ESG STUDIES REVIEW
ENVIRONMENT SOCIAL GOVERNANCE
SUSTAINABLE DEVELOPMENT GOALS
e-ISSN: 2966-1129

CIRCULAR ECONOMY IN THE STEEL SECTOR: FUTURE TRENDS AND CHALLENGES IN BRAZIL

Solange Akiama[1]
Renata Giovinazzo Spers[2]

ABSTRACT

Purpose: Examine the role of the circular economy in the steel sector, highlighting trends and challenges faced in its transition to a more sustainable practices.

Methodology/approach: This research is centered on a qualitative analysis of the steel production chain in Brazil. Information was gathered using in-depth interviews and was examined through an abductive approach involving purposive sampling.

Originality/relevance: This study highlights the main trends, examines the challenges, and outlines the best practices within the Brazilian industry steel sector, framed within the context of the circular economy.

Key findings: The results show that Brazil is aligned with global sustainability and circularity trends in the steel industry, albeit with particular challenges.

Theoretical/methodological contributions: The findings of this investigation are intended to establish a basis for mapping out the trends in Brazil's steel industry by 2035.

Keywords: Circular economy, Steel in Brazil, Carbon market, Global sustainability.

Received on: January/24/2024
Approved on: May/08/2024
DOI: https://doi.org/10.37497/esg.v7iesg.1621

---

[1] Universidade de São Paulo (USP), São Paulo (Brazil).

[2] Universidade de São Paulo (USP), São Paulo (Brazil). **Email:** journalfuturesrj@gmail.com Orcid: https://orcid.org/0000-0003-1240-0530

1 INTRODUCTION

In the last decade, global steel production has grown by 2.5% annually, reaching 1.951 billion tons, with an average capacity utilization of 70.8%. Steel plays a crucial role in the global economy, generating over US$2.5 trillion in revenue and employing around 6 million people (WSA, 2021). Nevertheless, the steel industry is highly competitive and fragmented, with the top ten producers accounting for only 25% of global production. The leading iron ore producers are countries with lower steel consumption, such as Australia and Brazil, posing logistical challenges in meeting the demands of major consumers such as China, the United States, and India.

The primary applications for steel include buildings (33%), infrastructure (22%), machinery and equipment (17%), vehicles (15%), and consumer goods (13%). Steel production involves an intensive process that utilizes natural resources, energy, and logistics, emitting a significant amount of CO2. The steel industry is the largest industrial emitter, contributing to 7% of total direct emissions. In 2018, approximately 1.85 tons of CO2 were produced per ton of steel (IEA, 2020). Substantial operational and business strategy reforms are necessary to reduce its contribution to global warming and achieve the CO2 emission reduction targets. Steel plants worldwide are adopting measures to reduce and offset their emissions, with a growing trend of integrating clean energy sources and technological innovations to produce steel with lesser environmental impact.

Steel production generally involves two metallic inputs: iron ore and recycled steel scrap. Primary steel results from operations where iron ore is a predominant component (maximum of 25% scrap), while secondary steel comprises primarily scrap. Currently, primary and secondary steel account for 70% and 30% of steel production, respectively. In primary steelmaking, the blast furnace is the primary equipment, with coal as the main energy input, while secondary production, which is more sustainable, utilizes the electric arc furnace. Energy and raw materials combined typically account for between 60% and 80% of steel production costs (IRENA, 2023; WSA, 2021).

Given the high consumption of raw materials and energy, along with the importance of preservation practices and reducing environmental impact, industries need to explore alternatives for current production methods. This highlights the interest in the circular economy of steel. Unlike linear production, which extracts, processes, uses, and discards raw materials, the circular economy involves recycling steel back to the beginning of the chain after consumption. This approach not only reduces the extraction of raw materials but also decreases the amount of energy used in the production process (Pauliuk, Wang, & Müller, 2012).

1.1 Overview of the steel sector in Brazil

The steel sector plays a key role in the economy, being one of the pillars for the development of a country due to its extensive application across various industries (Steel Institute Brazil, 2023). Politically, there is a growing pressure from international clients for suppliers to demonstrate progress or plans to achieve Net Zero, reflecting a demand trend for sustainability policies beyond legislative obligations. Additionally, the government's role in regulating and formalizing the sector serves to provide greater stability and encourage companies to adopt sustainable innovation practices. There is even progressive governmental pressure to adopt regulations that emphasize sustainable practices, including the possibility of applying stricter standards and encouraging voluntary certifications.

Socially, there is a growing pressure for sustainable practices, transcending legislative boundaries and becoming a demand from significant and conscious international clients. Renowned companies are demanding that national suppliers adopt policies that align with goals such as Net Zero. This pressure trend reflects a paradigm shift whereby market-leading companies drive suppliers towards sustainability, illustrating a new social dynamic in business.

Similarly, initiatives that surpass current regulations, such as voluntary certifications, indicate a tendency towards sustainability stemming from non-mandatory motivations, i.e., not based on government regulations, pointing to a social movement influenced both by corporate pressure, which sees strategic value in sustainability, and by the recognition that responsible business practices can be competitive mechanisms.

Additionally, public policies to organize and enable a more stable and predictable business environment in the steel sector are a relevant condition for fostering sustainable practices. By regulating these policies, the government not only provides incentives for adopting clean and effective technologies but also creates a conducive ecosystem for activities like recycling and material reuse, adding value to corporate social responsibility and increasing society's engagement in environmental issues.

Regarding the technological aspect, it is necessary to innovate and adopt cleaner and more efficient technologies. According to Bataille et al. (2023), the latest technologies to foster low-carbon steel production are the reduction of iron use directly with green or blue hydrogen for use in electric arc furnaces, and carbon capture and storage technologies. There are also opportunities for Brazilian companies to become leaders in green production, selling to subsidized developed markets and eventually serving broader global and domestic markets (Nogueira & Madureira, 2022).

