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Statistics and sustainability in the iron and steel industry: from resources to low-carbon technologies

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ABSTRACT

Iron and steel are indispensable materials in modern civilization, enabling key sectors such as construction, transportation, and energy. However, the iron industry faces growing challenges related to uncertain resources, environmental limitations aimed at decreasing carbon footprints, and the rising demand for sustainable manufacturing practices. The industry accounts for approximately 7–9% of global CO_2 emissions, underscoring the urgent need for technological innovation and policy-driven decarbonization strategies. This review gathers current statistics on global iron ore reserves, prices, production of various steel grades, and emerging production routes. Additionally, it addresses best available technologies (BAT), the potential impact of CO_2 taxes, and alternative reduction processes like hydrogen-based metallurgy. A comprehensive overview of these aspects will assist stakeholders in improving economic competitiveness, resource efficiency, and environmental sustainability.

Keywords: Iron and steel production; iron ore; carbon footprint; CO_2 taxes; best available technologies (BAT); sustainable development of the iron and steel industry.

1. Introduction

Iron and steel have been the foundation of technological development for centuries, supporting everything from infrastructure projects to advanced mechanical systems. Combination of strength, ductility, and cost-effectiveness has ensured a persistent demand for iron and steel worldwide. As a critical input for multiple industries, iron's economic significance and societal impact make it one of the most important materials of the modern age.

Despite its acknowledged role, the iron industry faces numerous challenges today. Fluctuating iron ore prices and quality, uncertainty in global distribution of reserves, and rising energy costs strain traditional production routes. Additionally, environmental concerns—particularly carbon emissions—have prompted stricter regulations, such as CO_2 taxes, and a growing push for cleaner, more sustainable processes.

The objective of this review is to offer a thorough examination of the present state of the iron industry, which covers global ore reserves, pricing mechanisms, and production trends for both raw iron and specialized steel types. The other objective is to make an overview of best available technologies (BAT) in iron and steel manufacturing, analyze the role of CO_2 taxes, and discuss new and emerging production methods—particularly those utilizing hydrogen or other environmentally friendly alternatives (Zhang et al. 2024). This overview and data provide a current image of the iron industry with the aim of understanding and shaping the future of iron production.

2. Global Iron Ore Production and Market Trends (2008–2024)

Iron ore, as a main source of steel production, has undergone transformative shifts over the past 15 years, driven by industrialization, geopolitical dynamics, and sustainability imperatives. It is the essential raw material for steelmaking, supporting industries from construction and infrastructure to automotive and manufacturing worldwide. Since the late 2000s, iron ore markets have been shaped by increasing demand from Asia—particularly China—alongside significant expansions by major mining companies in Australia and Brazil (Figure 1).

Australia and Brazil have solidified their positions as cornerstones of the global iron ore supply. In Australia's Pilbara region, rich hematite reserves and large-scale investments by BHP, Rio Tinto, and Fortescue Metals Group elevated production from 342 million metric tons (Mt) in 2008 to 953 Mt in 2023. Australia, with ores containing an average of 61–62% iron (Fe), utilized advanced facilities and economies of scale to dominate shipping, representing 37% of global exports by 2024 (Yellishetty et al. 2022, Wang et al. 2023, USGS 2025).

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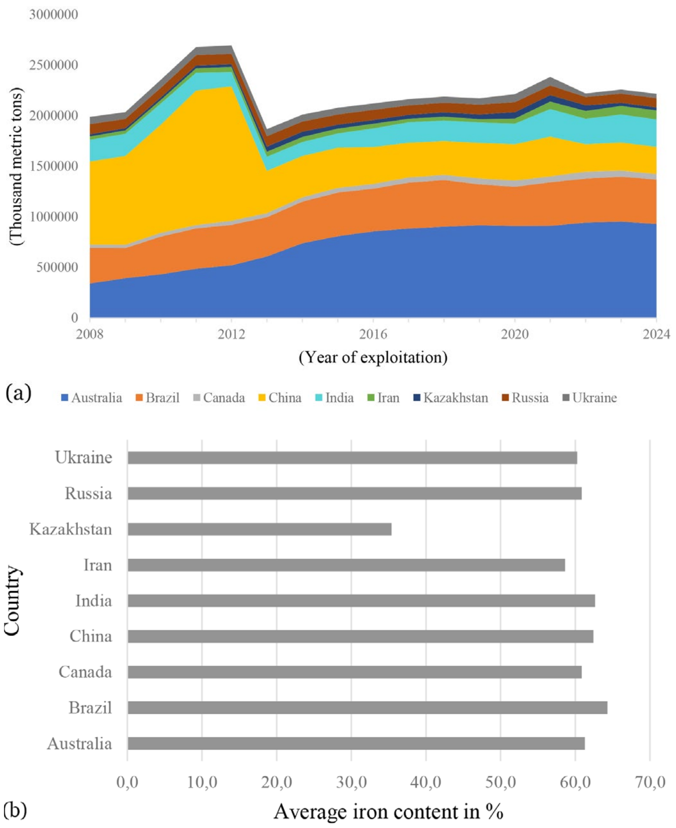

