plant would planned to be installed by late 2023 (Valor Econômico, 2023b), but not updated information is available.

In addition, CSN will use its own renewable power generation for the first phase of its 100-MW Selene green H_2 project, with a 5-MW phase already under construction. Power for phase one will come from CSN Energia's hydro and wind assets, with operations set for December 2025. Phase one and the 40-MW phase two of the Selene project are in Araucaria, State of Paraná, where CSN has a steel rolling and coating line. Phase three will be in the State of Rio de Janeiro, near CSN's BF-BOF mill. Phase two is to start in 2027-2028, with phase three in 2029-2030 (Platts Steel Markets Daily, 2024).

In December 2024, CSN and Petrobras signed a protocol of intent as the first step towards establishing a business partnership to implement a commercial-scale low-carbon hydrogen plant in Paraná, south Brazil (Valor Econômico, 2024). The main goal is to use low-carbon hydrogen in industrial processes or as a fuel, produced through the electrolysis of water powered by renewable electricity sources. The plant's scale, timeline, and investment amount remain undisclosed.

At least two other emerging technologies for the iron and steel industry warrant discussion: Tecnored and Boston Metal. In April 2022, the iron ore miner Vale announced the commencement of construction for the first commercial Tecnored plant in Marabá, north Brazil. The Tecnored process aims to produce pig iron by reducing self-reducing agglomerates (briquettes or pellets) (Fernandes *et al.*, 2024). The Tecnored furnace is notably smaller than a traditional BF and highly adaptable in terms of raw material usage, which can include iron ore fines, steel residues, and dam sludge. As a fuel source, the furnace can be fed by carbonized biomass, such as sugarcane bagasse and eucalyptus. These materials are transformed into briquettes (small compact blocks) and fed into the furnace, generating green pig iron. The furnace also has the capacity to use thermal coal as fuel. In its initial phase, fossil fuel will be utilized to assess the plant's performance, making the first large-scale operation of the technology. Over time, coal will be replaced by carbonized biomass until the goal of 100% biomass usage is achieved (Vale, 2022).

The first phase of Tecnored's commercial plant will have a capacity of 250 kt/year, with the potential to double it. The start-up is scheduled for 2025 with an estimated investment of approximately US$ 345 million. Developed over the past 35 years, the Tecnored's technology eliminates the need for BF and sintering processes – stages prior to the steel production in the steel mill that are intensive in the emissions of GHG. Thus, using the Tecnored furnace could lead to a cost reduction of up to 15% in the investment of new steel plants (Vale, 2022). Vale operates a demonstration Tecnored's plant in Pindamonhangaba, southeast Brazil, with a rated capacity of 75 kt/year. Having started operations in 2011, this plant was instrumental in developing the technology and assessing its technical and economic feasibility. BNDESPar, a subsidiary of BNDES (Brazilian developing bank), was shareholder in Tecnored from 2008 to 2014. Since 2014, Tecnored has been solely owned by Vale, although the technological project began in 1980. De Paula (2003) analyzed the first two decades of Tecnored's trajectory, noting that its main financial support came from strategic alliances. These alliances seemed primarily motivated by the lack of alternative mechanisms in the Brazilian economy for high-risk, long-maturation period, radical technological projects.

In February 2021, Vale invested US$ 6 million in the Boston Metal to acquire a minority stake and promote the development of a technology focused on decarbonizing steel. Boston Metal is a pre-operational company founded in 2012 by Massachusetts Institute of Technology (MIT) professors with the objective of developing an innovative technology called Molten Oxide Electrolysis (MOE). This process reduces metallic oxides such as iron ore with the usage of electricity, enabling the production of steel with zero CO_2 emissions. It may also produce high-value metals, such as tin, tantalum, and niobium.

According to De Boer *et al.* (2024), the MOE process results is molten iron that is immediately suitable for transfer to the refining stage, where carbon and other elements are added to transform the molten iron into refined steel. The only significant byproduct of this process is oxygen, derived from the iron oxide in the iron ore. For the process to be completely carbon-neutral, the electricity used to power the reactor should come from renewable sources. Additionally, MOE's specific energy consumption (13 GJ/t) is considerably lower than that of BF-BOF process (24 GJ/t).

Boston Metals obtained US$ 25 million in Serie A fundraising in 2018, US$ 60 million in Serie B in 2021, and US$ 120 million in Serie C in 2023. The latter Series C round was led by ArcelorMittal, with participation from other investors, including Microsoft. Existing investors include strategic players such as Vale, BHP, and BMW, climate-tech-focused groups such as Energy Impact Partners and Breakthrough Energy Ventures, and deep-tech specialists such as The Engine. In March 2023, IFC announced an equity investment of US$ 20 million in Boston Metal. In May 2023, Boston Metal declared it would invest approximately US$ 113 million to implement its first plant, capable of operating on a commercial scale, in Coronel Xavier Chaves, southwest Brazil, with the construction planned to start in 2023 (Valor Econômico, 2023c). In September 2023, additional US$ 122 million was obtained through an extension of Serie C, led by Aramco Ventures. In January 2024, an additional US$ 20 million, via Serie C2, was received from Marunouchi Innovation Partners (Brasil Mineral, 2024). Production is scheduled to begin in 2024 on a small scale, with plants to increase production volume over time. The plant is expected to commence operations by 2026. Thus, Tecnored and Boston Metal aim to develop radical innovations to address steel decarbonization, highlighting that the former is a proprietary technology of Vale, while the latter can be seen as consortium of many enterprises, including ArcelorMittal, which has extensive operations in the Brazilian steel industry.

3. Public policies in selected countries

3.1. Productive structure

The decarbonization of the steel industry depends not only on operational improvements in the scope of technological routes, but also on changing the relative importance of such routes and also on the development of new technologies and the reduction of input costs (such as H_2). In this context, countries that use the BF-BOF route more intensively (such as China) will inevitably have greater difficulty and higher costs in carrying out decarbonization than those in which the diffusion of the semi-integrated route (such as the US) is bigger. Consequently, it is quite important to look at the productive structure of the steel industry in selected countries and consider their specificities when thinking about decarbonization policies. The countries and regions chosen are the world's largest steel producers (China, India, Japan, EU-27, and the US), a country with large mineral resources and high proportion of renewable energy (Canada), the second largest Latin American steel producer (Mexico) and, of course, Brazil.

This subsection presents a comparative overview of the current production structure in selected countries, which the following ones pay attention to the main public policy initiatives aimed at decarbonizing the steel industry. As can be seen in Table 1, the production structure is very different in the sample of selected countries. The share of BOF reaches 91% in China, around 75% in Japan and Brazil, but is only 32% in the US and 7% in Mexico. Individually, this is the main factor that impacts specific CO_2 emissions. The exception is India, which despite having a BOF share (44%) that is substantially below the world average (71%), its specific CO_2 emissions (2.28) are well above the global parameter (1.87), according to WSD's data (2023). This is due to the fact that the Indian steel industry is intensive in RD, based on non-coking coal. Such modules are relatively small and have poor energy and environmental performance. In fact, according to BigMint (2023), the specific emissions of coal-based RD in India are 3.05. In fact, even in other technological routes, the Indian performance is unsatisfactory, being 2.60 for BF-BOF (compared to 2.32 for the world average) and semi-integrated (1.20 versus 0.70, respectively), utilizing WSA (2024b)'s information.

Table 1 - Steel production and consumption indicators, and specific emissions of CO_2, 2023

	World	China	India	Japan	UE-27	US	Canada	Mexico	Brazil
Crude steel production (Mt)	1.892	1019	141	87	126	51	12	16	32
BOF (%)	72	90	44	74	55	32	58	7	76
EAF (%)	29	10	56	26	45	68	42	93	23
Pig iron production (Mt)	1,314	871	86	63	64	21	6	1	31
DRI production (Mt)	137	0	51	0	0,3	5	2	6	0
Rolled steel consumption (Mt)	1,763	896	133	53	128	91	13	29	24
Share of consumption by constrution (%)	52	57	64	36	36	46	...	55	39
Net scrap export (Mt)	...	-0,5	-11,8	6,8	14,7	11,2	4,0	-1,8	1,1
Specific emission CO_2 (2019)	1,87	2,20	2,28	1,64	1,31	1,00	...	1,18	1,70

Note: Japan's emissions considered also South Korea and Taiwan; US's emissions considered also Canada and Mexico; Mexico's and Brazil's emissions refer to 2023
Source: WSA (2024a), Eurofer (2024), Aço Brasil (2024), Sindifer (2024), for production, consumption and export data; WSD (2023), Yuan (2024), Canacero (2024) for CO_2 emissions.

Generally speaking, the more developed a country is, the less important construction tends to be regarding steel demand. For example, this proportion is 36% in Japan and the EU-27, compared to 64% in India. This has implications in terms of the formation of the obsolescence scrap reservoir. In fact, ferrous scrap originating from construction has a longer recovery cycle and a lower recovery rate than that from the metal-mechanical chain. Consequently, one of the biggest problems in decarbonizing the steel industry in emerging countries is the reduced size of the obsolescence scrap pool.

In fact, developed nations tend to be net exporters of metallic scrap. In 2023, UE-27 had net exports of 14.7 Mt, followed by the US (11.2 Mt), Japan (6.8 Mt) and Canada (4.0 Mt). On the other side of the spectrum, India (11.8 Mt), Mexico (1.8 Mt) and China (0.5 Mt) were net importers. Brazil was as exception, because it was a net exporter of 1.1 Mt, which can largely explained by the fact that charcoal-based pig iron is produced by some steelmakers and the independent pig iron producers also commercialized the input in the domestic market, in order to offset the scarcity of obsolescence scrap in the country. In 2023, the charcoal-integrated mill produced 2.3 Mt of pig iron and *guseiros* sold 1.5 Mt pig iron in domestic market, totaling 3.8 Mt, which is considerable higher than the net exports of metallic scrap.

3.2. European Union 27

The EU's public policies are driving the industrial decarbonization process through three different main channels: i) regulated carbon market – European Union Emissions Trading System (EU ETS); ii) international trade measures – EU Carbon Border Adjustment Mechanism (CBAM) and European Waste Shipment Regulation (WSR); and iii) financial support via subsidies, as analyzed below.

In 2023, the EU-27 produced 126 Mt of crude steel, accounting for 6.7% of global production. The EU ETS is recognized as the world's first international trading system for CO_2 emissions and applies not only to the EU Member States but also to Norway, Iceland, and Liechtenstein. It covers over 11,000 heavy energy-using installations (power stations and industrial plants) and airlines operating between these countries, collectively responsible for 40% of the region's total GHG emissions.

In December 2022, The European Parliament and European Council agreed to further delay the planned phase-out of free CO_2 allowances as part of the EU ETS. As a result, the complete phase-out of CO_2 allowances is now set for 2034, two years later than previously indicated. Nevertheless, emissions in the EU ETS sectors must be cut by 62% by 2030 compared to 2005 levels. It should be emphasized that installations covered by the EU ETS have already reduced emissions by about 35% between 2005 and 2021.

The CBAM was introduced as a part of the European Green Deal, which serves as a guide for both tax and non-tax policy initiatives in the EU-27 to achieve its ambitious target of becoming climate neutral by 2050. According to KPMG (2023, p. 1):

> CBAM levies a carbon price on the imports of the target goods with the intention of equivalent carbon pricing on imports, mirroring the EU Emissions Trading System (ETS) for production in the EU. This is to ensure the competitiveness for both the manufacturers of the ETS-covered goods in the EU and the importers of CBAM-covered goods in the EU, making the Customs Union attractive for those companies and countries which produce and export less emission-intensive goods. Conversely, it signals disruptive changes and new roles and responsibilities for the customs authorities in the EU, as well as companies importing the covered goods.