The steel sector in Brazil faces significant changes driven by political and economic factors that highlight the importance of integrating sustainable practices. Government engagement, along with pressure from stakeholders and the exploration of emerging markets, such as carbon credits, is an aspect that redefines the dynamics of the steel market, driving the sector towards sustainability. In this sense, in 2023, Bill No. 2148/2015 was approved, regulating the carbon market in Brazil, creating the Brazilian System of Greenhouse Gas Emissions Trading (SBCE), which establishes caps on emissions and a market for selling titles.

The Brazilian government, through its Nationally Determined Contribution (NDC), has committed to implementing studies to finance low-carbon measures in sectors such as the steel industry. Some strategies suggested for this sector include increasing recycling in the electric arc furnace route and replacing mineral coal with charcoal in the blast furnace route. Carbon pricing scenarios have significant implications in energy policy to implement nationally determined contributions and to reduce or nullify emissions in the industrial sector.

Another factor intrinsically linked to the sustainability of the Brazilian steel sector is the circular economy. Recycling and reusing steel scrap are economic practices that reduce energy consumption and dependency on primary resources. The formalization and structuring of the scrap market can be driven by public policies, favoring the transition to more sustainable practices.

Globally, the circular economy has been promoted as a cross-cutting approach to meet the United Nations Sustainable Development Goals. Initiatives such as circularity in the use of materials help minimize waste and pollutant emissions, enhancing resilience and contributing to the sustainability of the Brazilian steel sector, which, aligned with global trends and dynamics, must adapt and adopt practices that lead it to a position of sustainable leadership. Engagement with global sector institutions and the integration of initiatives aimed at the circular economy and carbon credit management are key strategies that will define the sector's competitiveness and permanence.

In the light of the foregoing, this article aimed to map the trends for 2035 in the Brazilian steel sector, considering the framework of the circular economy, as well as to outline the best practices of companies in the sector and identify their challenges. To this end, this research was conceived as a qualitative investigation and used purposeful sampling. Thus, the concepts of the circular economy, trends, challenges, and best practices according to sector experts interviewed for this research who work in various stages of the steel production chain in Brazil will be presented.

2 THEORETICAL REFERENCE

The circular economy is a redefinition of the notion of growth, dissociating economic development from the consumption of natural resources (MacArthur & Heading, 2019). It replaces the final disposal of waste through reduction, reuse, recycling, and material recovery, making recycling a key component to achieve this efficiency. Additionally, it provides solutions for materials, increasing their lifespan and avoiding disposal, exemplifying the process of reincorporating materials into the production cycle.

The circular economy also advocates for a model to "create and recreate/reuse and repurpose" resources and products, with the European Commission (2015) having already emphasized this goal in its action plan. This approach aims to enhance materials, limit the use of non-renewable resources, and propose a significant circulation of waste and by-products through their reuse, contributing to social, economic, and environmental sustainability.

In this context, the steel product chain is designed to include a series of stages that highlight the principles of the circular economy. The product design is planned to facilitate recycling and enable the use of recyclable raw materials. During production, environmentally respectful technologies are used, along with efficient methods that reduce resource consumption and waste formation. In the usage stage, the goal is to maximize the lifespan of steel products and extract maximum functionality. After the end of the product's useful life, the products are collected for recycling, returning to the production cycle as raw material for new steel items, or even in other forms, such as components for repairs, reflecting the reuse stage. All these practices aim to reduce the consumption of natural resources and the environmental impact throughout the production chain, aligning with the principles of the circular economy (Bocken, Pauw, Bakker, & Van der Grinten, 2016; Branca et al., 2020; Haas, Krausmann, Wiedenhofer, & Heinz, 2015; Instituto Aço Brasil, 2023; Morseletto, 2020; WSA, 2023a). In summary, these are the steel circularity strategies: reduce, reuse, remanufacture, and recycle. Next, the description of the stages of the steel production chain and how they relate to circularity strategies will be presented.

2.1 Steel Production Cycle

To understand the trends of the circular economy in the steel sector, it is necessary to comprehend the stages of its production, namely: 1) Extraction of raw materials or mining: the initial stage of the steel production cycle involves the extraction of iron ores, coal, and other necessary materials; 2) Iron reduction: Iron ore is processed to produce pig iron. Due to the high temperature required (1400-1600 °C) and the use of coal as an energy source, this is the most emissions-intensive stage in the entire production chain; 3) Steel production or refining: Pig iron is processed at high temperatures with the addition of other elements, such as carbon, to produce steel. The high temperatures and energy use also contribute to CO2 emissions; 4) Steel processing or manufacturing: Steel is transformed into different shapes and sizes, such as sheets, profiles, bars, and tubes. The energy used in this stage also contributes to CO2 emissions; 5) Product manufacturing: Steel is used in industries as a raw material for product manufacturing; 6) Usage: corresponds to the period during which the product is used for its purpose. During this stage, there is a high energy consumption, generating CO2 emissions - considering a closed cycle, the steel composing the product is considered as part of the stock. The end of this period is the end of its useful life; and 7) Waste management and recycling: at the end of its useful life, steel-derived products, especially scrap, can be discarded or recycled, returning to be part of the chain.

The Figure 1, based on the concept of Life Cycle Assessment (LCA), presents the stages of the steel chain (Thomas & Birat, 2013). With it, the aim is to understand the material flows within and outside the system boundaries, especially in the case of scrap, which does not follow a linear flow. Scrap originates from manufacturing and recycling stages, as well as from circular economy strategies of various phases of the steel cycle. Losses occur during the processes, which may or may not be recycled. Furthermore, there is a need to move materials and products through various stages, from mining to their disposal in local and/or international markets. The fuel used by vehicles during movements adds to CO2 emissions.

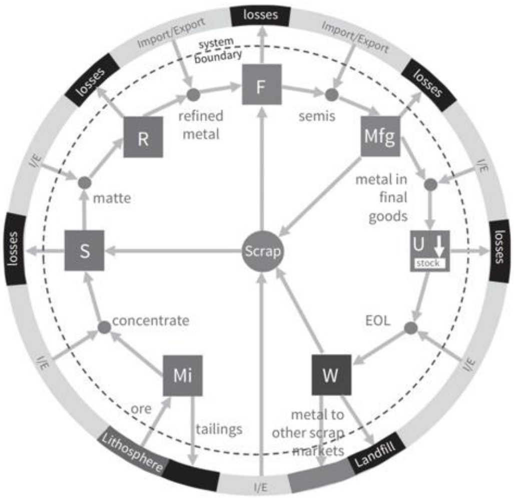

Figure 1. Generic circular diagram for metals, with the main processes.