Fig. 1. (a) Exploitation of iron ore of the world's leading countries (more than 90% of world production), and (b) average iron content in these ores (China calculated from 2013)

Brazil followed closely, with output rising from 350 Mt in 2008 to 445 Mt in 2023, stationed by Vale's Carajás mining operations. These high-grade deposits containing 63–65% Fe offered a competitive edge, although production faced sporadic disruptions after the 2015 Samarco and 2019 Brumadinho (both in the state of Minas Gerais, Brazil) tailings dam failures (Primo et al. 2021). These events not only triggered stricter international standards for tailings management but also temporarily limited Brazil's exports by about 10% in 2019, without significantly hindering the longer-term recovery of its capacity (USGS 2025).

China, the world's largest steel producer, historically reported "crude ore" production exceeding 1.3 billion tons (Bt) in 2012. China's iron ore reserves, estimated at 20 Bt by the US Geological Survey (USGS), or more than 70 Bt according to the Chinese Geological Survey, are predominantly low grade. Raw iron ore mined material with highly variable iron (Fe) content, often averaging between 30% and 34.5%, making it an unreliable metric for assessing actual steelmaking potential. Unlike major iron ore-producing countries such as Australia and Brazil, where high-grade hematite dominates, China's iron ore deposits are characterized by low-grade ores, including magnetite, vanadium-titanium (V-Ti) magnetites, limonite, siderite, and polymetallic formations (averaging around 30–33% Fe) (Holmes et al. 2022). Even with beneficiation, much of the ore mined domestically struggles to compete with high-grade seaborne imports. Given these structural limitations, China has aggressively pursued beneficiation and technological innovations in ore processing. Integrated mining and beneficiation plants, particularly in key iron ore provinces such as Hebei, Liaoning, and Sichuan, employ techniques such as low-intensity magnetic separation (LIMS) for magnetite recovery, wet high-intensity magnetic separation (WHIMS) for hematite, and flotation methods for separating iron minerals from gangue. In the case of V-Ti magnetites, beneficiation plants recover vanadium and titanium alongside iron, reflecting China's approach to maximizing resource utilization (Figure 2). By 2013, recognizing the need for a more accurate representation of its domestic iron ore supply, the China Iron and Steel Association (CISA) revised its reporting standards to focus on "usable ore," defined as beneficiated concentrates with higher Fe content. That year, CISA estimated that the average Fe grade of China's usable iron ore had reached 61.8%, accounting for approximately 98% of its total reported output (USGS 2025). Nevertheless, Chinese steel mills continued to rely on imported ores for around 70% of their needs by 2024, with Australia and Brazil together supplying over 80% of those imports (USGS 2025). This heavy reliance on foreign supply chains has exposed China's steel industry to price volatility, trade tensions, and logistical disruptions.

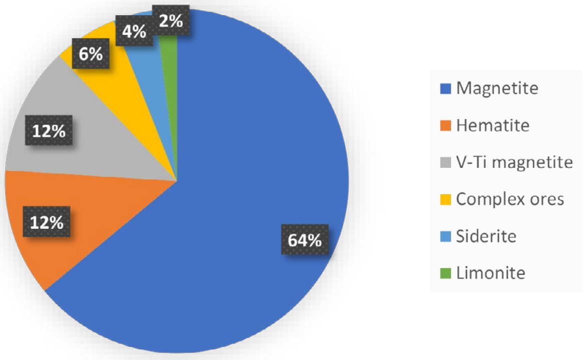

Fig. 2. Distribution of various iron ore types within China's confirmed reserves (Holmes et al. 2022).

India has emerged as a significant iron ore producer, with output fluctuating due to shifting mining policies and regulatory constraints. By 2024, production stabilized at around 270 Mt, primarily from hematite-rich reserves in Odisha, Chhattisgarh, Karnataka, and Jharkhand (USGS 2025). While India is largely self-sufficient in iron ore, its high-grade reserves are depleting, necessitating the exploration of lower-grade ores and advanced beneficiation techniques. The country's deposits predominantly consist of Banded Hematite Quartzite (BHQ) and Banded Hematite Jaspilite (BHJ), with some magnetite resources in ecologically sensitive areas, restricting large-scale exploitation. State-owned entities like the National Mineral Development Corporation (NMDC) and Steel Authority of India (SAIL), alongside private firms such as Tata Steel and Jindal Steel, dominate the sector (Holmes et al. 2022). To preserve domestic resources, India has imposed a 30% export duty on high-grade iron ore, curbing shipments and prioritizing local steel production. Despite its resource base, iron ore imports, particularly pellets, have risen in recent years to support growing domestic demand. Meanwhile, smaller global producers, including Sweden's LKAB, have capitalized on high-grade magnetite concentrates (66–71% Fe), which are increasingly valued for hydrogen-based direct reduction (USGS 2025).