The CBAM entered into force in its transitional phase as of October 2023, with the first reporting period for importers ending in January 2024. Initially, it is applied to imports of certain goods and selected precursors whose production is carbon-intensive and at most significant risk of carbon leakage: cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen. When CBAM is fully phased in, it will capture more than 50% of the emissions in ETS-covered sectors. The objective of this transition period is to serve as a pilot and learning phase for all stakeholders (importers, producers, and authorities) and to collect useful information on embedded emissions to refine the methodology for the definitive period. KPMG (2023) highlighted that CBAM is certain to have substantial effects on the companies trading in the growing list of covered commodities. It is also expected to generate a disruptive impact on general global trade, as measures such as CBAM will probably become the new normal.

Once fully implemented in 2026, CBAM will operate as follows: EU importers of goods covered by the mechanism will need to purchase CBAM certificates, with prices calculated based on the weekly average auction price of EU ETS allowances, expressed in €/t CO_2 emitted. By May of each year, EU importers must declare the quantity of goods imported into the EU in the previous year and the number of embedded emissions in those goods. At the same time, importers will depend of a number of CBAM certificates corresponding to the amount of GHG embedded in the imported products. If importers can provide verified information from third-country producers that a carbon price has already been paid during the production of the imported goods, the corresponding amount can be deducted from their final bill.

Within the scope of measures likely to impact scrap exports in the coming years, the revised WSR is crucial. Implemented in May 2024 to ensure the availability of high-quality scrap within the EU as part of the bloc's decarbonization targets, the WSR aims to restrict scrap exports to countries that do not adopt waste treatment standard equivalent to those of the EU. To import from the EU, other nations will be required to conduct independent audits of their processing facilities. Stricter export rules for ferrous scrap, including the proposed audit of facilities for non-OECD scrap buying countries, are expected to be implemented in May 2027, following a three-year transition period. The burden of proof that importers of ferrous scrap have facilities equivalent to EU standards will rest with European exporters (SBB Daily Briefing, 2023a). For OECD member countries, audits will not be required if there is an agreement between the EU and the country in question. Nonetheless, exports of ferrous scrap from the EU will be monitored even to OECD member countries (BLEES, 2023).

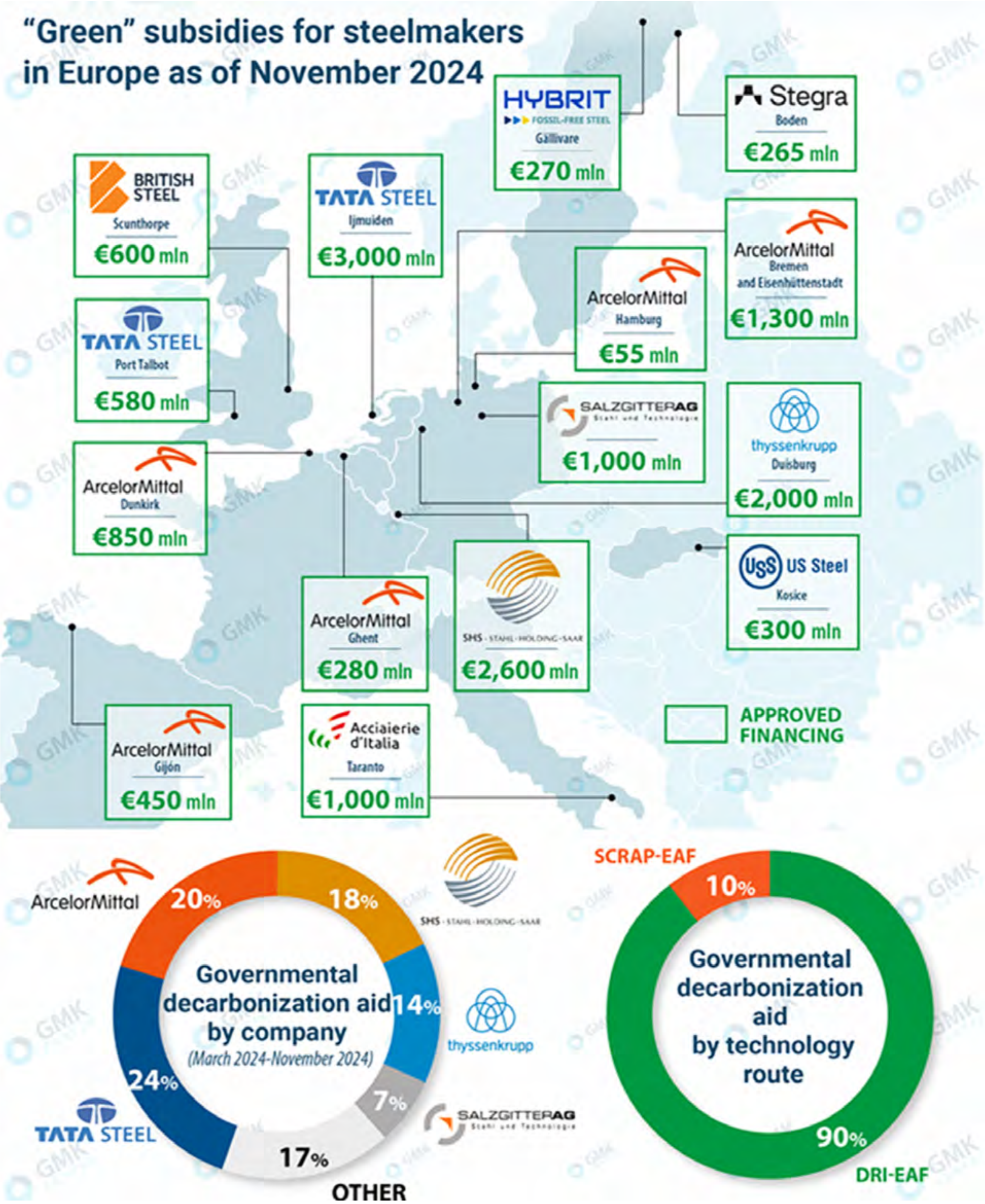
According to the WSR's rules, non-OECD countries must submit a request to the European Commission by February 2025 to continue importing waste from the EU, including steel scrap; otherwise, exports will be halted by May 2027. Such a request must come from the importing country's competent authority and include detailed documentation on waste management practices, ensuring alignment to EU standards. The European Commission will create a list of authorized destinations with approved requests, and exports to unlisted nations will not be allowed (Kallanish, 2024). It is reasonable to assume that the WSR mechanism will be adopted by other developed countries, similarly to what is happening with CBAM.

Regarding EU's financial support to the steel industry, an important case is the Hydrogen Breakthrough Ironmaking Technology (HYBRIT) project, a joint venture between steelmaker SSAB, iron ore LKAB, and energy utility company Vattenfall to develop H_2-based DRI. HYBRIT was established in 2016 to develop a technology for fossil-free iron and steelmaking. Pilot plant started test operations for fossil-free steel in Lulea, northern Sweden, in 2020, and claimed to deliver the world's first fossil-free steel in August 2021. It is important to clarify that fossil fuel free does not mean CO_2 free: SSAB Zero™ generates less than 0.05kg CO_2e/kg of steel in scope 1 and 2, regarding operations, including purchased energy and transportation. More importantly, with a grant of € 143 million from the EU Innovation Fund, the HYBRIT Demonstration project aims to put green steel on the market before 2030. This fund is financed by the revenues from the EU ETS (The HYBRIT..., 2023), demonstrating how different public policy instruments can work together to address decarbonization.

Along 2023-November 2024, European countries have approved (and was dealing to approve) various grants aiming to subsidize steel decarbonization's effort, in many countries, such as: Belgium, France, Germany, Spain, Sweden, Slovakia, and United Kingdom, totaling € 14.6 billion (Figure 3). A total of 15 subsidy decisions have been announced in European countries, with an average amount of assistance per project of around € 1 billion. It is important to highlight that 90% of this amount is dedicated to DRI-EAF route and the remaining 10% to the semi-integrated route.

It is interesting to highlight the experience of Salzgitter, the second-largest steel mill in Germany, with an annual capacity of 7 Mt of crude steel. Its SALCOS project consists of a DRI, an EAF (1.9 Mt) and a 100 MW electrolysis plant for H_2 production, expected to start operations in 2025-2026. The total investment is approximately € 2.3 billion, € 1 billion of which (equivalent to 43%) is subsidized by the German government. As of February 10th, 2025, Salzgitter's market capitalization was € 1.13 billion. Therefore, while the value of SALCOS project exceeds the company's market capitalization, the project will be responsible for decarbonizing only 30% of the company's nominal capacity.

Figure 3 - Government Subsidies for Decarbonization in the European Steel Industry, 2023-2024 (in € million)



Source: GMK Center (2024a).

3.3. The United States

In 2023, the US produced 81 Mt of crude steel, accounting for 4.3% of the world output. The country is in a favorable position regarding the decarbonization of the steel industry, as 68% of its production is based on EAFs, particularly mini-mills, which has a lower emission intensity compared to BF-BOF and DRI-EAF mills. Additionally, in 2023, the US also produced 5.2 Mt of DRI-HBI using NG. Given this context, it is useful to investigate the regulated carbon market, the potential to replicate CBAM, and the available financial support.

California operates its own carbon market and issues credits to residents for gas and electricity consumption. The number of credits issued each year is typically based on emissions targets and is frequently issued under a "cap-and-trade" program. However, the largest steel producer in California is a re-roller, meaning it acquires slabs from third parties. In other words, the state has only rolling mills not steel shops. Other sub-national legislations in the US include the Regional Greenhouse Gas Initiative (RGGI), a market-based effort among the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia to cap and reduce CO_2 emissions from the power sector (ICAP, 2022). It is worth noting that the regulated carbon market for the steel industry is much less significant in the US rather than in EU-27, not only because it is a state-level instrument but also due to the lesser relevance of the route BF-BOF in that country.

In July 2023, the US International Trade Commission (USITC) announced a fact-finding investigation to assess the GHG emission intensity of steel and aluminum produced in the US, at the request of the US Trade Representative (USTR). The investigation will analyze data on scopes 1, 2, and 3 and was expected to be concluded by January 2025 (USITC, 2023). Additionally, Louisiana Republican Senator Bill Cassidy has been working on legislation dubbed the "Foreign Pollution Fee" to establish a trade mechanism. Proponents of a border fee for high-carbon imports argue that the US must also act following the EU's enactment of similar rules (SBB Daily Briefing, 2023b). Thus, the US is expected to adopt a mechanism similar to CBAM in the coming years.

Estevez *et al* (2024) summarize industrial policy tools for a green steel transition available in the US, categorizing them into "carrots" (incentives) and "sticks" (regulations). The incentives include the Inflation Reduction Act of 2022 (IRA), grants, rebates, and cooperative agreements related to the Infrastructure Investment and Jobs Act (IIJA), the Department of Energy (DOE) Loans Program Office (LPO) lending authority, the

Greenhouse Gas Reduction Fund, Government procurement, the Defense Production Act (DPA), several tax credits, and trade tools. The regulatory measures encompass the Clean Air Act, the Clean Water Act and the Occupational Health and Safety Act, and several national and international precedents.