Source: Based on Reck, Müller, Rostkowski and Graedel (2008) and Li, Chertow, Guo, Johnsone and Jiang (2020).

Caption: Mining/Milling (Mi), Reduction (S), Refining (R), Fabrication (F), Manufacturing of products using steel in their composition (Mn), Use of the final product and part of the steel stock (U), and Waste management and recycling (G). Note: The processes are connected to other markets through import and export (I/E). Losses occur at stages of the chain.

2.2 Scrap in Steel Production Routes

Steel production routes are divided into primary and secondary. The primary involves the blast furnace with basic oxygen and the direct route of the reduced iron electric arc furnace, while the secondary route is that of electric arc furnaces. Figure 2 presents the steel production routes and the main technologies of these stages.

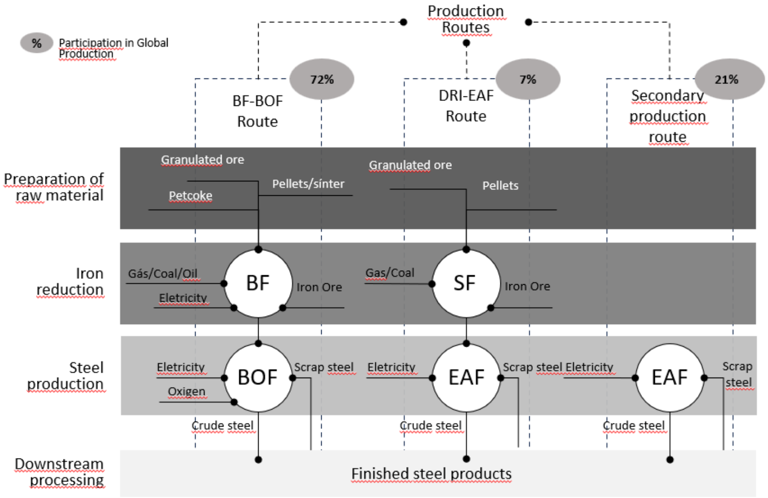

Figure 2. Steel Production Routes and Main Technologies

Source: Lopez, Farfan, and Breyer (2022) and WSA (2023a).

Caption: BF (Blast Furnace); SF (Shaft Furnace); DRI (Direct Reduced Iron); BOF (Basic Oxygen Furnace); EAF (Electric Arc Furnace).

The blast furnace route accounted for, in 2023, 72% of global steel production (WSA, 2023a). The Basic Oxygen Furnace (BOF) converts pig iron from the blast furnace (BF) and ferrous scrap into crude steel. During the conversion process, carbon and other impurities are reduced by an injection of an oxygen jet onto the pig iron, generating slag. The blast furnace will maintain its primary position in the production of iron-based alloys, being significant for integrated steel mills. Considerable efforts in heat and gas recovery technologies can reduce emissions by 46 KgCO2/t of product and by 0.92 GJ/t of fuel consumption (Cavaliere, 2019).

In 2023, the second primary route accounted for approximately 7% of global steel production (WSA, 2023b). Direct Reduced Iron (DRI) involves the reduction of oxygen from iron ore in its solid state. This technology encompasses various processes based on different raw materials, reactors, and reducing agents, such as natural gas or gasified coal. The production of directly reduced iron is expected to increase in the near future due to continuous plant innovations, leading to decreased energy consumption and CO2 emissions. In this respect, technological solutions are advancing towards residual energy recovery and the use of CO and

H2 as reducing agents. The size of the plant is increasing to become similar to the blast furnace-based route. Additionally, mini plants based on direct reduction reactors are typically very energy efficient.

The secondary route via the Electric Arc Furnace (EAF) accounted for nearly 21% of total production in 2023 (WSA, 2023). EAF is the main alternative to the BF-BOF route. In this method, steel is produced solely by melting scrap metal. Scraps, directly reduced iron, pig iron, and additives are melted by high-power electric arcs formed between a cathode and the anodes. The grades of scrap vary in terms of their chemical composition and geometry, which affects their price. High-quality materials lead to reduced energy consumption and decrease the amount of slag produced.

Iron ore is abundant worldwide, but the availability of scrap is limited by the end-of-life rate of steel products and the efficiency of collection systems. Approximately 650 Mt of scrap are consumed annually worldwide to produce steel (compared to a total volume of crude steel production of 1,869 Mt per year) and similar amounts are used in the primary and secondary routes. This prevents the emission of approximately 975 Mt of CO2 per year and significantly reduces the use of other natural resources, such as iron ore, coal, and limestone. The WSA estimates that the global foundry sector uses about 70 Mt of ferrous scrap each year. With a total of 720 Mt, the recycling of ferrous scrap constitutes the largest recycling activity in the world (WSA, 2021).

Scrap originates from the steel production process, from the manufacturing of steel products, and from post-consumption. Home scrap is generated in the steel production process, when steel mills and foundries manufacture new products, rarely leaving the production area. Technological advances have significantly reduced the generation of home scrap, which represents approximately 29% of the total scrap. Industrial scrap is generated in manufacturing plants of steel products and includes items such as trimmings, cuttings, and stamping leftovers. This material is typically sold to the scrap metal industry, which processes it to sell it to steel mills and foundries. It represents approximately 23% of the total steel scrap. Finally, post-consumer scrap results from industrial and consumer steel products that have ended their useful life, representing approximately 48% of the total (Javaid & Essadigi, 2003).

Recycled steel is not only an indispensable iron raw material for the modern steel industry but the only sustainable raw material capable of replacing iron ore in large quantities. The quality of recycled steel affects the quality of the cast steel, making it necessary to classify and evaluate recycled steel before it enters the furnace (Xiao et al., 2023).