Russia, with its vast iron ore deposits and access to low-cost natural gas, is also positioned to develop low-carbon steel production hubs as the industry shifts toward cleaner technologies. The country holds an estimated 25 Bt of crude iron ore reserves, containing approximately 14 Bt of iron, with nearly 60% concentrated in the Kursk Magnetic Anomaly in European Russia. This region, home to some of the world's largest iron ore deposits, accounts for over half of Russia's production, with additional contributions from the Urals and Siberia. In 2019, Russia produced 97.5 Mt of usable iron ore, ranking as the world's fifth-largest producer. Production was expected to reach 115 Mt annually by 2020, driven by increased investment in mining and beneficiation capacity (Holmes et al. 2022).

2.1. Market Dynamics: Pricing, Grades, and Sustainability

The iron ore market transitioned from annual benchmark pricing to index-linked mechanisms post-2010, amplifying price volatility. Historically, iron ore was traded through long-term contracts, but the introduction of spot pricing mechanisms and financial derivatives markets has accelerated price fluctuations. The Platts IODEX 62% Fe index has exhibited extreme volatility in recent years, which was $39 per tonne in December 2015, reaching $218 per ton in mid-2021 due to strong post-pandemic recovery, before stabilizing around $120 per ton in late 2023 (Figure 3) (Pan et al., 2024).

Market fluctuations have disproportionately impacted lower-grade iron ore producers, particularly those supplying ores with 58–62% Fe, as prices frequently drop below $100 per ton, compressing profit margins. In contrast, high-grade iron ores (>62% Fe) continue to command a price premium of 5–10%, reflecting their superior efficiency in blast furnace operations and lower carbon emissions per ton of steel produced (USGS 2024; World Steel Association 2022; EUROFER 2024, European Commission 2024). The iron ore futures markets have also grown in importance, providing price discovery and hedging options for major producers and buyers.

Fig. 3. Prices for iron ore with a 62% iron content from 2010 (Trading Economics 2025)

Regulatory and environmental factors have reshaped iron ore production, with significant policy-driven shifts toward sustainability and safety. The Global Tailings Review, initiated in response to catastrophic tailings dam failures in Brazil, established stricter standards, requiring comprehensive risk assessments and emergency response plans for tailings management worldwide (EUROFER 2019). Compliance with these regulations has increased operational costs for mining companies but has also improved industry resilience.

Decarbonization policies have driven demand for high-purity ores that facilitate low-carbon steelmaking. Sweden's HYBRIT project, a collaboration between SSAB, LKAB, and Vattenfall, exemplifies this shift by pioneering the use of hydrogen-based direct reduction (H-DRI) as a substitute for coal in steel production. This transition is supported by the availability of high-grade DR-grade pellets (67% Fe) sourced from LKAB. Similarly, Vale has introduced "green briquettes" (63% Fe), designed to reduce carbon emissions in blast furnace operations, aligning with the EU's Carbon Border Adjustment Mechanism (CBAM) and China's stricter emissions caps, which prioritize low-impurity ores (European Commission 2024).

2.2. Geopolitical Risks, Supply Chain Vulnerabilities, and Future Perspectives

The COVID-19 pandemic underscored iron ore's critical role in economic resilience. China's infrastructure stimulus propelled imports to 1.12 Bt in 2021, revitalizing Australian and Brazilian exports. Global geopolitical conflicts, particularly the Russia-Ukraine war, have exacerbated supply chain disruptions, impacting mineral trade flows and price stability. The World Bank reported a 15.8% increase in iron ore prices in response to heightened market uncertainty and trade restrictions (OECD, 2022; World Bank, 2022). However, the post-2022 slowdown in China's property sector, coupled with global inflation and energy crises, moderated demand growth. The World Steel Association projects global steel demand to rise by just 1.9% annually through 2025, a stark contrast to the 5–7% growth rates of the mid-2000s (USGS 2025, Ayaaba 2024). China, the world's largest steel producer, remains highly dependent on iron ore imports, sourcing 83% of its iron ore from Australia and Brazil, with 66% coming from Australia alone. This reliance exposes China to supply disruptions, prompting research into the economic and environmental implications of a large-scale import shortage (Jiang et al., 2024).