The IRA, signed into law in August 2022, directs new federal spending toward reducing carbon emissions, lowering healthcare costs, funding the Internal Revenue Service (IRS), and improving taxpayer compliance. It allocates US$ 394 billion of federal funding to clean energy, with the goal of substantially lowering the nation's carbon emissions by the end of the 2020 decade. The funds will be delivered through a mix of tax incentives, grants and loan guarantees (McKinsey, 2022). Moreover, in March 2023, the USA has announced that it will direct US$ 6 billion in grants to accelerate decarbonization projects in energy-intensive industries such as steel, aluminum and cement production. These industrial sectors account for nearly 25% of US' GHG emissions. The proposed initiative, named Industrial Demonstrations Program, provides competitive grants to technology developers, industry, universities, and others of up to 50% of the cost of projects aimed at reducing emissions in industry, according to the US Department of Energy (DoE) (GMK Center, 2023).

In March 2024, the US government selected six steel decarbonization projects to receive US$ 1.5 B or 25% of the Industrial Demonstration Program's budget (Metal Expert, 2024b, p. 20):

> Six decarbonisation projects from five steel companies were selected to receive a total government investment of $1.5 billion funded by the president Biden's Bipartisan Infrastructure law and Inflation Reduction Act. They are expected to reduce CO_2 emissions by 2.5 million t annually. (...)
>
> Cleveland-Cliffs (Cliffs), US largest flat steel producer, was selected for total award negotiations of $575 million for two projects – Middletown Works, Ohio, and Butler Works, Pennsylvania (see separate article in World Steel News edition).
>
> Sweden's SSAB was selected for an award of $500 million for the construction of 100% green hydrogen-based commercial-scale HYBRIT DRI facility in Perry County, Mississippi. The project will use the experience of a similar facility currently developed at SSAB's European operations. Besides, the project is planned to expand SSAB's existing 1.25 million HRC operations in Montpelier, Iowa, by using the resulting DRI.

Another project ($282.9 million in federal award) will involve iron ore miner Vale for the construction of cold-agglomerated iron ore briquette production on the US Gulf Coast. Vale's briquettes can be used as a low-emission alternative to pellets. Besides, the miner may develop additional, customized facilities in Brazil and world wide, to reach around 100 million t of agglomerates production by 2030, including iron ore briquettes and pellets. This technology reduces emissions from iron ore processing and the need for industrial heat, 'resulting in a flexible product that can be used at both direct-reduced and blast furnace ironmaking routes,' according to the DOE's statement.

The remaining two projects are for replacing traditional coke-fired heating furnaces with electric induction melting furnaces at two pipe companies: American Cast Iron Pipe Company (up to $75 million award) and United States Pipe and Foundry Company (up to $75.5 million). The former will replace its Birmingham, Alabama based cupola furnace with four induction furnaces, reducing melt process car bon dioxide emissions by an estimated 95%. The same replacement at the latter company would result in an estimated 73% reduction in carbon intensity at the Alabama Works ductile iron pipe production facility in Bessemer.

The largest subsidized project mentioned above refers to stimulate Cleveland Cliffs replacement of the existing BF with a 2.5 Mt/year DRI-EAF. This substitution aligns with several European projects that also received subsidies. In the case of Vale, the project involves industrial-scale production of its innovative iron ore briquette, tailored for the DRI route. The plant is designed for a capacity of 1.5 Mt/year, with potential for expansion. These briquettes can help reduce GHG emissions in steel production by up to 10% compared to traditional processes, by eliminating the carbon-intensive sintering stage. This approach optimizes technological innovation. Notably, HYBRIT has also secured subsidies in Europe. Nevertheless, in January 2025, SSAB withdrew from federal award investment negotiations with the US DoE but continues to advance decarbonization projects in the country, including HYBRIT. The steelmaker declined to elaborate on the decision (GMK Center, 2025).

Another significant initiative is the US DoE's US$ 7 billion funding, under the Bipartisan Infrastructure Law, allocated to the Regional Clean Hydrogen Hubs Program (H2Hubs) in October 2023. One of these H_2 hubs is the Midwest Alliance for Clean Hydrogen (MachH2), which will serve Northwest Indiana near Cleveland-Cliffs' two largest steel mills, Indiana Harbor, and Burns Harbor. Cleveland-Cliffs is currently constructing a pipeline to transport H_2 to Indiana Harbor Blast Furnace #7, at a cost of US$ 9 million

(Cleveland Business Journal, 2023). Meanwhile, the federal government will invest up to US$ 1 billion in this H_2 hub.

Somehow, the USA replicates the EU-27's strategy, albeit with lower intensity in terms of regulated carbon market and the amount of subsidies, and with some delay regarding CBAM. Conversely, the construction of H_2 hubs is an outstanding achievement for the coming decades for an industry that already has lower levels of CO_2-specific emissions.

3.4. Canada

In 2023, Canada produced 12 Mt of crude steel, accounting for 0.6% of the global output, with 58% produced through the BF-BOF route. The country also produced 1.6 Mt of DRI based on NG. In addition, Canada had a 4.0 Mt ferrous scrap net export position in 2023, which can be seen as a stimulus to expand the share of EAF. Canada shares two similarities with Brazil: a high iron ore net export ratio in 2023, with the former at 67% and the latter at 82%; and they had the world's second and third largest hydropower generation in 2023, totaling 431.28 terawatt-hours and 365.39 terawatt-hours, respectively.

According to Olexiuk, Sadikman, and Guindi (2023): "Despite nearly 30 years of interest in emissions trading, carbon credit markets in Canada remain fragmented, lack liquidity and require regulatory development and stability. Canada has yet to create a national, integrated market for carbon emission reduction products with fungibility and transparency." Regarding the mandatory carbon market, the large emitters are under legal obligations to diminish carbon emissions or use carbon credits established under such regulatory frameworks to meet those obligations.

The federal industrial compliance market regulates carbon emissions from large industrial emitters through minimum carbon pricing standards. Its framework was established by the Greenhouse Gas Pollution Pricing Act (GGPPA) of 2018. The Canadian government claimed to have implemented a rigorous carbon pricing system and set an ambitious trajectory to reach C$ 170/t CO_2 by 2030. For that reason, Canadian companies might not be subject to the CBAM when it is fully implemented (Government of Canada, 2024). In this context, Canada is already discussing the establishment of its own CBAM.

ArcelorMittal Dofasco hosted groundbreaking ceremony for its transformational low-carbon emissions steelmaking project in October 2022. The mill, located in Hamilton, Ontario, represents a total investment of C$ 1.8 billion. The governments of Canada and Ontario committed C$ 400 million and C$ 500 million, respectively, accounting for half of total project investment. Th plant will convert BF-BOF into a 2.5 Mt/year DRI-EAF. The new DRI module will initially operate on NG but will be constructed "H_2 ready," allowing it to transition to green H_2 as a clean energy input as and when a sufficient, cost-effective supply of green H_2 becomes available. In this case, government subsidies have fostered a higher diffusion of the DRI-EAF route, which is also the most common priority among the subsidies granted in Europe.

Other strategies for decarbonizing the Canadian steel industry has been employed in the country. According to Warrian and Afshar (2023), Algoma Steel decided to fully convert from BF-BOF to semi-integrated mill until 2030. The mill is fed through the Ontario electricity grid, which is 93% non-emitting. Its plant is located in Sault Ste. Marie, near to key steel-consuming regions of the US Midwest and Northeast and Canada's Southern Ontario. The location is also close to significant scrap trade flows, including prime scrap. Toronto, Chicago, and Detroit, the three main scrap sources in North America, are near the Algoma mill and could provide enough scrap for the future EAF operation. Based on electricity and ferrous scrap availability, Algoma opted for a 100% scrap EAF, with the lowest expected emissions. It is definitely a good solution, bearing the capex and availability of scrap and hydro energy. Algoma is constructing the two new state-of-the-art EAFs to replace its existing BF-BOF operations and expects first steel production by the end of March 2025 (Metal Expert, 2025).

Stelco, another BF-BOF mill located in Hamilton, Ontario, has decided to maintain its technological route and not to accelerate transition to DRI/EAF anytime soon. This strategy, referred to as "optimization of current assets" by Warrian and Afshar (2023), includes constructing a CCUS facility in collaboration with Pond Technologies. However, the CCUS facility's capacity is reported to be 6.3 kt/year, considerably lower than the emission reduction amounts announced by ArcelorMittal Dofasco and Algoma. Stelco's decarbonization activities are a moderate bet, as funding is secure and the scale of the project is relatively small. It is worth noting that Cleveland Cliffs acquired Stelco in November 2024 for US$ 2.5 billion, and the new management announced plans for modernizing the BF at Lake Erie Works in Nanticoke steelworks by implementing a new stove for the BF to enhance efficiency and lower emissions. The company has decided not to pursue the installation of an EAF at the site as it would result in job reductions (Metal Expert, 2024c).

3.5. Mexico

Mexico produced 16 Mt of crude steel in 2023, accounting for 0.9% of the global output. The relative importance of the BF-BOF route fell from 23% in 2019 to 7% in 2023, a trajectory largely influenced by AHMSA, a 5.5 Mt/year BF-BOF mill that stopped operations in January 2023 due to insolvency (Steel Orbis, 2024). Additionally, Mexico's production of DRI-HBI was considerable, accounting for 4.3% of the global production of this input. The DRI-EAF route's specific emissions are higher than those of the semi-integrated route, which helps explain why, despite having a BF-BOF share of only 7%, Mexico's specific CO_2 emissions was 1.18 in 2023. Notably, the world's first commercial DRI module (HyL I) was developed in Mexico in 1957 by Hylsa (Astier, 1991), now under the control of Techint group.

The most important public policy instrument in Mexico is the regulated carbon market. The Mexican ETS, the first in Latin America, was implemented in January 2020. It covers direct CO_2 emissions from fixed sources in the energy and industry sectors emitting at least 100 kt CO_2/year, accounting for around 40% of national GHG emissions and 90% of emissions reported in the National Emissions Registry (RENE). According to IETA (2023), in September 2022, the Mexican Environment Ministry confirmed that the national ETS would begin operations in January 2023, following a three-year pilot phase. However, the Ministry was not expected to publish the final regulations until June 2023, which would reportedly include details on the allowance caps. Auctions are not planned to take place until 2025 at the earliest.

At a first glance, it appears that no Mexican steel company has been awarded subsidies toward decarbonation. Nonetheless, Ternium, a Techint's group subsidiary, is investing US$ 3.5 billion to promote backward vertical integration in Pesquería, Nuevo León. This project, initially conceived to be downstream, involves producing hot-rolled, cold-rolled, galvanized and color coated coils, from slabs sourced from Ternium Brazil and third parties. The company was expected to implement a 550 kt/year pickling line and the first lines in a new service center by December 2024. Additionally, it plans to add a 1.6 Mt/year cold-rolling mill and 600 kt/year hot-dip galvanizing line by the end of 2025. By 2026, a 2.1 Mt/year DRI module and 2.6 Mt/year EAF should be commissioned (Metal Expert, 2024d). Pesquería's new slab steel mill will be equipped with carbon capture capability, with the potential to utilize green H_2 when market conditions permit, allowing the company to further advance its decarbonization roadmap.

Other important project under development is being carried out by Deacero. The company is investing US$ 1 billion in 1.5 Mt/year semi-integrated mill focused on long steel products (De Paula, 2024). The new plant will reinforce the significance of EAF in Mexican steel industry and highlight the dependence on ferrous scrap imports. In 2023, the country registered a 1.8 Mt scrap deficit.

Regarding solar energy, Pima Solar PV Park is located in Sonora, Mexico, with 110 MW capacity. The project was developed by Infraestructura Energetica Nova (IEnova). Its construction commenced in 2018 and subsequently entered into commercial operation in 2019. At a cost of US$ 115 million, it generates 293 GWh electricity and supplies enough clean energy to supply 147 thousand households, offsetting 195kt CO_2/yr. The project consists of 443k PV modules, spread over an area of 362 hectares. The power generated from the project is sold to Deacero, under a power purchase agreement for a period of 20 years (De Paula, 2023b).