A study by Fărcean, Proştean, and Socalici (2023) on the sustainable development of the steel sector highlighted the indicators most related to the circular economy: 1) CO2 emissions: The reduction of CO2 emissions is directly linked to the circular economy, as measures to decrease them often include recycling and reusing materials; 2) Energy intensity: Energy efficiency is a crucial aspect of the circular economy. Using energy more effectively often involves recycling and reusing materials, which consume less energy to produce than new materials; 3) Material efficiency: This indicator is particularly relevant for the circular economy, as it promotes the efficient use of materials and the incorporation of waste into the production process, minimizing waste and maximizing material use; 4) Environmental management system: Although not specifically mentioned in relation to the circular economy, a robust environmental management system can facilitate the implementation of circular practices, such as waste management and reducing environmental impact; 5) Investment in new processes and products: By investing in new technologies and innovations, companies can develop processes and products that align with the principles of the circular economy, such as durability, recyclability, and reusability.

2.3 Emissions and energy in the steel chain

The steel sector is the largest industrial contributor to CO2 emissions and the second in energy consumption. It is responsible for 2.6 Gt of CO2 emissions annually and heavily relies on coal for energy, resulting in 1.4 t of direct CO2 emissions. The projected growth in demand and emissions indicates a global steel demand increase of more than a third by 2050. Thus, without specific measures to reduce demand and renew production, CO2 emissions are expected to rise by 7% by 2050 (IEA, 2020).

Much of the CO2 emissions from the steel production chain are associated with the iron production process. Low-carbon iron production technologies, such as those using iron ore, scrap, and biomass, can be utilized to reduce CO2 emissions. In this way, the steel sector can benefit from the circular economy, reducing its operational costs and environmental impacts by increasing steel recycling and using renewable energy sources.

3 METHODOLOGY

To map the trends for 2035 in the Brazilian steel sector, considering the framework of the circular economy, this research was conceived as a qualitative investigation, in order to deeply understand the particularities of the phenomena, something that would be limited by quantitative methods (McNulty, Zattoni, & Douglas, 2013). For the collection of fluid and detailed data, the method of in-depth interviews was chosen (Hoon & Baluch, 2020). The interpretation of the collected data was carried out through the abductive approach (Cocchieri, 2008) and used purposive sampling (Spaulding et al., 2010), aiming to identify experts who operate at various stages of the steel chain in Brazil.

To add solidity to the study, a combination of secondary data from literature and sectoral statistics with primary data obtained through interviews was used, thus allowing triangulation. This procedure is considered relevant in exploratory and explanatory research, especially when there are uncertainties about the accuracy of information provided by respondents (Corley & Gioia, 2011).

The selected participants were experts with renowned knowledge in fields that span the various stages of the steel chain in Brazil. They were invited through personal contact and subsequent referral of some experts who had already participated in the research, thus using purposive sampling (Spaulding et al., 2010).

Additionally, professionals were selected with: 1) Training compatible with their area of expertise; 2) A minimum of ten years of experience; 3) Involvement in the private, academic sectors, sectoral entities, and regulation; and 4) International exposure. All participation was completely voluntary and informed consent was obtained before the interviews, where the research objectives, methodology, confidentiality, and their autonomy to decide not to answer any question or withdraw from the investigation were indicated, in addition to signing the Informed Consent Form.

Initially, exploratory in-depth interviews with four participants were conducted. The objective was an efficient questionnaire and the collection of high-quality data, accurately reflecting the perspectives and opinions of the respondents. The pre-test was conducted through exploratory interviews with four executives of national and international reference in mining, steelmaking, metallurgy, civil construction, the automotive industry, and climate economy and sustainability, between August and September 2023.

4 RESULTS AND DISCUSSIONS

Mapping the trends in the steel sector, according to Dragt (2017) and Rech (2016), serves as a tool to detect, understand, and act upon changes, helping to identify potential paths and future events from a historical contextualization of reality. According to Rech and Maciel (2015), trend studies allow, through a collective reflection on future challenges, to structure and assess their strategic and marketing options, with a view to guiding actions of national strategic interests, the generation of technological policies in specific segments, and regional development and production clusters. The main future trends for the circular economy of the steel sector are related to the adoption of circularity principles, the closing of the circular economy cycle, international coordination for sharing practices, and the removal of international trade barriers (IEA, 2020; IRENA, 2023).

4.1 Trends in the steel value chain

In the mining and refining stages, the main trends are related to technologies aimed at mitigating emissions and using green renewable energy sources, as these encompass processes for iron reduction and steel production. In mining, this involves reusing limited resources from process waste, such as iron ore (Carmignano et al., 2021; Yuan, Zhang, Yin, & Li, 2021), while in refining it implies optimizing the use of scrap in both primary and secondary routes. Secondary steel production uses renewable energies in electric arc furnaces, whereas primary production still relies on fossil fuels (IRENA, 2023). The use of renewable hydrogen to reduce iron ore is an alternative that enables the production of primary steel with almost zero carbon emissions.

Technological innovation is also a strong trend for the circularity of steel, being crucial for efficiently separating valuable materials from other substances. Furthermore, there is a trend in policies and science to promote the use of resource-efficient technologies, to both increase material and energy security and to minimize environmental impact (IEA, 2021; Munaro, Tavares, & Bragança, 2020).

Moreover, in terms of technological innovation, the following initiatives are underway, according to Lopez et al. (2022): 1) Biomass opportunities in steelmaking; 2) Hydrogen production and storage; 3) Technological innovation for the steel industry; 4) Integration of renewable energies into the steel industry; and 5) Global potential for green ammonia and carbon capture and utilization.

Another driving force for the circular chain and material utilization is related to their efficiency in dematerialization and the technological performance of alloying and steel production stages. Strategies to increase material efficiency to reduce consumption can contribute to balancing the growth in global demand for steel with mineral extraction (IEA, 2020). Following a similar principle, special alloys, like ferroalloys, provide higher performance and durability and less resource usage, as in the "same product with less steel" concept by Wang et al. (2021). These alloys also contribute to increasing the lifespan of the products made with them.