Employing predictive models Jiang et al. determined that a significant deficit in iron ore imports could lead to a 5.6% decline in China's GDP by 2035, accompanied by a 9.9% decrease in carbon emissions resulting from reduced industrial activity. While increasing domestic mining and reducing steel import tariffs could mitigate economic impacts, these measures would be most effective when combined with carbon pricing mechanisms to maintain environmental targets (Jiang et al., 2024).

Governments and industry stakeholders are implementing strategic responses to ensure supply security and environmental compliance. The EU's Green Deal Industrial Plan and U.S. Inflation Reduction Act offer financial incentives for low-emission steelmaking technologies, while global forums, such as the OECD Global Forum on Steel Excess Capacity, seek to harmonize carbon pricing policies to prevent market fragmentation. Conversely, the recent introduction of U.S. tariffs on steel and aluminum has affected worldwide market volatility, resulting in a more than 15% increase in U.S. steel prices within two weeks and disrupting supply chains for companies dependent on these materials. Moreover, the U.S. exit from the Paris Agreement, combined with these policies, has caused regulatory and pricing inequalities among key steel-producing countries, affecting global competitiveness.

Eventually, forthcoming production will rely on sustainability and cost-effectiveness. Operators in Australia's Pilbara decreased operating expenses by 15% through the implementation of autonomous haulage systems and digital twin technologies, whereas Brazil emphasized "dry processing" techniques to reduce tailings. Meanwhile, Guinea's Simandou deposit, slated to produce 60 Mt/year by 2028, promises to diversify supply chains but faces logistical challenges, including a 650 km railway through ecologically sensitive regions (USGS 2025).

2.3. Gangue Elements in Iron Ore

The presence of elevated gangue content in iron ore significantly impacts the efficiency and environmental footprint of steel production. Gangue minerals, such as silica (SiO_2), alumina (Al_2O_3), and phosphorus (P), are non-ferrous components that, when present in higher concentrations, necessitate additional processing to remove impurities (MacRae et al. 2011). This leads to increased energy consumption, higher CO_2 emissions, and elevated production costs. Moreover, the accumulation of gangue results in greater slag volumes during smelting, which can adversely affect furnace productivity and the quality of the produced steel (Oh et al. 2020).

Globally, Australia and Brazil are the leading sources of iron ore. However, the quality of iron ore from these sources has been declining, with increasing levels of gangue components over the years. This trend is partly due to the depletion of high-grade reserves and the necessity to exploit lower-grade deposits to meet global demand (Roy et al. 2020). Similarly, the mineral phase composition of iron ore significantly influences the economic efficiency of iron production. Ore's rich in hematite and magnetite are highly required after due to their elevated iron content, which enhances blast furnace productivity and reduces energy consumption (IEA 2020, Mochizuki and Tsubouchi 2019). The presence of SFCA (silico-ferrite of calcium and aluminum) phases, which influence the strength and reducibility of the sinter, was found to depend on the basicity and alumina content. The positions of metallic atoms in SFCA are determined by the substitution reaction $2(Fe^{3+}, Al^{3+}) \leftrightarrow (Ca^{2+}, Fe^{2+}) + Si^{4+}$, with variations in Fe and Si occupancy affecting its structural characteristics and, consequently, the performance of the sintered ore in ironmaking processes (Yellishetty et al. 2010, Park et al. 2020).

A detailed study on phosphorus incorporation in goethite-rich iron ores has highlighted the complexity of impurity distribution, particularly in Australian deposits. The findings indicate that goethite is the principal host of phosphorus, often associated with elevated levels of aluminum and silicon. This observation led to the proposal of a coupled substitution mechanism: two silicon ions (Si^{4+}) are replaced by one phosphorus ion (P^{5+}) and one aluminum ion (Al^{3+}) within the goethite structure (Mochizuki and Tsubouchi 2019).

Several mineral processing techniques have been developed to enhance ore quality by removing gangue minerals such as silica, alumina, and phosphorus. Conventional methods such as gravity concentration, magnetic separation, and flotation exploit differences in density, magnetic susceptibility, and surface chemistry between iron oxides and impurities. More complex ores, where gangue minerals are finely interlocked with iron phases, often require alternative beneficiation strategies. Thermal treatments, including reduction roasting, can convert goethite and hematite into magnetite, facilitating downstream magnetic separation (Su et al. 2023). Additionally, emerging techniques such as ultrasonic pre-treatment and magnetic carrier technology have demonstrated potential in improving liberation and impurity removal (Roy et al. 2020). Depending on the iron ore type, studies demonstrated effective removal of Si, Al, and P that ranged at 10–92%, 38–70%, and 37–78% . This process enhances the Fe content of the ore, thereby improving its economic value and suitability for steel production (Mochizuki and Tsubouchi 2019). Additionally, the composition of gangue affects the melting behavior of iron ore during smelting. Studies have shown that variations in gangue composition can alter the fluidity of slag, influencing the melting separation temperature and time of iron ore–coal composite pellets (Zhang et al. 2019).