3.6. Japan

In 2023, Japan produced 87 Mt of crude steel, accounting for 4.6% of the world's total. The Japanese steel industry is quite mature, and although reliant on imports of iron ore and metallurgical coal, the BF-BOF route's participation remains relatively high, accounting for 76% compared to 71% globally. Even though the country is a large net exporter of metallic scrap, EAF's participation has not improved substantially, moving from 23% in 2015 to 25% in 2019 and 26% in 2023. The steel industry is responsible for 14% of country's CO_2 emissions (Government of Japan, 2024).

According to OECD (2022b), the explicit carbon prices in Japan consist of ETS permit prices and carbon taxes, covering 73.3% of GHG emissions in CO2e in 2021. Additionally, in February 2023, the Japanese government announced the introduction of an ETS as a part of a carbon pricing mechanism integral to the "Basic Policy for the Realization of Green Transformation (GX)." In June 2003, the Tokyo Stock Exchange (TSE) announced plans to establish a Carbon Credit Market around October 2023. Trial trading for GX-ETS was scheduled to begin in Fiscal Year (FY) 2023 and become full-scale operation in FY 2026, which raised expectations for a carbon credit market being created in FY 2023.

A key characteristic of the Japanese steel industry is its high concentration, led by Nippon Steel and JFE, both of which are minority shareholders in several mini-mills. In 2012, Nippon Steel merged with Sumitomo Metal Corporation, the country's third largest steelmaker at the time. Additionally, Nippon Steel has a cross-ownership with Kobe Steel, a peculiar ownership arrangement that has allowed for more collaboration between domestic steelmakers, including technological efforts. Another important distinguishing aspect of the Japanese steel industry is its relatively early focus on decarbonization, as explained ahead.

The development of technology that allows the use of H_2 as a reductant has garnered significant attention in the industry. Since 2008, this innovation has been pursued under the Federal Government Project called "CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50" (or simply COURSE50), led by Nippon Steel. The goal is to develop this technology around 2030 and commercialize it by 2050, enabling a 30% reduction in CO_2 emissions from BF-BOF mills. The COURSE50 project includes participation of Nippon Steel, JFE Steel, Sumitomo Metals (which merged with Nippon Steel), Kobe Steel, and Nisshin, the largest steelmakers in Japan. The project is fully funded by the Japanese government. The first phase (2008-2012) had a budget of US$ 126 million, while the second (2013-2017) had a budget of US$ 189 million. These subsidies were aimed at a technological breakthrough for domestic steelmakers.

Supported by the government and the biggest steelmakers, the Japanese strategy toward steel decarbonization is wholly based on the COURSE50 project, which aims to create radical innovation. Conversely, companies in Europe, the US, Canada, and Mexico prefer to start with temporary or transitional solutions such as NG-based DRI, only moving to adopt H_2 in DR modules as a second step. Transition Asia (2023, p. 2-3, emphasis in original) made harsh criticisms of the Japanese approach to decarbonizing the steel industry:

> In the pursuit of emissions reductions, steel companies have endorsed the development of retrofitted technologies for BFs. In Japan, the most well-known and prominent solutions for achieving such reductions is via a technology called COURSE50.
>
> COURSE50 is a technology under development by the three largest Japanese steelmakers (Nippon Steel, JFE and Kobe Steel). The core of the technology is injecting hydrogen back to BFs, which is retrieved from by-product gas emitted from the BFs. Injected hydrogen works as a reducing agent for iron ore and partially replaces the primary reducing agent, i.e. coking coal. This will bring a 10% emission reduction in comparison to full coke-based iron making. Additionally, COURSE50 will employ carbon capture and storage (CCS) technology and the aggregated emissions reduction effectiveness is a maximum of 30% in total. COURSE50 is planned to be

developed into SuperCOURSE50, ready for commercial operation around 2050. Companies are hoping that this technology will result in emissions reductions of up to 50% compared with conventional BF-BOF steel, which still leaves a large gap from meeting the afore mentioned definitions for green steel.

COURSE50 remains an unproven at scale and high cost technology that has been under development since 2008 and is still not expected to be in commercial operation until 2030 – an expected development timeline of more than 20 years. Its carbon reduction effectiveness is only a theoretical 30%. Moreover, 20% of that 30% is reliant on CCS, known for being technologically and economically challenging due to low BF CO_2 concentrations, amine volatility and the additional energy requirements for the equipment.

Transition Asia (2024) argued that the Japanese steel industry's decarbonization strategy should focus on a higher diffusion of EAF technology and bigger imports of HBI. The Japanese government recently established the "Energy and Manufacturing Process Transformation Support Business (Business I (Steel))" program, based on the Green Transformation (GX) Promotion Act, with applications accepted starting October 8, 2024. Nippon Steel announced that it has applied for this type of subsidy but has not disclosed the exactly amount requested. However, the government will allocate a maximum of about US$ 3.3 billion to the entire funding scheme under the program (GMK Center, 2024b).

One subsidy has already been approved by the Japanese government to substitute BF for EAF. According to JFE's statement, the maximum amount of government support will be US$ 665 million, while the overall investment to implement the project is estimated at US$ 2.1 billion. The project involves the construction of a 2 Mt/year EAF at the Kurashiki mill for high-quality steel to be used in the automotive sector, which is expected to be commissioned in 2028 (Metal Expert, 2024e). Two factors must be highlighted: the approval process was quite fast, taking less than three months; and although the project represents a very conventional way to decarbonize steel operations, the Japanese government is subsidizing around 32% of it.

3.7. China

The Chinese steel industry is heavily based on the BF-BOF route. In 2023, 90% the country's production utilized this route compared to 49% in other countries (WSA, 2024). As a result, the steel industry contributes with 15% to 18% of China's total CO_2

emissions (XUE, 2021; SANDERSON; HUME; HALE, 2021) and 7% to 9% of global CO_2 emissions (WSA, 2021).

The 14th Five-Year Plan (FYP), covering the period 2021-2025, focuses on sustainable development and technological leadership. Breaking up with previous practice, the Ministry of Industry and Information Technology (MIIT) has not published an exclusive plan for the steel industry as a result of the 14th FP, which is now dealt with under the 14th Raw Materials FYP, covering several sectors. However, the 14th FYP on developing scrap steel industry was unveiled (EUROPEAN COMMISSION, 2024). Thus, in the context of the 14th FYP, the Chinese government determined that the proportion of steel produced in semi-integrated mills (whose main input is ferrous scrap) should expand from 10% in 2020 to at least 15% by 2025 (ZHANG; CHOW, 2022), contributing to the reduction of CO_2 specific emissions. In the same direction, the MIIT declared in August 2022 that this share is expected to exceed 20% by 2030 (ZONG, 2022).

Data provided by the OECD (2022a) show that the number of restrictions on ferrous scrap exports worldwide jumped from 373 in 2009 to 579 in 2021, implying a Compound Annual Growth Rate (CAGR) of 3.7%. The imposition of as many as 580 restrictions in just one year highlights the growing importance of this public policy instrument. The number of nations that adopted measures to restrict exports of ferrous scrap amplified from 35 in 2009 to 42 in 2021, leading to an average increase in restrictions per country from 10.7 to 13.8 over the period. It is noteworthy that restrictions on ferrous scrap exports did not follow the respective price cycle.

In 2021, 42 countries were adopting some measure restricting ferrous scrap exports (OCDE, 2022a) and they collectively produced 1.34 Bt of crude steel, accounting for 68.5% of the global output. This may be the most significant indicator of the relative importance of restrictive measures. The OECD (2022a) shows that all China's measures included the imposition of 40% export taxes on scrap export from 2009 to 2021. According the Mysteel (2024):

> China's Ministry of Industry and Information Technology (MIIT) has been actively pressing scrap recycling and processing enterprises to become qualified under its certification system.
>
> The companies qualified by MIIT are required to have the scrap processing capacity above 150,000 t/y, and the facilities they use must have high processing efficiency and low energy consumption, according to the ministry's criteria.

Once recognized by MIIT, the companies can enjoy a number of preferential policy benefits that will help them ease their operation costs, as reported.

As of this month, a total of 825 ferrous scrap processing companies nationwide had obtained MIIT's qualification certification.

The Chinese steel industry is marked by a large proportion of State-owned enterprises (SOEs) and structural granting of subsidies not restricted to investments aiming to improve environmental performance. In 2021, the combined rated capacity of SOEs in the country's steel industry was 400 Mt, accounting for almost 40% of the industry's share (OECD, 2022c). According to WSA (2024a), concerning the ownership structure of the world's 50 largest steel companies, as many as 14 were SOEs in 2023 and, of this total, 13 were Chinese. These Chinese SOEs produced 398 Mt of crude steel in 2023, accounting for 21.1% of the world output.

It should be noted that subsidies are a permanent instrument, resulting in an uneven playing field and revealing competitive asymmetries. Several countervailing duty (CVD) investigations by the European Commission (EUROPEAN COMMISSION, 2024, p. 403-404) have found that Chinese steelmakers benefit from numerous types of subsidies, such as:

- **preferential policy loans, credit lines, preferential interest rates, other financing, and guarantees;**
- **grants;**
- **direct tax exemption and reduction programmes;**
- **indirect tax and import tariff programmes;**
- **Government provision of goods and services for less than adequate remuneration ('LTAR'), including inputs, land use rights, water and electricity;**
- **equity programs, including debt for equity swaps, equity infusions and unpaid dividends.**

CREA (2024) revealed that the Chinese steel companies received approvals for many new projects aimed at manufacturing primary iron and crude steel via the BF-BOF route during the period 2017-2023. At that time, 99% of the authorized primary iron capacity was for BF and 70% of the steel mill capacity was for BOF. However, no new permits were issued for coal-based steel projects in the first half of 2024, according to data compiled with Chinese provincial governments. This is the first time that, on a half-year basis, no new permits have been issued since China announced dual carbon targets in September 2020. This could represent a turning point for the Chinese steel industry in terms of halting new investments in BOF steelmaking capacity.

According to Midrex (2023), China produced 600 kt of DRI-HBI in 2007 but stopped manufacturing this material in 2010. In 2023, a direct reduction module was implemented in China at Tianjin Iron & Steel, with an annual capacity of 300 kt. Additionally, three modules were under construction: Baosteel Zhanjiang Iron & Steel (annual capacity of 1 Mt), Hegang (Hebei Iron & Steel or HBIS, 600 kt), and Shanxi Taihang Mining (300 kt). These three DR modules can consume H_2 to some extent, but their combined annual capacity reaches 1.9 Mt, a significantly small value considering the scale of the Chinese steel industry.

Shanghai Metals Market (SMM, 2023) mentions several official documents, from 2021 to 2023, that highlight the governmental intention to advance the use of hydrogen in the Chinese steel industry. These documents include: the Implementation Measures for Capacity Replacement in the Steel Industry, the Action Plan for Carbon Dioxide Peaking Before 2030, the 14th Five-Year Plan on Industrial Green Development, the Guiding Opinions on Promoting High-Quality Development of the Steel Industry, the Medium and Long-Term Plan for the Development of Hydrogen Energy Industry, the Implementation Plan for Carbon Dioxide Peaking in Industrial Sector, the Guiding Catalogue for Industrial Structural Adjustment (2023 Draft), the Work Plan for Stable Growth in the Steel Industry, and the Notice on Organizing the Recommendation of Low-Carbon Metallurgical Technology Research Projects. Nonetheless, it appears that the impacts of such measures are yet to be observed in the medium and long terms.