Thus, the main trends regarding the use of products are related to extending their lifespan, technologies to repair, reuse, requalify, and remanufacture, as well as the need for laws, subsidies, and incentives to promote remanufactured products. In this context, Allwood et al. (2013) describe strategies for steel circularity identified as trends by IRENA (2023) and the IEA (2020): 1) Steel reuse; 2) Resource efficiency; 3) Economic efficiency; 4) Lifespan extension; and 5) More intensive use. Particularly, it highlights the importance of implementing circular practices in the construction scenario, the sector that consumes the most steel, by designing circular systems and materials to extend the value and lifespan of resources, as well as including comprehensive decision criteria in project planning.

4.2 Challenges in the implementation of the circular economy

The transition of the steel industry to greener processes is crucial to boost global efforts to reduce emissions. Despite this, current commercial steelmaking technologies, such as EAF and BF-BOF systems, need significant technological advancements to meet emission reduction targets. While EAF technology represents a shift towards more electrified and less emissive steelmaking processes, it faces limitations, including the lack of sufficient scrap, the need for high-quality iron ore, and product quality issues, making it unlikely that EAF will completely replace BF-BOF production in global markets (Carvalho, 2024).

According to Lopez et al. (2022), transitioning to a defossilized steel industry requires significant demand for low-cost renewable electricity and the use of green hydrogen. Among the viable technologies to move from fossil fuels to electricity-based technologies, standout options include hydrogen direct reduction (H2 DR), which proposes using hydrogen as a reducing agent, potentially reducing CO2 emissions by 35% compared to the traditional BF-BOF route; and Electro Voltaic Iron-making (EWIN), which has the potential to eliminate CO2 emissions by up to 98%, but is still largely in its research phase, with the possibility of being available on an industrial scale by 2040.

Another barrier to circular economy practices is related to product design, as the expansion of the materials set available to designers has complicated the recycling process. Products have become more functional and reliable, but their complexity makes recycling a challenge. Thus, according to Reck and Graedel (2012), it is necessary to improve the development and design of products to facilitate disassembly, as well as considering the potential reuse of steel at the end of its life for other applications with minimal processing.

Regarding the regulatory issues affecting the transition to a circular model, according to Graedel, Reck, Ciacci, and Passarini (2019), it is necessary to assess the environmental repercussions of international recycling. International trade in secondary materials and their recycling in different countries can lead to "leakages" in carbon accounting, when climate change mitigation actions are undermined due to discrepancies in process efficiency and CO2 emission intensity between different countries. These trends highlight the complexity of achieving true circularity for materials like steel, where the location of production and use, as well as processing efficiency and international trade policies, play significant roles.

The relevance of the role of institutions and international trade was studied by Graedel et al. (2019), who concluded that further refinement is needed in the roles of institutions and international trade regarding the concept of a circular economy. Commitments must be balanced with individual corporate efforts for profitability and production capacity. Moreover, the handling of materials and the necessary maritime transport for circularity need to be weighed against the potential environmental impacts of these activities. The concept of a circular economy remains a promising goal, but it should not be pursued uncritically, to the detriment of other environmental objectives.

Finally, another barrier refers to traditional business models and the need for innovation. The roadmap developed by the IEA (2020) identifies measures for optimizing technological performance and material efficiency, which can already be adopted to make more efficient use of energy and steel in the steel industry. These include operational improvements and the adoption of state-of-the-art technologies available in steel mills, in addition to material savings along value chains, achieving immediate emission reductions, improving the performance of existing steel mills, and setting the stage for long-term reductions in steel demand. Regarding the current asset park, a plan must be established to address existing steel mills. This plan should indicate a reduction in the CO2 intensity of production required within just one investment cycle. At the same time, in the short term, a coordinated effort is needed to plan and build new support infrastructure for hydrogen, low-emission electricity generation, and the transport and storage of CO2 to prepare for the rapid deployment of innovative steel technologies after 2030.

The roadmap (IEA, 2020) also signals that it is necessary to establish a clear and stable policy signal early on for long-term emission reductions, which will be an important catalyst for decisions on existing and new infrastructures. Pilot and demonstration projects for nearly zero-emission innovative technologies over the next decade must be consistent with post-2030 deployment ambitions. Government financial support and coordination will be critical.

Additionally, according to Munaro et al. (2020), specifically for the construction industry, one of the sectors that uses steel extensively, challenges for the circular economy of steel may include the development of standards and regulations that favor the reuse and recycling of steel, education and awareness of stakeholders about the importance of closed value cycles, and the integration of decision-making systems that consider life cycle analyses and the potential for material reuse at the end of its life cycle. Trends are expected to develop materials and construction systems that allow for longer life cycles, as well as revitalize used steel and promote a design that facilitates disassembly, in addition to seeking innovations in consumption taxation policies and regulations that encourage the use of regenerated resources.

Considering the increasing potential of scrap in the construction sector, there is a need for a coordinated approach in the construction supply chain, aimed at addressing systemic barriers, which are identified as more pressing than technical ones. These barriers include the creation of a database of suppliers and availability of reused sections, demonstration of customer demand, technical guidance and education for the industry, as well as strong governmental leadership, disassembly strategies, and acceptance criteria for the use of secondary materials and waste (Munaro et al., 2020).

Another trend is the optimization of separation technologies to favor recycling in product design and reduce net additions to stocks, which can increase metal recycling. Large accumulations of materials and high growth rates of global stocks are barriers to achieving circularity. Materials used for energy generation, especially those that carry fossil fuels, pose challenges to closing the cycle and reducing the degree of circularity (Graedel et al., 2019; Haas et al., 2015).

These themes were also addressed in interviews conducted with industry experts for this research. They highlighted the topics that are currently at the forefront of the Brazilian steel sector reality. Accordingly, the respondents pointed out that the most relevant technological stages are mining and refining, and transformation. The national steel industry faces the challenge of developing and implementing environmentally less aggressive technologies that are sustainable in the production process. The search for innovation and research is essential to achieve the goal of carbon neutrality by 2050, especially in phases like refining and transformation, which are major energy consumers and emit significant amounts of carbon. There is also market resistance to paying more for low-carbon footprint steel, which complicates the implementation of sustainability practices.