The composition of iron ore significantly influences the efficiency and environmental impact of Direct Reduced Iron (DRI) production, a method gaining prominence for its potential to reduce CO_2 emissions in steelmaking. Utilizing high-quality iron ore with minimal impurities is essential for optimizing the DRI-EAF route's energy efficiency and environmental benefits. Impurities such as phosphorus necessitate increased lime addition during steelmaking to facilitate dephosphorization, leading to higher CO_2 emissions due to the calcination of limestone. Additionally, elevated gangue content in the ore results in increased slag formation, which in turn escalates energy consumption within the electric arc furnace (EAF) as more heat is required to melt the additional slag volume. Therefore, careful selection and beneficiation of iron ore are crucial steps in minimizing impurities, thereby enhancing energy efficiency and reducing the carbon footprint of steel production via the DRI-EAF route (Zhang et al. 2019, Oh et al. 2020).

3. Iron and Steel Production Overview

3.1. *Major Global Producers*

The global production of crude steel has displayed significant regional trends over the last decade, reflecting the unique industrial, economic, and technological trajectories of different parts of the world. EU27, once a global leader in steel production, has seen a marked decline in output (Figure 4). This trend is mirrored across many other European nations, as well as in the CIS (Commonwealth of Independent States, Russia and Ukraine in particular), North America, and South America (Figure 4). Stricter environmental regulations, aging industrial infrastructure, and shifts toward greener technologies have led to a reduced emphasis on traditional steel production. Countries like Germany, Italy, France, and Spain exemplify this trend, as their outputs have diminished steadily, despite occasional peaks. Rather than focusing on sheer volume, European steelmakers are now prioritizing high-value and sustainable steel production, accelerating the transition from conventional Blast Furnace/Basic Oxygen Furnace (BF-BOF) steelmaking to hydrogen-based direct reduction (H-DR) and electric arc furnaces (EAF). By 2030, with appropriate carbon pricing mechanisms, green steelmaking is expected to become cost-competitive, making investment decisions in this decade crucial for the future of the European steel industry (Lopez et al. 2023, Boldrini et al. 2024).

This transition affects regions beyond Europe, as steel supply chains adapt to the changing cost dynamics of low-carbon steel manufacturing. Hydrogen production costs remain a key determinant of competitiveness, and while H_2 from Morocco and Chile is expected to be more affordable than European production, high transportation costs favor localized hydrogen use. However, importing hot briquetted iron (HBI) from North Africa could leverage the region's low hydrogen costs while ensuring the viability of European EAFs. Such a strategy could also raise industrial development in the Global South, where growing H-DR capacities may position emerging economies as key players in the future green steel market.

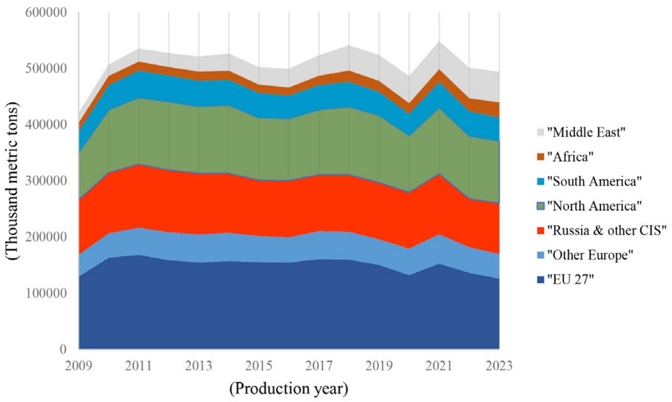

Fig. 4. Production of crude steel in: EU27, Other Europe, Russia and other CIS, North America, South America, Africa, and Middle East (WSA 2025)

Middle East and Africa show opposite trends to Europe, with crude steel production on the rise (Figure 4). In the Middle East, countries like Iran and Saudi Arabia have dramatically expanded their production capacity, supported by investments in industrial diversification and infrastructure development. Africa, though producing far less than other regions, has seen significant growth led by nations like Egypt, Kenya, and Algeria, where increased urbanization and industrialization drive demand. As the EU increasingly sources green steel from North Africa, these regions could further integrate into global steel supply chains, accelerating their own industrial and energy transitions.

Asia, however, continues to dominate global steel production, led by China, India, and emerging nations like Indonesia and Vietnam (Figure 5). India's rapid industrialization and infrastructure expansion have propelled a remarkable rise in crude steel output, reflecting its broader economic progress and deeper integration into global manufacturing. Similarly, Vietnam and Indonesia have seen strong growth, driven by rising regional demand for steel amid urbanization and industrialization. Japan and South Korea, while still major producers, have largely maintained steady production levels, focusing instead on advanced steel products and high-value manufacturing (Figure 5). Notably, as Europe moves toward hydrogen-based steelmaking, South Korea and Japan are also exploring similar pathways, potentially positioning themselves as future leaders in low-carbon steel.