3.8. India

India produced 141 Mt of crude steel in 2023, accounting for 7.5% of the global output. The country's steel industry has a unique production structure, with a high share of DRI-HBI (37.2% of the world output). Furthermore, in India, 81% of the DRI-HBI utilized coal as reductant and consequent only 19% is NG-based (MIDREX, 2024). Just for comparison, the proportion of NG is 70% globally (including India).

Public policies toward decarbonizing the steel industry in India are quite different from those implemented in China. Nonetheless, the two countries share one similarity: the imposition of export tariffs on metallic scrap. India imposed a 15% export tax from 2009 to 2021. Furthermore, it frequently resorted to adopting "other measures," such as charging railway congestion fees of 20% to 25% on traffic to Bangladesh and Pakistan (OECD, 2022a). From May to November 2022, the Indian government temporarily adopted a 15% export tariff on pig iron due to input price jumps caused by the Russia-Ukraine conflict. It is worth noting that in the Indian steel industry, SOEs' capacity reached 20 Mt in 2021, accounting for 14% of the national installed capacity (OECD, 2022c). Therefore, the relative importance of SOEs in the Indian industry is quite smaller than that in China's.

The most striking feature of the Indian steel industry, compared to other countries examined in this section, is that it is experiencing a high growth trajectory. Indeed, the National Steel Policy 2017, announced in May 2017, includes plans to increase the country's crude steel capacity to 300 Mt, with a production of 255 Mt by 2030-31. The finished steel per capita consumption is estimated to increase from 61kg/inhabitant to 158kg/inhabitant by 2030-31 (GOVERNMENT OF INDIA, 2017). The goals are more quantitative than qualitative-oriented, aiming to expand the steel production without much focus on decarbonization.

BigMint (2024) observes that the steel industry, contributing around 2% of India's GDP, recorded a 14-15% year-on-year increase in demand in 2024. Such growth stems largely from the government's extensive infrastructure projects aimed at boosting the transportation, housing, and energy sectors. Historically, steel demand in India followed economic cycles closely, but in recent years, it has grown independently of GDP due to increased public investment in infrastructure and manufacturing.

As the world's second-largest steel producer, India reached the milestone of 144 Mt of crude steel production in 2024, reflecting a 28% growth since 2019. BigMint (2024) estimates that India will reach 210 Mt of crude steel production by 2030, marking a substantial 47% increase over current levels. To meet the projected demand, India's steel capacity is expected to achieve 240-250 Mt by 2030, nearing the government's ambitious target of 300 Mt.

India's production route mix is also evolving. Currently, the BF-BOF technological route contribute approximately 46%. By 2030, this ratio is projected to reach 56%, reflecting new investments in large-scale, efficient production facilities. This expansion will add approximately 80 Mt of steel production capacity by 2030, of which 56% will be from the BF-BOF route (BIGMINT, 2024). Therefore, by taking advantage of large mills to appropriate economies of scale and the restricted availability of obsolescence scrap reservoir, India will increase its dependence on BF-BOF, while the previously examined countries are going into the opposite direction.

McKinsey (2024a, p. 16-17) emphasized that:

> To meet growing domestic demand, India's major steel players have announced greenfield and brownfield expansion plans to add steel capacity of around 60 million to 80 million metric tons in the next decade, mostly through the currently prevalent coal-based integrated BF-BOF route. The country's steel sector accounts for about 12 percent of total greenhouse gas emissions, with an average emission intensity of 2.55 tons of CO_2 per ton of crude steel, compared with a global average of 1.9 tons of CO_2 per ton of crude steel. Since integrated BF-BOF assets tend to have a life of 30 to 50 years, emissions from the steel industry could remain high for years to come.
> (...)
> The government of India is initiating decarbonization efforts for the steel industry. The Ministry of Steel has set up 14 task forces to identify different levers of decarbonization and prepared a road map. Addressing environmental concerns while ensuring India's self-reliance on steel has a direct impact on the capital expenditure needs and technological choices of India's steel manufacturers. To achieve its decarbonization targets, the industry will need to invest around $250 billion to $300 billion by 2050.

After reviewing selected international experiences, the next section pays attention to the Brazilian public policies.

4. Public policies in Brazil

In terms of decarbonization, the current situation of the Brazilian steel industry can be considered advantageous in relation to that of China and India, due to several factors: i) the high quality of management and inputs used, resulting in lower specific CO_2 emissions by BF-BOF mills compared to their international counterparts; ii) a higher reliance on renewable energy, which significantly impacts scope 2 emissions and is an important factor for semi-integrated mills; iii) the peculiarity of the charcoal-based steel industry, which has lower specific emissions compared to the BF-BOF and DRI-EAF routes. However, the limited diffusion of mini-mills, due to the minor reservoir of obsolescence scrap, is a strong negative factor compared to developed nations. Large net ferrous scrap exporters, such as the US, EU-27, Japan, and Canada, have an easier path to decarbonization that is unavailable to most emerging countries, emphasizing the importance of the semi-integrated mills and increasing the proportion of scrap in the metallic charge in all technological routes. Mexico is an exception: despite its small scrap reservoir, it is fairly integrated to the US scrap market.

It is also worth highlighting that the iron and steel industry in Brazil accounts for approximately 4% of GHG emissions (YUAN, 2023), compared to the 7%-9% global average. These numbers show that the Brazilian steel industry is in a very comfortable position compared to China (where steel accounts for 15% to 18% of the country's total CO_2 emissions), Japan (14%), and India (12%). However, in Brazil, Agriculture and Land Use, Land Use Change, and Forestry (LULUCF) sectors generate the largest share of GHG emissions (65%) (YUAN, 2024). These activities have very strong political representation in Congress and will likely face less pressure to contribute to the country's decarbonization efforts. In this context, manufacturing industries (steel and cement, in particular) are easier targets for public policy measures.

Overall, the governmental initiatives to decarbonize the Brazilian steel industry are modest compared to those seen in the countries examined in the previous section. There are no major subsidies aimed at increasing the diffusion of DR technology, as observed in the EU-27, the US, and Canada. There is no government-funded technological program focused on the development of radical technologies, as verified in Japan. There are no subsidies for various purposes, as in China. The Brazilian steel market is also not growing rapidly, as it is in India, which could foster greenfield projects. Thus, the Brazilian situation is more comparable to that of Mexico, with the disadvantage that the regulated carbon market is relatively delayed in Brazil and the attractiveness of DRI is lower due to higher natural gas costs compared to Mexico.

From an institutional perspective, in December 2024, Law #15,042 was passed to create the Brazilian Greenhouse Gas Emissions Trading System (SBCE). Although this regulation takes immediate effect, the SBCE itself will be implemented gradually. Once the law is published, a deadline begins for implementing regulations that are crucial for the system to function properly. According to Mattos Filho (2024, p. 6):

> **Operators will be subject to SBCE regulation if responsible for facilities and sources that emit:**
>
> - **Above 10,000 tCO_2e per year: i. obligation to submit a monitoring plan to the SBCE management body; and ii. obligation to submit a GHG emissions and removals report in line with the approved monitoring plan.**
> - **Above 25,000 tCO_2e per year: items (i) and (ii) above, as well as a report demonstrating periodic reconciliation of the operator's compliance with obligations concerning environmental commitments within the scope of the SBCE, via the ownership of assets that are part of the SBCE in an amount equal to its net emissions.**

The government has two years from the passing of the law to regulate the mandatory carbon market. A federal committee will set emission limits for each economic activity, and companies will have additional time to comply. Businesses emitting gases above the established threshold must purchase carbon credits from sustainable projects, such as reforestation initiatives. Additionally, the law allows the private sector to participate and vote in the Carbon Market Regulatory Affairs Chamber and ensures the SBCE aligns with sector-specific carbon pricing mechanisms, such as those for biodiesel and ethanol production (Valor International, 2024). According to the Ministry of Finance, the regulated carbon market is expected to be fully functioning in 2030. Brazil’s regulated carbon market aligns with those of several other countries, but the timing of such measure is comparatively late.

Law #14,948, passed on September 2024, establishes the legal framework for low-carbon H_2. The law includes: i) the Low-Carbon H_2 Development Program (PHBC), a funding source for energy transition projects; ii) the Special Incentive Regime for the Production of Low-Carbon H_2 (Rehidro), which waivers taxpayers from paying PIS/Pasep (a type of social tax) for five years; and iii) the Brazilian Hydrogen Certification System (SBCH2), which will voluntarily certify H_2 produced in Brazil. The PHBC will grant tax credits for the commercialization of low-carbon H_2 and derivatives produced in the country. The total tax credits to be granted between 2028 and 2032 will amount to R$ 18.3 billion (approximately US$ 3 billion at the current exchange rate), with annual credit limits of R$ 1.7 billion in 2028, R$ 2.9 billion in 2029, R$ 4.2 billion in 2030, R$

4.5 billion in 2031, and R$ 5.0 billion in 2032. These subsidies are aimed to promote the use of low-carbon H_2 in industrial sectors that are difficult to decarbonize, such as fertilizers, steel, and petrochemicals, as well as in heavy-duty transportation (Uso do hidrogênio..., 2024).

Known as “Fuel of the Future Law,” the Law #14,993, passed in October 2024, creates national programs for green diesel, sustainable aviation fuel, and biomethane, in addition to increasing the blending of ethanol and biodiesel into gasoline and diesel, respectively. It also establishes the regulatory framework for CCS, which might play a supplementary role in the decarbonization of the steel industry. It is important to highlight that these three laws were passed within just four months, indicating that decarbonization has gained significant momentum in the Brazilian Congress.

Regarding funding, it is worth noting that the National Bank for Economic and Social Development (BNDES), a federal government development bank, launched the "BNDES Green Hydrogen Program," encouraging pilot projects for the production of green H_2 using renewable energy. BNDES intends to subsequently expand its support, including financing large plants serving both the domestic market and exports of low-carbon H_2. Their financial lines include the "Climate Fund," the "BNDES Finem Environment," and the "Finem Innovation" (ROLLENBERG, 2024).

BNDES also launched “BNDES Charcoal” as part of the “Climate Fund” to finance sustainable projects aimed at producing charcoal. The first operation was approved in August 2023, granting R$ 54.5 million to Vallourec Tubos do Brasil, with the total investment reaching R$ 90 million. According to BNDES (2023):

> The approved financing provides for the installation of three continuous vertical reactors for the production of charcoal on one of the Vallourec Group's properties in Minas Gerais.
>
> The technology was developed and patented by the company itself, in search of a more efficient way to produce charcoal with better quality and benefits to the environment, in addition to greater economic competitiveness. Each reactor replaces seven conventional masonry kilns.
>
> This reactor, known as Carboval, has zero methane emissions, compatible with sustainability requirements and in line with the Vallourec Group's greenhouse gas reduction strategies. It also enables better energy use from the forest and greater charcoal production with a smaller amount of wood.

The technology also allows for the cogeneration of electricity and additional production of other marketable inputs, such as bio-oil (tar) and pyroligneous extract, in addition to the charcoal itself.

Carboval is one of the best technologies for producing charcoal in the phase prior to pig iron production. The process reduces the raw material transformation cycle from 16 days to 16 hours, without the release of methane and using about 95% of the energy contained in the wood. According to Dezanet (2023), the specific emission of CO_2e for pig iron is only 0,20, which is an outstanding performance. Nonetheless, the amount financed by BNDES is relatively modest and low risk because the technology is already proven.