Regarding the business model, the most relevant points are the stages of waste management and product usage. There is a complex balance between importation and domestic production, with a tendency for some major mills to prefer importing steel, affecting the competitiveness of national production. Moreover, there is the challenge of adapting scrap management, essential for the sustainable production of steel, which may mean changes in the supply chain structure. The dependence on scrap prices and the cost of electricity are also significant challenges for secondary steelmaking.

Finally, for the regulatory dimension in Brazil, the most relevant challenge is waste management, followed by product usage. In terms of regulations, the steel sector needs to navigate the transition to zero-emission operations, which is particularly challenging due to the sector's high carbon intensity. The lack of public policies with predictability and clarity, such as carbon pricing, is a significant obstacle. Moreover, consumer awareness and pressure for sustainable practices can influence the sector's direction towards sustainability, even more so than governmental incentives.

4.3 Opportunities and best practices

Best practices for the steel industry involve the implementation of environmentally-respecting technologies, adaptation of business models aligned with the concept of circular economy, and compliance with strict environmental regulations. Technology, business model, and regulation are crucial to promote greater use of waste and increase circularity in the steel sector.

Moreover, global cooperation and coordination to promote sustainable regulatory policies are seen as achievable goals, despite differences in implementation stages and regional challenges.

For the Brazilian steel sector to evolve in terms of circular economy by 2035, in line with global and national expectations, a strategic mindset that prioritizes innovations, integrating environmental, economic, and social considerations, is essential to overcome challenges and capitalize on the opportunities of this new industrial scenario.

In this section, the best practices identified by steel industry experts regarding technology, business models, and regulation will be discussed. A summary of these best practices will then be presented to reflect a strategic vision for the sector until 2035.

4.3.1 Technology

The recycling of scrap in steel production is widely recognized as a sustainable and advantageous practice, with an expectation of complete technological advancement by 2035, making steel production more sustainable. Additionally, the CECarbon software is identified as a valuable tool for measuring energy consumption and carbon emissions, benefiting the steel usage phase, while the Construction Performance Information System (Sidac) allows for calculating environmental performance indicators of construction products based on Brazilian data and life cycle assessment (LCA) concepts.

Industrialized construction practices are significant due to waste reduction and resource efficiency, contributing to the sector's sustainability. The specification of materials in compliance with sustainability requirements and certification systems, such as Cradle to Cradle (C2C), is also essential to attest to the sustainability of the process.

Modular construction is a technology that produces large 2D and 3D elements in an industrial environment, which are later transported and assembled on-site. This practice minimizes waste generation and allows for more efficient control of the resources used, in addition to favoring the disassembly and reuse of materials, including steel structures. A sample of the evolution of this sector can be observed in the roadmap published by the Alliance for Modular Construction in 2024 (ABCM, 2024).

There are already practices of using Urban Solid Waste (USW) as fuel in furnaces. This practice could be a precursor of trends for the steel industry, aiming to reduce emissions and better utilize waste.

Regarding iron mining, the reuse of mining materials is one of the good practices, such as in deactivated dams containing materials of superior quality to those currently being prospected, aiming to reintegrate them into the production cycle.

In the mining and refining stage, the recycling of all waste, including rolling scale, is considered a relevant practice. Previously not utilized, it is now integrated into the production of iron ore, optimizing the use of by-products from the steelmaking process.

Finally, carbon pricing can lead steel users to improve their processes and adopt more efficient solutions. It is noted that good practices involve innovation and a constant search for more efficient processes with a lower environmental impact.

4.3.2 Business model

Urban mining is a growing trend: 35% of steel production in Brazil comes from scrap recycling, epitomizing the concept of a circular economy in the industry. Another good practice in investing in research and development of innovation projects in urban mining can be exemplified by the following companies: Tupy, BMW Group Brazil, Senai Paraná, and the Technological Research Institute (IPT). They are developing a project that includes the recycling of electric vehicle batteries through the recovery of chemical compounds from batteries using hydrometallurgy, a more sustainable process. The technology involves fewer emissions and utilizes urban mining. With this, it is possible to implement business models where circularity is the main strategy.

Finally, the scrap market is increasingly oriented towards sustainability, recognizing the importance of steel in this context. The scrap recycling sector, particularly steel, is motivated not only by the idea of "circular steel" but also by the essential role of carbon and goals to decarbonize. An example of this is Tegra, a construction company in São Paulo that initially purchased specific products at a higher cost but managed to recover the values through benefits such as green financing and the increased demand for sustainable constructions, which include the use of steel from recycling.

4.3.3 Regulation

One example involving good practices related to the regulation of the steel sector is the waste management actions of one of the largest companies in the steel industry, which is pushing for legislative changes to facilitate the recycling of impounded cars. This highlights the importance of good practices in waste collection and recycling.

Raising awareness and coordinating scrapyards to send scrap in accordance with the proper norms is also positive. Companies in the supply chain are taking steps for proper waste disposal, separating materials that can be harmful from those that are non-contaminants and can be properly reused, such as copper waste.

Additionally, another good practice is the preparation of the steel industry for low-carbon policies that have not yet been implemented. This suggests that for an effective circular economy, there need to be policies and regulations that encourage sustainable practices and internalize environmental costs.

These practices reflect the steps being taken by the Brazilian steel sector in pursuit of a greener and economically viable future, focusing on innovation and efficiency as fundamental pillars. The good practices indicate that actions by various actors in the supply chain are already underway to push the steel sector more rapidly towards a circular economy. The concept of a circular economy is not just a passing trend, but a paradigm shift that is here to permanently reshape the practices of the steel industry.

5 FINAL CONSIDERATIONS

In this article, the main trends for the steel sector have been mapped out as follows: 1) circular economy as a new paradigm for the steel industry; 2) technological development, particularly renewable energies; 3) consolidation of waste management as an indispensable part of the steel chain; 4) the need for incentives and regulation of sustainable practices to facilitate a transition to a low-carbon emission scenario. Additionally, the most relevant challenges and best practices aligned with these trends were delineated, considering the horizon of 2035. In summary, it was demonstrated that Brazil is aligned with global sustainability and circularity trends within the steel chain. However, the country faces particular challenges due to boundary conditions, which reflect subtle route divergences rather than opposition to global trends, thus laying the foundation for the directions needed to keep the country in line with global transformations in the sector.