China maintains to dictate global trends in steel production, accounting for more than half of the world's crude steel output (Figure 6). Its enormous increase in production aligns closely with its economic trajectory, marked by large-scale infrastructure development, urbanization, and industrial expansion. As China's steel production sets the pace for the global market, the world steel industry reflects the broader story of China's unprecedented economic transformation and its integral role in global supply chains. This dominance underscores the nation's influence not only on the steel market but also on the broader global economy.

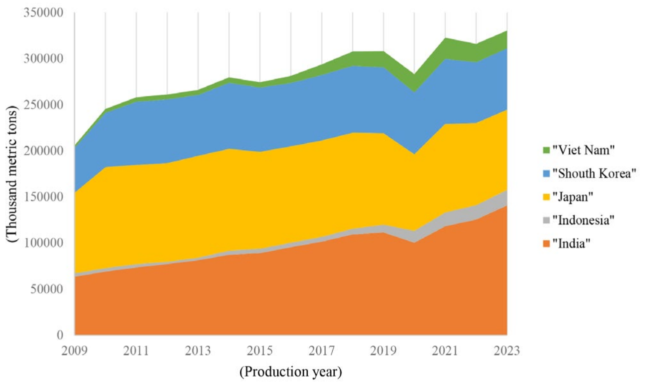

Fig. 5. Production of crude steel in major Asian countries (WSA 2025)

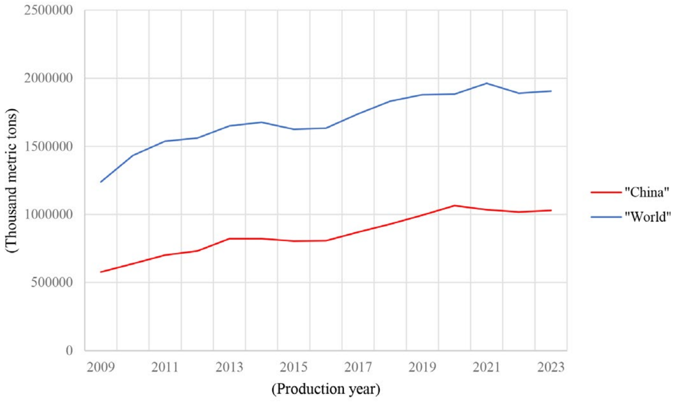

Fig. 6. Comparation of China and World crude steel production (WSA 2025)

3.2. Trends in Production of Specialized Steel Grades

Cost-Effective Alloy Design Optimization of Structural Steels

Optimizing alloy composition in structural steel manufacturing can yield significant cost savings while maintaining or improving mechanical properties. The strategic adjustment of basic elements—carbon (C), manganese (Mn), and silicon (Si)—alongside microalloying elements such as niobium (Nb) and vanadium (V), can lead to substantial reductions in alloying costs. Depending on the scale of production, cost savings can range from $2 to $20 per ton, translating to annual savings of $400,000 to $20 million for steel mills producing between 200,000 and 1 million tons annually (Rodriguez-Ibabe et al. 2020, Stalheim et al. 2018).

The metallurgical mechanisms contributing to strength and ductility in structural steels include:

- Grain size refinement,
- Solid solution strengthening, and
- Precipitation hardening.

By engineering these mechanisms more effectively within a mill's processing capabilities, alloy costs can be minimized while maintaining process stability, reducing yield losses, and improving mechanical properties.

For instance, reducing manganese content by 0.30–0.50% while adding a dilute amount of 0.010% Nb can lower production costs by $1.31–4.59 per ton. Structural mills producing lower-strength grades such as S235, S275, and S355 could achieve annual savings of up to $2.3 million. A similar approach can replace or minimize vanadium (V) by using minor additions of niobium (Nb), further optimizing costs (Varanasi et al. 2022).

Beyond direct material savings, alloy optimization improves inventory management, yield performance, and overall process efficiency, highlighting its essential role in the evolving steel production landscape.

Microalloyed Steels

Microalloyed steels have evolved significantly over the past century, driven by the demand for stronger, lighter, and more cost-effective materials (Villalobos et al., 2018). Initially developed for oil and gas pipelines, these steels now play a critical role in automotive, infrastructure, and heavy industrial applications.

Microalloyed steels combine high strength and ductility through controlled additions of elements like niobium (Nb), titanium (Ti), and vanadium (V) (Sun et al. 2022, Chen et al. 2024). Thermomechanical processing (TMP) and controlled cooling further refine their microstructures, enhancing properties such as toughness and weldability. Recent advancements have focused on achieving martensite–bainite microstructures with acicular ferrite, particularly for hydrogen-rich environments where steel corrosion and embrittlement are concerns.