Rollengerg (2023) highlights additional Brazilian governmental initiatives addressing the decarbonization of the steel industry: i) the "National Strategy for the Decarbonization of Industry" (ENDI), which focuses on preparing the Mitigation Plan and Decarbonization Targets for Brazilian Industry; ii) the "Industrial Decarbonization Hub," a jointly initiative between Brazil's Ministry of Development, Industry, Trade and Services (MDIC) and the UK Department of Energy Security and Decarbonization, to facilitate the engagement of economic agents in the process; iii) the "Strategic Research, Development and Innovation Call # 23/2024: Hydrogen in the Context of the Electric Sector," a joint initiative between MDIC and the Brazilian Electricity Regulatory Agency (Aneel); iv) the Working Group for "Gas for Employment," established by the National Energy Policy Council (CNPE) in March 2023 to increase the federal government's supply of natural gas in the domestic market; and v) the Brazilian federal government establishing tariff-quotas for 11 steel products, a measure in force for one year period. Among these initiatives, the latter two should be observed closely.

As mentioned throughout this paper, NG is a crucial input for steel decarbonization, primarily as a temporary solution until H_2 becomes available in sufficient quantity and at a lower cost. Some European countries, the US, and Canada are subsidizing the conversion of BF-BOF to DRI-EAF. However, the Brazilian current situation is unsatisfactory, because: a) the NG's price is prohibitive: Brazil (US$ 16.8/MMBTU), Mexico and US (US$ 6.5/MMBTU), Argentina (US$ 3.9/MMBTU) – YUAN (2023); b) the existing infrastructure for transporting and distributing NG is insufficient to meet future demand for the input (YUAN, 2024). Aço Brasil estimates that current demand for steel companies is around 5 million cubic meters/day, while the potential demand as of 2030 is estimated at 19 million cubic meters/day. Consequently, a key priority of governmental measures for decarbonizing the Brazilian steel industry is to address the NG issue, not only to improve consumption in existing mills but also to foster new DR modules. In the medium term, H_2 seems to be a better solution, but the risks are considerable high at present.

In April 2024, the Brazilian government introduced a tariff-quota, allowing a limited quantity of specific products to be imported at standard tariff rates. Eleven steel products were initially included in this temporary tariff quota regime: eight flat steel products (heavy plate in coils, HRC, CRC, HDG, and aluminium zinc sheets), one long steel product (wire rod), and two types of tubes (welded line pipes, seamless casing, and other pipes for the oil and gas industry). Of these product categories, nine are produced by companies related to the Brazil Steel Institute and accounted for 43.1% of the country's imports of steel products in 2023. MDIC is monitoring market conditions to evaluate whether the measure is efficient to keep the market balanced. Under this new regime, a quota equivalent to 130% of the average import volume from 2020 to 2022 was established. This measure was also late compared to similar measures adopted in the US, the EU-27, and Mexico. Additionally, the level of protection for the domestic industry was low, as the additional tariff includes an extra 30% volume on top of an already higher import volume.

At first glance, it may look unusual to relate trade defense measures and decarbonization efforts. However, they are connected in a much simpler way than it may appear. To carry out the significant investments required for decarbonization, steel mills need to ensure sufficient cash generation, which is currently challenging due to structural excess installed capacity and low profit margins. The full implementation of CBAM will further clarify the association between trade defense measures and decarbonization. The issue is that while China has granted massive subsidies to its steel industry (CARVALHO, 2024), the US, Canada, and the EU-27 have implemented substantial antidumping, CVD, and safeguard measures to protect their steel industries. Consequently, there is a significant trade diversion regarding Chinese steel exports, and Brazil is one of the countries most negatively impacted.

Compared to Mexico, Brazil has adopted relatively modest trade defense measures. In August 2023, the Mexican government increased import tariffs by 25% on 205 tariff items, based on the behavior of steel and aluminum imports from countries without trade agreements. This measure is set to remain in effect until July 2025. However, despite its broad scope, it was a delayed reaction to the application of Section 232 by the US government during the first Donald Trump administration in 2018.

In April 2024, the Mexican government increased steel import tariffs again. The measure is temporary and applies to 544 tariff items, including steel, aluminum, textiles, clothing, footwear, wood, plastic, chemical products, paper, and cardboard. For cold and hot rolled coils, it has been set at 25%, while for profiles, coated material, reinforcing bars, wire rod and tubes. it has been established between 25% and 35%, depending on the case. The purpose is to stabilize the Mexican industry and eliminate trade distortions. The decree is valid until April 2026.

In December 2024, the Brazilian government launched “Mission 5” of the “New Brazil Industry,” allocating roughly US$ 79 billion from public and private resources for bioeconomy and decarbonization. Of this amount, US$ 15 billion is sourced from public funds for credit lines for projects involving activities such as innovation, exportation, and productivity. Private investments will reach US$ 64 billion by 2029. Therefore, the relevance of public funds within this mission is relatively low (19%). Six production chains have been defined as priority for industrial development under Mission 5: green diesel and sustainable aviation fuel (SAF); low-carbon hydrogen; biomethane; green steel and cement; wind turbines; and solar panels. The amount of funds available for each priority chain has not been disclosed.

So far, the Brazilian government’s measures to foster the steel industry’s decarbonization can be considered modest (in terms of financial funds and trade defense measures) and delayed (legal and institutional issues, and trade defense measures too), compared to other countries. It seems difficult to replicate the strategy implement by Europe, but CBAM or some kind of trade defense measures should be in place. In the coming years, if more funds become available and existing institutional measures deliver results, the level of industry’s trade defense measures should be reduced accordingly.

5. Conclusion

The pursuit of decarbonizing the steel industry is a complex, multifaceted challenge. It requires transformative shifts in technology, policy, and corporate responsibility across global and national contexts. This paper highlights the high stakes involved, given the steel industry's substantial contribution (approximately 7%-9%) to global CO_2 emissions. Concerted efforts are necessary to align the industry's production processes with climate goals, particularly in light of international obligations and national interests.

The various technological routes available for steel production, particularly BF-BOF and semi-integrated mills, highlight potential pathways toward to reduce carbon emissions. Integrated mills utilizing BF are still common due to historical and infrastructural factors. However, transitioning to more sustainable technologies such as EAF, DRI, and H_2-based processes presents opportunities to significantly mitigate carbon output. Ongoing innovations in electricity procurement, especially from renewable sources, will be crucial in reducing specific emissions in EAF operations, thereby aligning the steel industry with sustainability targets.

The experiences of leading steel-producing nations provide evidence of the diverse challenges and strategies involved in decarbonizing the industry across various countries and regions. Developed economies often have greater resource availability and established frameworks that facilitate technological shifts, enabling them to move toward reducing GHG emissions more smoothly. In general terms, in the examined selected international experiences, public policies that impact the decarbonization of the steel industry have contemplated:

- **regulated carbon market: EU-27, in particular, but a trend of increasing importance in Canada, Mexico and Japan, at least;**
- **CBAM: EU-27, tending to be reproduced in other countries;**
- **restrictions on scrap exports: export tariffs have been applied in China and India for several years, while the EU-27 is going to implement the WRS;**
- **specific subsidies for decarbonization: EU-27, US, Canada and Japan, with an emphasis on replacing the BF-BOF route with DRI-EAF, based on NG in the short term and on H_2 in the long term;**
- **subsidies that are not restricted to decarbonization and with great relevance of SOEs in the industry: China.**
- **Mexico and India are those nations in which policies aimed at decarbonization are weaker, and in the case of the latter, in a peculiar way, an increase in the relative importance of the BF-BOF route is expected.**

Brazil's steel industry has unique characteristics, such as its reliance on charcoal-integrated production methods, which contribute to lower emissions compared to traditional BF-BOF and DRI-EAF routes. Nevertheless, there are significant barriers to expanding the charcoal-based technological route. More importantly, the limited availability of obsolete steel scrap reservoir and, consequently, the small diffusion of EAF are obstacles to broader decarbonization efforts. Public policies aimed at fostering innovation, including recent laws promoting low-carbon H_2 production and emissions trading, will play a critical role in shaping Brazil's energy transition and overall industrial competitiveness.

Despite the advancements, significant hurdles remain. High levels of embedded carbon in existing production processes and the long lifespan of steel production infrastructure complicate immediate transitions. Stakeholders must also confront economic pressures and competitive dynamics in a global market where cost disparities can impact business viability and investment capacity. Accordingly, aligning financial incentives and regulatory support will be vital in facilitating a smoother transition to cleaner technologies.

Decarbonizing the steel industry presents grater challenges in Brazil compared to the EU-27, the US, Canada, and Mexico due to their lower specific emissions of CO_2, more intensive use of the mini-mill route and wider application of trade defense measures. The Japanese strategy is difficult to replicate and may be too risky to be rewarded; however, the government has recently begun subsidizing the conversion of BF-BOF to EAF methods. It can be argued that the Brazil’s current situation is much better than that of China and India. Nonetheless, Brazil lacks the benefits of high economies of scale and massive, recurrent subsidies as seen in China, as well as the gains from a high-speed market as seen in India. In light of this context, it can be concluded that the institutional and financial resources available for fostering and pressuring the Brazilian steel industry to decarbonize have been quite limited and clearly insufficient to achieve a desirable outcome.

References

Aço Brasil. *Anuário estatístico 2024*. Rio de Janeiro: Instituto Aço Brasil, 2024a. Available at: https://www.acobrasil.org.br/site/wp-content/uploads/2024/07/Anuario_Completo_2024.pdf. Accessed: March 22, 2025.

Aço Brasil. *Mercado brasileiro do aço: análise setorial e regional.* Rio de Janeiro: Instituto Aço Brasil, 2024b. Available at: https://www.acobrasil.org.br/site/wp-content/uploads/2024/08/MBA_Edicao-2024.pdf. Accessed: March 10, 2025.

Alves, F. Boston Metal: Engenheiro troca a aposentadoria pelo cargo de CEO na empresa que revolucionou a metalúrgica do aço. *Brasil Mineral,* v. 61, n. 439, p. 40-47, 2024.

Astier, J. Competitividade da indústria siderúrgica dos países em desenvolvimento. *Metalurgia ABM*, v. 47, n. 393, p. 26-32, 1991.

Banco Nacional do Desenvolvimento Econômico e Social (BNDES). *BNDES aprova primeira operação de carvão vegetal do Fundo Clima.* Brasília: BNDES, August 10, 2023. Available at: https://www.bndes.gov.br/wps/portal/site/home/imprensa/noticias/conteudo/bndes-aprova-primeira-operacao-de-carvao-vegetal-do-fundo-clima. Accessed: March 10, 2025.

Uso do hidrogênio de baixa emissão de carbono agora é lei. *Agenda Senado,* Sept. 30, 2024. Available at: https://www12.senado.leg.br/noticias/materias/2024/09/30/uso-do-hidrogenio-de-baixa-emissao-de-carbono-agora-e-lei. Accessed: March 10, 2025.

BigMint. *Shaping the future of steel: India's expansion and growth strategy.* Raipur: BigMint, 2024. Available at: https://www.bigmint.co/events/all-india-steel-conclave-2.0/blog/shaping-the-future-of-steel-indian-expansion-and-growth-strategy. Accessed: March 22, 2025.

BigMint. *How will Indian mills make the transition to low-emissions steel*? Raipur: BiMint, 2023. Available at: https://www.bigmint.co/insights/detail/how-will-indian-mills-make-the-transition-to-low-emissions-steel-471777. Accessed: March 22, 2025

Blees, J. The European green deal & its implications for the EU recycling industry. ISRI *Convention.* Nashville: Institute of Scrap Recycling Industries (ISRI), 2023.