Looking ahead to 2035, the main trends in the steel sector in Brazil, with a focus on circular economy, are:

Emission Reduction: 1) Adoption of technologies aimed at emission reduction, focusing on primary and secondary steel production routes, which have the highest emissions in the production chain; 2) Innovative use of renewable hydrogen in iron ore reduction, representing a viable path for producing primary steel with minimal emissions; 3) Utilization of charcoal-fired blast furnaces as a non-fossil and sustainable alternative that highlights Brazil in the route of innovation; 4) Increased use of scrap to reduce furnace temperature in steel production and as a strategy to increase recycling percentage, aiming to reduce emissions through technological improvements.

Waste Management: 1) Trend towards reuse of waste such as iron ore and materials previously considered of lesser value; 2) Increased recovery of steel from previous process slags; 3) Growing use of recyclable materials in steel production and stimulation of domestic scrap production, aiming to reduce dependency on imports; 4) Maintenance of the scrap dealer business model in Brazil, preventing the formation of too powerful market players; 5) Scarcity of scrap

Regulation: 1) Implementation of incentives and regulation of practices to favor a transition to a low-emission scenario; 2) Financial and regulatory incentives for companies to adopt circular economy practices effectively and diligently, considering higher initial investments; 3) Recognition of the need to adapt to sustainability policies to avoid future impacts on prices and demand for steel and scrap; 4) Use of public policies to promote recycling in various sectors and other processes that may influence the dynamics of scrap market prices.

These trends reflect the paradigm shift in favor of the circular economy and indicate a steel industry focused on innovation and efficiency to remain competitive amid the demands of a global market concerned with environmental issues. Brazil is aligned with the global movement in various stages of the steel cycle, mainly focusing on optimizing resource use and adopting processes that reduce emissions through technological innovation. Globally, especially in more developed countries, carbon market regulation, along with many projects, is in the pilot phase, supported by government financial backing to foster low-emission technologies. In Brazil, the adoption of renewable hydrogen and non-fossil charcoal in the mining and refining process stands out. However, the country faces specific challenges, such as waste management at less mature stages compared to the U.S. market, as well as the need for the creation of more effective public policies that boost the circular economy, contrasting with the global trend of intensifying the use of regenerated resources and sustainable regulatory policies.

Future research might propose a roadmap for Brazil that would be very relevant to guiding the main actions for the steel sector in the coming years. When considering directions for future research in this field, some areas of study might be particularly promising, as presented below:

Sustainable logistics in the steel industry: Given the commitment of major iron mining companies to reduce their carbon footprint, including the use of fossil fuels in their logistics, it is vital to develop more sustainable solutions. Research aimed at optimizing routes, improving the efficiency of trains and trucks, and incorporating clean energy sources can be very valuable in defining emissions across the entire chain (upstream and downstream).

Use of Brazilian siderurgical biomass: The use of biomass, particularly the use of charcoal in blast furnaces, represents a unique and sustainable practice in Brazil. Studies that delve deeper into the more representative implementation of this practice, exploring its differential in product quality, can reveal important insights for the competitiveness and sustainability of the sector. Comparing Brazilian practices with those of other markets and investigating successful international public policies and regulations is also advisable to identify models adaptable to Brazil.

Utilization of slag and steel waste: Interviews point to the existence of opportunities for the recovery of steel contained in steelmaking slag, suggesting that they are directed towards innovation in metal recovery and recycling processes, from waste that can lead to significant advances in the circularity of the sector.

Expansion of scrap use: Research on how to increase the use of scrap in primary route steel production, as well as exploring innovative technologies and processes for the secondary route, where scrap is the main metallic source, is essential to drive the circular economy.

Integration of renewable energies: Deepening the integration of renewable energies in steel production is fundamental, aiming to reduce CO2 emissions, including the potential of green hydrogen and ammonia, as well as carbon capture technologies, considering Brazil's more favorable energy matrix.

All these areas support technological and sustainable advancement in Brazil and contribute to global efforts to reduce emissions from climate change.

REFERENCES

ABCM. (2024). *Roadmap Brasil da construção modular*. https://bit.ly/3W9hduL

Allwood, J. M., Cullen, J. M., & Milford, R. L. (2010). Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environmental Science & Technology*, *44*(6), 1888-1894. https://doi.org/10.1021/es902909k

Andrade, M. L. A. D., Cunha, L. M. D. S., & Gandra, G. T. (2000). *A ascensão das mini-mills no cenário siderúrgico mundial*. BNDES.

Bataille, C., Stiebert, S., Hebeda, O., Trollip, H., McCall, B., & Vishwanathan, S. S. (2023). Towards net-zero emissions concrete and steel in India, Brazil and South Africa. *Climate Policy*, 1-16. https://doi.org/10.1080/14693062.2023.2187750

Bocken, N. M. P., Pauw, I., Bakker, C., & Van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308-320. https://doi.org/10.1080/21681015.2016.1172124

Branca, T. A., Colla, V., Algermissen, D., Granbom, H., Martini, U., Morillon, A. . . ., & Rosendahl, S. (2020). Reuse and recycling of by-products in the steel sector: Recent achievements paving the way to circular economy and industrial symbiosis in Europe. *Metals*, *10*(3). https://doi.org/10.3390/met10030345

Carmignano, O. R., Vieira, S. S., Teixeira, A. P. C., Lameiras, F. S., Brandão, P. R. G., & Lago, R., M. (2021). Iron ore tailings: Characterization and applications. *Journal of the Brazilian Chemical Society*, *32*(10), 1895-1911. https://doi.org/10.21577/0103-5053.20210100

Carvalho, D. (2024, 30 de Janeiro). What's next for green steelmaking technologies? *Woodmackenzie*. https://bit.ly/4d8MfJ4

Cavaliere, P. (2019). *Clean ironmaking and steelmaking processes: Efficient technologies for greenhouse emissions abatement*. Springer.

Cocchieri, T. (2008). *Criatividade em uma perspectiva estético-cognitiva* (Dissertação de Mestrado). Universidade Estadual Paulista "Júlio de Mesquita Filho", Marília, SP.