The push for high-strength low-alloy (HSLA) steels has led to significant improvements in mechanical performance while minimizing alloying costs. HSLA steels generally contain low carbon content (0.05–0.25%) and small amounts of strengthening elements such as Mn (up to 2%), Cr, Mo, Cu, and Ni. The American Petroleum Institute (API) classifies these steels based on strength levels (e.g., X-42 to X-120).

Key advancements in HSLA steels include:

- Weathering steels, which incorporate small amounts of Cu and Cr for corrosion resistance.
- Microalloyed ferrite-pearlite steels, strengthened via precipitation hardening using V and Ti.
- Acicular ferrite steels, which offer improved toughness and hydrogen resistance.
- Dual-phase steels, designed with a ferrite-martensite matrix to balance strength and ductility.

Controlled microstructure refinement is essential to achieve these properties (Küçükakarsu et al. 2022). Microalloying elements influence critical phase transitions, such as the grain coarsening temperature, recrystallization temperature, and transformation temperature during cooling. Table 1 summarizes the primary effects of microalloying elements in steel production.

Future Trends in Microalloyed Steel Production

The future of microalloyed steels will be shaped by advances in computational metallurgy (artificial intelligence, machine learning techniques coupled by metallurgical knowledge, rolling technology, and process control. Predictive metallurgical models allow for more precise control over microstructure evolution, ensuring optimal mechanical properties while reducing energy consumption and material costs (Manojlovic et al. 2022, Küçükakarsu et al. 2022).

Key trends expected to drive the next generation of microalloyed steels include:

- Integration of advanced modeling tools to optimize alloy design and processing parameters.
- Increased use of artificial intelligence (AI) and machine learning to refine thermomechanical processing strategies.
- A shift toward hydrogen-based steelmaking (H-DR-EAF) to reduce carbon emissions while maintaining high-performance material properties.
- Greater emphasis on resource conservation, yield improvement, and lightweight steel designs for automotive and aerospace applications.

Microstructure control will remain central to these developments, ensuring that future steels meet the demands of emerging applications while aligning with sustainability goals.

Table 1. Principal effects of microalloyed elements (Baker 2016)

Element	wt %	Effect
C	<0.25	Strengthener
Mn	0.5–2.0	Retards the austenite decomposition during accelerated cooling; Decreases ductile to brittle transition temperature; Strong sulfide former
Si	0.1–0.5	Deoxidizer in molten steel; Solid solution strengthener
Al	<0.02	Deoxidizer; Limits grain growth as aluminum nitride
Nb	0.02–0.06	Very strong ferrite strengthener as niobium carbides/nitrides; Delays austenite-ferrite transformation
Ti	0–0.06	Austenite grain control by titanium nitrides; Strong ferrite strengthener
V	0–0.10	Strong ferrite strengthener by vanadium carbonitrides
Zr	0.002–0.05	Austenite grain size control; Strong sulfide former
N	<0.012	Strong former of nitrides and carbonitrides with microalloyed elements
Mo	0–0.3	Promotes bainite formations; Ferrite strengthener
Ni	0–0.5	Increases fracture toughness
Cu	0–0.55	Improves corrosion resistance; Ferrite strengthener
Cr	0–1.25	In the presence of copper, increases atmospheric corrosion resistance
B	0.0005	Promotes bainite formation

4. Environmental and Regulatory Aspects

Global CO2 emissions trends since 2019 highlight both resilience and vulnerability within the global energy transition. While the expansion of clean energy infrastructure has moderated the rate of emissions growth, systemic dependencies on fossil fuels—particularly in industrial and power generation sectors—continue to impede progress toward Paris Agreement targets. Absent immediate and coordinated global action, the window to limit warming to 1.5 °C will close irreversibly, emphasizing the urgent need for sector-wide transformative measures. Following a transient decline during the COVID-19 pandemic (2020), emissions rebounded sharply in 2021, reaching 36.3 gigatonnes (Gt) and exceeding pre-pandemic levels. This rebound was fueled by rapid economic recovery, energy market volatility, and heightened coal consumption, which offset record renewable energy deployment. By 2023, energy-related emissions climbed to a historic peak of 37.4 Gt, reflecting persistent structural dependencies on fossil fuels despite accelerating clean energy transitions (IEA 2024). Despite progress in renewable energy and efficiency improvements, global CO2 emissions from the steel industry remain a major challenge. While advanced economies are making strides in decoupling economic growth from emissions, the steel sector's transition to a low-carbon future depends on international collaboration, technological innovation, and stringent regulatory measures. The pace of change will determine whether the industry can align with global climate goals and contribute meaningfully to emissions reduction efforts (IEA 2022, 2023, 2024, 2025).