Fernandes, P. D.; Mesquita, P. P. D.; Braga, J. P. C. H.; Souza, R. M. L. *Descarbonização da indústria de base*. Rio de Janeiro: BNDES, 2024. Available at: https://web.bndes.gov.br/bib/jspui/bitstream/1408/25847/1/PRLiv_216288_Descarboniza%c3%a7%c3%a3o%20da%20ind%c3%bastria%20de%20base.pdf. Accessed: March 10, 2025.

Camara Nacional de la Industria del Hierro y del Acero (Canacero). *Radiografía de la industria del acero 2024*. Ciudad de México: Canacero, 2024. Available at: https://www.canacero.org.mx/aceroenmexico/descargas/Radiografia_2024_vpub.pdf. Accessed: March 10, 2025.

Carvalho, A. Global steel excess capacity: Some key messages. *In:* Congresso Aço Brasil 2024. São Paulo, Instituto Aço Brasil, Aug. 5-7, 2024. Available at: https://congressoaco-brasil.org.br/wp-content/uploads/2024/08/Painel-2-Brazil-conference-key-messages.pdf. Accessed: March 10, 2025.

Carvalho, P. S. L.; Mesquita, P. P. D.; Araújo, E. D.G. Sustentabilidade da siderurgia brasileira: eficiência energética, emissões e competitividade. *BNDES Setorial,* n. 41, p. 181-236, 2015. Available at: https://web.bndes.gov.br/bib/jspui/bitstream/1408/4287/2/BS%2041%20Sustentabilidade%20da%20siderurgia%20brasileira_.pdf. Accessed: March 10, 2025.

Centre for Research om Energy and Clean Air (CREA). *Turning point: China permitted no new coal-based steel projects in H1 2024 as policies drive decarbonisation*. Helsinki: CREA, 2024. Available at: https://energyandcleanair.org/publication/turning-point-china-permitted-no-new-coal-based-steel-projects-in-h1-2024-as-policies-drive-decarbonisation/.

Cleveland Business Journal. *Cleveland-Cliffs becoming champion of using hydrogen to 'green' steelmaking*. Cleveland: Cleveland Business, 2023. Available at: Cleveland-Cliffs champions hydrogen to 'green' steelmaking - Cleveland Business Journal. Accessed: March 12, 2025.

CRU. *Steel decarbonization: how will green steel be priced?* London: CRU Group, 2024. https://www.crugroup.com/en/communities/webinars/2024/steel-decarbonisation-how-will-green-steel-be-priced/

De Boer, M.; Frascati, G.; Khawsam-ang, M.; Riaz, H.; Kim, H. R.; Wagne, G. *Decarbonizing steel*. New York: Columbia Business School, Sept. 16, 2024. Available at: https://business.columbia.edu/sites/default/files-efs/imce-uploads/CKI/Documents/CKI%20Steel-241017.pdf. Accessed: March 10, 2025.

De Paula, G.M. Deacero's new mil and shredders. *Steel Times International*, v. 48, n. 2, p. 10-11, 2024.

De Paula, G.M. The growing importance of wind energy. *Steel Times International Digital,* n. 26, p. 25-26, 2023a. Available at: https://issuu.com/quartzbusinessmedia/docs/steel_times_international_digital_june_2023/s/26125527. Accessed: March 10, 2025.

De Paula, G.M. Solar energy and the Latin American steel industry. *Steel Times International*, v. 47, n. 7, p. 17-18, 2023b. Available at: https://issuu.com/quartzbusinessmedia/docs/steel_times_international_october_2024. Accessed: March 10, 2025.

De Paula, G. M. CSN's race for green hydrogen. *Steel Times International Digital,* n. 22, p. 30-31, 2022.

De Paula, G. M. Siderurgia no Brasil 2010-2025: Subsídios para tomada de decisão. *Série Documentos Técnicos,* CGEE, n. 9, November 2010. Available at: https://www.cgee.org.br/documents/10195/734063/Siderurgia_no_Brasil__9567.pdf/893da7ee-8608-4251-adc1-10c2bf95b009?version=1.0. Accessed: March 10, 2025.

De Paula, G. M. Desenvolvimento tecnológico, alianças estratégicas e apoio governamental: o caso Tecnored. In: Encontro Anual da Anpad, 27., Atibaia, SP, 2003.

De Paula, G. M. *Privatização e estrutura de mercado na indústria siderúrgica mundial*. Thesis (Ph.D. in Economics) – Instituto de Economia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 1998.

Dezanet, A. New technological era in charcoal production. In: *ABM Week 2023*. São Paulo, Brazilian Association of Metallurgy, Materials and Mining, 1-3 August, 2023.

Estevez, I.; Kassem, H.; Kwon, Y.; Paul, I. *The political economy of steel decarbonization*: Prospects and challenges of a green steel transition in Dearborn, Michigan. New York: Roosevelt Institute, March 21, 2024. Available at: https://rooseveltinstitute.org/publications/the-political-economy-of-steel-decarbonization/. Accessed: March 10, 2025.

European Steel Association (Eurofer). *European steel in figures 2024*. Brussels: Eurofer, 2024. Available at: https://www.eurofer.eu/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2024. Accessed: March 10, 2025.

The HYBRIT story: unlocking the secret of green steel production. *European Commission*, Directorate-General for Climate Action, June 20, 2023. Available at: https://climate.ec.europa.eu/news-your-voice/news/hybrit-story-unlocking-secret-green-steel-production-2023-06-20_en. Accessed: March 10, 2025.

European Commission. *On significant distortions in the economy of the People's Republic of China for the purposes of trade defence investigations*. Brussels: European Commission (Commission Staff Working Document), 2024. Available at: https://ec.europa.eu/transparency/documents-register/detail?ref=SWD(2024)91&lang=en. Accessed: March 22, 2025.

Gerdau. *Notice to the market: Barro Alto Solar Park.* São Paulo: Gerdau, 2024.

GMK Center. *Swedish SSAB withdraws from negotiations on green project in the US*. Kiev: GMK Center, January 17, 2025. Available at: https://gmk.center/en/news/swedish-ssab-withdraws-from-negotiations-on-green-project-in-the-us/. Accessed: March 22, 2025.

GMK Center. *How Europe supports decarbonization of the steel industry v3.0.* Kiev: GMK Center, December 10, 2024a. Available at: https://gmk.center/en/infographic/european-countries-granted-e14-6-bln-for-decarbonization-of-the-steel-sector/. Accessed: March 22, 2025.

GMK Center. *Nippon Steel has applied for a subsidy to build new EAFs.* Kiev: GMK Center, October 16, 2024b. Available at: https://gmk.center/en/news/nippon-steel-has-applied-for-a-subsidy-to-build-new-eafs/. Accessed: March 22, 2025.

GMK Center. *The United States will allocate $6 billion in grants to decarbonize industry*. GMK Center, March 9, 2023. Available at: https://gmk.center/en/news/the-united-states-will-allocate-6-billion-in-grants-to-decarbonize-industry/. Accessed: March 22, 2025.

Gobierno de la Provincia de Formosa. *La planta "Fermosa Biosiderúrgica" alcanzó un nuevo hito: comenzó el montaje del alto horno.* Formosa: Gobierno de la Provincia de Formosa. Available at: https://www.formosa.gob.ar/noticia/32655/12/la_planta_fermosa_biosiderurgica_alcanzo_un_nuevo_hito_comenzo_el_montaje_del_alto_horno. Accessed: March 22, 2025.

Government of India. *National Steel Policy 2017.* New Dehli: Government of India, Ministry of Steel, 2017.

Government of Canada. *Carbon pricing as an asset for Canadian exports to Europe*. Longueuil: Université de Sherbrooke, 2024. Available at: https://www.international.gc.ca/country_news-pays_nouvelles/2024-06-13-france.aspx?lang=eng. Accessed: March 10, 2025.

Government of Japan. *The road to net zero with green steel*. Tokyo: Government of Japan, March 1, 2024. Available at: https://www.japan.go.jp/kizuna/2024/03/net_zero_with_green_steel.html. Accessed: March 10, 2025.

International Carbon Action Partnership (ICAP). *Emissions trading worldwide:* 2022. ICAP Status Report. Berlin: ICAP, March 2022. Available at: https://icapcarbonaction.com/en/publications/emissions-trading-worldwide-2022-icap-status-report. Accessed: March 10, 2025.

International Energy Agency (IEA). *Net zero roadmap:* A global pathway to keep the 1.5 °C goal in reach. Paris: IEA, 2023. Available at: https://iea.blob.core.windows.net/assets/8ad619b9-17aa-473d-8a2f-4b90846f5c19/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf. Accessed: March 10, 2025.

International Energy Agency (IEA). *Iron and steel technology roadmap:* Towards more sustainable steelmaking. Paris: IEA, 2020. Available at: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf. Accessed: March 10, 2025.

Institute of Energy Economics and Financial Analysis (IEEFA). *Carbon capture for steel? CCUS will not play a major role in steel decarbonisation*. Lakewood, Ohio: IEEFA, 2024. Available at: https://ieefa.org/articles/ccus-will-not-play-major-role-steel-decarbonisation. Accessed: March 10, 2025.

International Emissions Trading Association (IETA). *20–22 Greenhouse gas market report*. Geneva: IETA, 2023. Available at: https://ieta.b-cdn.net/wp-content/uploads/2023/09/IETA_GHGMarketReport_2022.pdf. Accessed: March 10, 2025.

International Renewable Energy Agency (IRENA). *Renewable energy highlights*. Masdar City: IRENA, 2024. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/Renewable_energy_highlights_FINAL_July_2024.pdf. Acessed: March 22, 20225.

JP Morgan (2021). *Green steel deep dive: technically possible, economically challenging. significant supply not a short-term reality.* Sydney: JP Morgan.

Kallanish. Argentina ends 16-year restriction on ferrous scrap exports. London: Kallanish, January 2, 2025.

Kallanish. *India faces race to secure EU-origin scrap supply.* London: Kallanish, December 11, 2024.

KPMG. *Carbon Border Adjustment Mechanism (CBAM):* Time to act for EU importers! Brussels: KPMG, 2023. Available at: https://kpmg.com/be/en/home/insights/2022/06/itx-carbon-border-adjustment-mechanism-cbam-time-to-act-for-eu-importers.html. Accessed: March 10, 2025.

Mattos Filho. *Law No. 15,042/2024 Brazilian Greenhouse Gas Emissions Trading System*. São Paulo: Mattos Filho, 2024. Available at: https://www.mattosfilho.com.br/wp-content/uploads/2024/12/241212-livreto-en-law-150422024-1.pdf. Accessed: March 10, 2025.

McKinsey & Company. *Evolving with steel:* Future growth and opportunities. New Dehli: McKinsey & Company, 2024a. Available at: https://www.mckinsey.com/in/our-insights/evolving-with-steel-future-growth-and-opportunities. Accessed: March 10, 2025.

McKinsey & Company. *Green-steel hubs:* A pathway to decarbonize the steel industry. Dusseldorf: McKinsey & Company, December 19, 2024b. Available at: https://www.mckinsey.com/industries/metals-and-mining/our-insights/green-steel-hubs-a-pathway-to-decarbonize-the-steel-industry. Accessed: March 10, 2025.

McKinsey & Company *The Inflation Reduction Act: Here's what's in it*. New York: McKinsey & Company, October 24, 2022. Available at: https://www.mckinsey.com/industries/public-sector/our-insights/the-inflation-reduction-act-heres-whats-in-it#/.
Accessed: March 10, 2025.