Comissão Europeia. (2015). Fechar o ciclo-plano de ação da UE para a economia circular. *Official Journal of the European Union*, *24*.

Corley, K. G., & Gioia, D. A. (2011). Building theory about theory building: What constitutes a theoretical contribution? *Academy of Management Review*, *36*(1), 12-32.

Dragt, E. (2017). *How to research trends: Move beyond trend watching to kickstart innovation*. Laurence King Publishing.

Fărcean, I., Proştean, G., & Socalici, A. (2023). Sustainable development indicators in the steel industry. *Journal of Physics: Conference Series*, *2540*(1). https://doi.org/10.1088/1742-6596/2540/1/012045

Graedel, T. E., Reck, B. K., Ciacci, L., & Passarini, F. (2019). On the spatial dimension of the circular economy. *Resources*, *8*(1). https://doi.org/10.3390/resources8010032

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European Union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765-777. https://doi.org/10.1111/jiec.12244

Hoon, C., & Baluch, A. M. (2020). The role of dialectical interrogation in review studies: Theorizing from what we see rather than what we have already seen. *Journal of Management Studies*, *57*(6), 1246-1271. https://doi.org/10.1111/joms.12543

IEA. (2020). *Iron and steel technology roadmap*. https://bit.ly/446QWz8

Instituto Aço Brasil. (2023). *Aço & sustentabilidade 2023*. https://bit.ly/3xICj99

IRENA. (2023). *Towards a circular steel industry*. https://bit.ly/3U6uRMr

Javaid, A., & Essadiqi, E. (2003). Final report on scrap management, sorting and classification of steel. *Natural Resources Canada*, *23*, 1-22. http://doi.org/10.13140/RG.2.2.29333.12003

Li, X., Chertow, M., Guo, S., Johnson, E., & Jiang, D. (2020). Estimating non-hazardous industrial waste generation by sector, location, and year in the United States: A methodological framework and case example of spent foundry sand. *Waste Management*, *118*, 563-572. https://doi.org/10.1016/j.wasman.2020.08.056

Lopez, G., Farfan, J., & Breyer, C. (2022). Trends in the global steel industry: Evolutionary projections and defossilisation pathways through power-to-steel. *Journal of Cleaner Production*, *375*. https://doi.org/10.1016/j.jclepro.2022.134182

MacArthur, E., & Heading, H. (2019). How the circular economy tackles climate change. *Ellen MacArthur Found*, *1*, 1-71.

McNulty, T., Zattoni, A., & Douglas, T. (2013). Developing corporate governance research through qualitative methods: A review of previous studies. *Corporate Governance: An International Review*, *21*(2), 183-198. https://doi.org/10.1111/corg.12006

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*. https://doi.org/10.1016/j.resconrec.2019.104553

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*, *260*. https://doi.org/10.1016/j.jclepro.2020.121134

Nogueira, I. M, & Madureira, M. T. (2022). A indústria siderúrgica no Brasil. *Research, Society and Development*, *11*(16). https://doi.org/10.33448/rsd-v11i16.38241

Pauliuk, S., Wang, T., & Müller, D. B. (2012). Moving toward the circular economy: The role of stocks in the Chinese steel cycle. *Environmental Science & Technology*, *46*(1), 148-154. https://doi.org/10.1021/es201904c

Rech, S. R. (2016). *A qualitative research on trends studies*. Artigo apresentado no III International Fashion and Design Congress, Buenos Aires.

Rech, S. R., & Maciel, D. M. H. (2015). *A proposal for prospective method based on grounded theory*. Artigo apresentado na XI International European Academy of Design Conference.

Reck, B. K., Müller, D. B., Rostkowski, K., & Graedel, T. E. (2008). Anthropogenic nickel cycle: Insights into use, trade, and recycling. *Environmental Science & Technology*, *42*(9), 3394-3400. https://doi.org/10.1021/es072108l

Reck, B. K., & Graedel, T. E. (2012). Challenges in metal recycling. *Science*, *337*(6095), 690-695. https://doi.org/10.1126/science.1217501

Spaulding, S. A., Irvin, L. K., Horner, R. H., May, S. L., Emeldi, M., Tobin, T. J., & Sugai, G. (2010). Schoolwide social-behavioral climate, student problem behavior, and related administrative decisions: Empirical patterns from 1,510 schools nationwide. *Journal of Positive Behavior Interventions*, *12*(2), 69-85. https://doi.org/10.1177/1098300708329011

Thomas, J. S., & Birat, J. P. (2013). Methodologies to measure the sustainability of materials: Focus on recycling aspects. Revue de Metallurgie. *Cahiers D'Informations Techniques*, *110*(1), 3-16. https://doi.org/10.1051/metal/2013054

Wang, P., Ryberg, M., Yang, Y., Feng, K., Kara, S., Hauschild, M., & Chen, W. Q. (2021). Efficiency stagnation in global steel production urges joint supply-and demand-side mitigation efforts. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-22245-6

WSA. (2021). *Climate change and the production of iron and steel*. https://bit.ly/4b6k4sD

WSA. (2023a). *Circular economy/steel: The permanent material in the circular economy*. https://worldsteel.org/circular-economy/

WSA. (2023b). *Sustainability indicators 2023 report*. https://bit.ly/3QaJMEj

WSA. (2023c). *World Steel in Figures 2023*. https://bit.ly/4b3aWEX

Xiao, Y., Ma, D., Zhang, F., Zhao, N., Wang, L., Guo, Z., ... & Xiao, Y. (2023). Spatiotemporal differentiation of carbon emission efficiency and influencing factors: From the perspective of 136 countries. *Science of the Total Environment*, *879*. https://doi.org/10.1016/j.scitotenv.2023.163032

Yuan, S., Zhang, Q., Yin, H., & Li, Y. (2021). Efficient iron recovery from iron tailings using advanced suspension reduction technology: A study of reaction kinetics, phase transformation, and structure evolution. *Journal of Hazardous Materials*, *404*. https://doi.org/10.1016/j.jhazmat.2020.124067