McKinsey Global Institute. *The net-zero transition:* What it would cost, what it could bring. Boston: McKinsey & Company, 2022. Available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the-net-zero-transition-what-it-would-cost-and-what-it-could-bring-final.pdf. Accessed: March 10, 2025.

Metal Expert. *Algoma Steel to indefinitely idle two lines*. Kiev: Metal Expert, January 21, 2025.

Metal Expert. *Daily price assessments for steel products and raw materials*. Kiev: Metal Expert, October 14, 2024a.

Metal Expert. *USA to invest $1.5 billion to decarbonize iron and steel sector*. Kiev: Metal Expert, March 27, 2024b.

Metal Expert. *Cliffs mulls upgrade of Stelco BF.* Kiev: Metal Expert, November 26, 2024cc.

Metal Expert. Ternium to complete expansion of Pesqueria finishing operations this year. Kiev: Metal Expert, November 11, 2024d.

Metal Expert. *In brief: JFE Steel to receive government support for new EAF in Kurashiki.* Kiev: Metal Expert, December 26, 2024e.

Midrex. *2023 World Direct Reduction Statistics.* Charlotte, NC: Midrex, 2024. Available at: https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2023.Final_.pdf. Accessed: March 22, 2025.

Midrex. *2022 Direct Reduction Statistics.* Charlotte, NC: Midrex, 2023. Available at: https://www.midrex.com/wp-content/uploads/MidrexSTATSBook2022.pdf. Accessed: March 22, 2025.

MySteel. F*EATURE: Chinese ferrous scrap suppliers struggling to survive.* Singapore, Myseel, May 30, 2024. Available at: https://www.mysteel.net/market-insights/5055164-feature-chinese-ferrous-scrap-suppliers-struggling-to-survive. Accessed: March 22, 2025.

Organisation for Economic Co-operation and Development (OECD). *Export restrictions on industrial raw materials.* Paris: OCED, 2022a.

Organisation for Economic Co-operation and Development (OECD). *Carbon pricing in Japan.* Paris: OCED, 2022b.

Organisation for Economic Co-operation and Development (OECD). State-owned enterprises in the steel sector: Subsidisation and performance of steel SOEs. *91st session of the Steel Committee virtual meeting.* Paris: OECD, 2022c.

Olexiuk, P.; Sadikman, J. A.; Guindi, S. Navigating Canada's evolving carbon markets. *2024 Olser Legal Outlook,* December 5, 2024. Available at: https://www.osler.com/en/insights/reports/2024-legal-outlook/navigating-canadas-evolving-carbon-markets/. Accessed: March 10, 2025.

Pinho, M. S. *Tecnologia e competitividade na indústria brasileira de aços não-planos comuns*. Dissertação (Mestrado em Economia) - Instituto de Economia, Universidade Estadual de Campinas, Campinas, 1993.

Platts Steel Markets Daily. *Brazil's CSN plans own power supply for Selene green hydrogen plant*. London: Platts, December 23, 2024.

Rollenberg, R. Painel 1: Transição energética e descarbonização: rumo à indústria com baixa emissão de GEE. *In:* Congresso Aço Brasil 2024. São Paulo, Instituto Aço Brasil, Aug. 5-7, 2024. Available at: https://congressoacobrasil.org.br/downloads/. Accessed: March 10, 2025.

Sanderson, H.; Hume, N.; Hale, T. China's environmental goals fire up metals prices. *Financial Times,* June 10, 2021. Available at: https://www.ft.com/content/cd88e1e1-396c-4b61-948a-0018e8c4fdfe. Accessed: March 10, 2025.

SBB Daily Briefing. *Revised EU waste shipment rules expected to start in 2024, impacting scrap exporters.* London: SBN, April 28, 2023a.

SBB Daily Briefing. *US carbon border adjustment 'critical' for decarbonizing steel, industrial sector.* London: SBB, July 20, 2023b.

Sindicato da Indústria de Ferro no Estado de Minas Gerais (Sindifer). *Anuário estatístico.* Ano Base 2023. Belo Horizonte: Sindifer, 2024. Available at: https://sindifer.com.br/sndfr/anuario-estatistico/. Accessed: March 10, 2025.

Shanghai Metals Market (SMM). *Another new project for hydrogen direct reduction iron has been announced.* How profitable such projects are remains to be seen. SMM, Metal News, October 25, 2023. Available at: https://news.metal.com/newscontent/102438427/another-new-project-for-hydrogen-direct-reduction-iron-has-been-announced-how-profitable-such-projects-are-remains-to-be-seen. Accessed: March 10, 2025.

Steel Orbis. *Brazil’s Gerdau acquires two hydroelectric power plants to meet clean energy needs*. Istanbul: Steel Orbis, January 23, 2025. Available at: https://www.steelorbis.com/steel-news/latest-news/brazils-gerdau-acquires-two-hydroelectric-power-plants-to-meet-clean-energy-needs-1375795.htm. Accessed: March 10, 2025.

Steel Orbis. *Judicial sale of Mexican steel company AHMSA begins due to bankruptcy.* Istanbul: Steel Orbis, November 8, 2024. Available at: https://www.steelorbis.com/steel-news/latest-news/judicial-sale-of-mexican-steel-company-ahmsa-begins-due-to-bankruptcy-1365107.htm?searchKey=ahmsa&sc=article. Accessed: March 10, 2025.

Steel Orbis. *Angola’s CSC inaugurates country’s first pig iron mil.* Istanbul: Steel Orbis, September 5, 2023. Available at: https://www.steelorbis.com/steel-news/latest-news/brazils-gerdau-acquires-two-hydroelectric-power-plants-to-meet-clean-energy-needs-1375795.htm. Accessed: March 10, 2025.

The HYBRIT story: unlocking the secret of green steel production. European Commission, Directorate-General for Climate Action, June 20, 2023. Available at: https://climate.ec.europa.eu/news-your-voice/news/hybrit-story-unlocking-secret-green-steel-production-2023-06-20_en. Accessed: March 10, 2025.

Transition Asia. Transition to EAFs and decommissioning of blast furnaces essential for Japanese steel industry to achieve emissions reduction goals. *Transition Asia,* November 15, 2023. Available at: https://transitionasia.org/press-release-transition-to-eafs-and-decommissioning-of-blast-furnaces-essential-for-japanese-steel-industry-to-achieve-emissions-reduction-goals/. Accessed: March 10, 2025.

United States International Trade Commission (USITC). *USITC assess greenhouse gas emissions in the U.S. steel and aluminum industries.* Washington, DC: 2023. Available at: https://www.usitc.gov/press_room/news_release/2023/er0706_64095.htm. Accessed: March 22, 2025.

Vale. Vale starts work on Tecnored's first commercial plant in Madaba (PA), which will contribute to the decarbonization of the steel industry. *Vale,* May 4, 2022. Available at: https://vale.com/w/vale-starts-work-on-tecnoreds-first-commercial-plant-in-maraba-pa-which-will-contribute-to-the-decarbonization-of-the-steel-industry. Accessed: March 10, 2025.

Valor Econômico. Petrobras assina acordo com CSN para estruturar parceria em planta de hidrogênio no Paraná. São Paulo: Valor Econômico, December 19, 2024. Available at: https://valor.globo.com/empresas/noticia/2024/12/19/petrobras-assina-acordo-com-csn-para-estruturar-parceria-em-planta-de-hidrognio-no-paran.ghtml. Accessed: March 22, 2025.

Valor Econômico. Vale pretende construir 'hub' voltado para descarbonização no Porto do Açu. São Paulo: *Valor Econômico,* September 26, 2023a. Available at: https://valor.globo.com/empresas/noticia/2023/09/26/vale-pretende-construir-hub-voltado-para-descarbonizacao-no-porto-do-acu.ghtml. Accessed: March 22, 2025.

Valor Econômico. Plataforma de inovação da CSN poderá se tornar o sexto maior negócio. São Paulo: *Valor Econômico,* August 14, 2023b. Available at: https://valor.globo.com/empresas/noticia/2023/08/14/plataforma-de-inovacao-da-csn-podera-se-tornar-o-sexto-maior-negocio.ghtml. Accessed: March 22, 2025.

Valor Econômico. Boston Metal vai investir R$ 573 milhões em planta de aço verde em MG, diz governo.

São Paulo: *Valor Econômico,* May 8, 2023c. Available at: https://valor.globo.com/empresas/noticia/2023/05/08/boston-metal-vai-investir-r-573-milhes-em-planta-de-ao-verde-em-mg-diz-governo.ghtml. Accessed: March 22, 2025.

Valor International. *Brazil's Lower House approves carbon market regulation.* São Paulo: Valor International, November 11, 2024. Available at: https://valorinternational.globo.com/politics/news/2024/11/20/brazils-lower-house-approves-carbon-market-regulation.ghtml. Accessed: March 22, 2025.

Warrian, P.; Afshar, H. Canada's pathway to hydrogen steelmaking. *Innovation Policy Lab Working Paper Series 2023-04*, Munk School of Global Affairs and Public Policy, University of Toronto, 2023. Available at: https://munkschool.utoronto.ca/media/4969/download?inline=/download. Accessed: March 10, 2025.

World Steel Association (WSA). *World steel in figures 2024.* Brussels: WSA2024a. Available at: https://worldsteel.org/wp-content/uploads/World-Steel-in-Figures-2024.pdf. Accessed: March 10, 2025.

World Steel Association (WSA). *Sustainability indicators 2024 report.* Brussels: WSA, 2024b. Available at: https://worldsteel.org/wp-content/uploads/Sustainability-Indicators-report-2024.pdf. Accessed: March 10, 2025.

World Steel Association (WSA). *Steel statistical yearbook*. Brussels: WSA, 2024c. Available at: https://worldsteel.org/media/publications/ssy_subscription-2024/, Accessed: March 10, 2025.

World Steel Association (WSA). *Climate change and the production of iron and steel*. Brussels: WSA, 2021. Available at: https://worldsteel.org/wp-content/uploads/Climate_PP_September-2024-1.pdf. Accessed: March 10, 2025.

World Steel Dynamics (WSD). G*lobal steel industry decarbonization Report #1:* the race to the 2030 starting line. Englewood Cliffs, NJ: WSD (2023).

Xue, Y. *Climate change policies*: China sets 2025 deadline for steel, cement, aluminium and output of raw materials to meet carbon neutral goals. Southern China Morning Post, Hong Kong, December 30, 2021. Available at: https://www.scmp.com/business/article/3161538/climate-change-policies-china-sets-2025-deadline-steel-cement-aluminium. Accessed: March 10, 2025.

Yuan, C.. Decarbonization roadmap of Brazilian steel industry. ABM Week 2023. São Paulo: Brazilian Association of Metallurgy, Materials and Mining, 2023.

Yuan, C. Descarbonização da indústria do aço: Desafios, avanços e perspectivas. Workshop: *Descarbonização das indústrias cimenteira e siderúrgica: desafios, avanços e perspectivas*. São Paulo: Insper, 2024.

Zhang, M.; Chow, E. China plans to increase iron ore output, boost use of steel scrap. *Reuters, B*eijing, February 7, 2022. Available at: https://www.reuters.com/article/markets/commodities/china-plans-to-increase-iron-ore-output-boost-use-of-steel-scrap-idUSL1N2UI0FL/. Accessed: March 10, 2025.

Zong, J. *China's EAF steel production to exceed 15% in 2025 for decarbonization*. Shanghai: Fastmarkets, 2022.

DECARBONIZATION AND INDUSTRIAL POLICY:
CHALLENGES FOR BRAZIL

DECARBONIZATION
& INDUSTRIAL POLICY