The post-2020 rebound was marked by divergent regional trends. Advanced economies, including the European Union and the United States, achieved structural emissions reductions through coal phase-outs, renewable energy integration, and industrial decarbonization policies. Conversely, emerging economies such as China and India experienced significant emissions growth, driven by coal-reliant energy systems, industrial expansion, and climate-induced disruptions to hydropower. China alone accounted for 565 Mt of the global increase in 2023, with per capita emissions now surpassing those of advanced economies. However, China's steel industry—a major contributor to its emissions—has been actively pursuing decarbonization strategies through a phased technological transition. These efforts include improving blast furnace-basic oxygen furnace (BF-BOF) efficiency, experimenting with non-blast furnace alternatives, and preparing for large-scale hydrogen-based metallurgy. Industrial-scale low-carbon technologies, such as the Baowu HyCORF process, gas-based direct reduction shaft furnaces, and CO2-enhanced converters, demonstrate China's commitment to achieving long-term carbon neutrality despite its current emissions trajectory (Pang et al., 2024, Zhang et al. 2022).

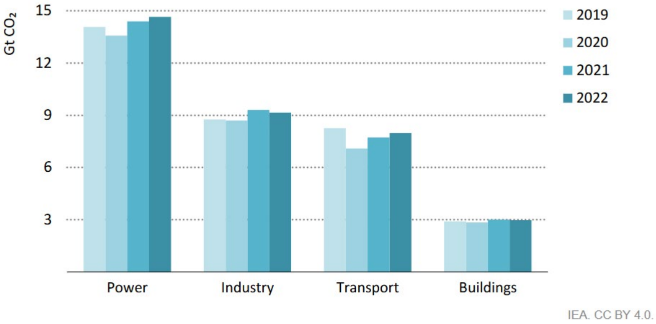

Fig. 7. Global CO_2 emissions by sector, 2019-2022 (IEA 2023)

The power sector remains the largest emissions contributor, exceeding 14 Gt in 2022 (Figure 7). Coal-fired generation rebounded post-2020, particularly in Asia, to meet surging electricity demand exacerbated by extreme weather and supply chain disruptions. While renewables mitigated approximately 550 Mt of potential emissions in 2022, fossil fuels still dominate the global energy mix.

Industrial emissions, led by steel and cement production, stabilized near pre-pandemic levels by 2022 (Figure 7). China's industrial sector briefly reduced emissions through coal-use restrictions and manufacturing slowdowns, but global decarbonization efforts in heavy industry remain incremental. The transport sector saw emissions recover to 2019 levels by 2022, driven by rebounding aviation and road freight activity. Electric vehicle adoption and efficiency gains partially offset this growth, yet oil demand continues to rise.

The steel industry exemplifies the tension between economic growth and emissions reduction. While advanced economies are decoupling production from emissions via hydrogen-based direct reduction and carbon capture technologies, emerging economies face structural barriers, including reliance on coal-fired blast furnaces and limited access to green financing. The 2022 energy crisis further complicated progress, as nations temporarily reverted to coal amid natural gas shortages, elevating coal-related emissions to a record 15.5 Gt. Notably, clean energy deployment has begun to temper emissions growth. In 2023, renewables and electrification prevented an estimated 700 Mt of CO2 emissions globally. Europe's emissions fell to 1960s levels, demonstrating the viability of policy-driven transitions. However, achieving net-zero targets requires unprecedented scaling of low-carbon infrastructure, grid modernization, and international cooperation to address disparities in technological adoption.

Figure 8 presents a historical overview of global energy-related CO2 emissions from 1900 to 2023, illustrating both the long-term trend and the annual variations in emissions (IEA 2024). The upper graph shows a continuous rise in emissions over the past century, with a particularly steep increase from the mid-20th century onward, reflecting rapid industrialization, economic expansion, and fossil fuel dependency. The most significant acceleration occurred after World War II, aligning with global economic growth, urbanization, and energy demand surges. Despite brief slowdowns during economic downturns and crises, emissions have consistently followed an upward trajectory, reaching a new record high of approximately 37.4 Gt in 2023. The lower bar chart captures annual changes in CO2 emissions, highlighting periods of rapid growth and occasional declines. The most notable drop occurred in 2020 due to the COVID-19 pandemic, which led to widespread economic shutdowns and reduced energy consumption. However, the strong rebound in emissions in 2021 and continued increases in subsequent years underscore the challenges of achieving sustained emissions reductions. The recent years show a structural slowdown in emissions growth compared to previous decades, driven by the increasing adoption of clean energy technologies, energy efficiency improvements, and policy measures aimed at reducing carbon intensity. However, emissions remain at historically high levels, and the continued reliance on coal and fossil fuels, particularly in emerging economies, indicates that deep decarbonization efforts are still needed.

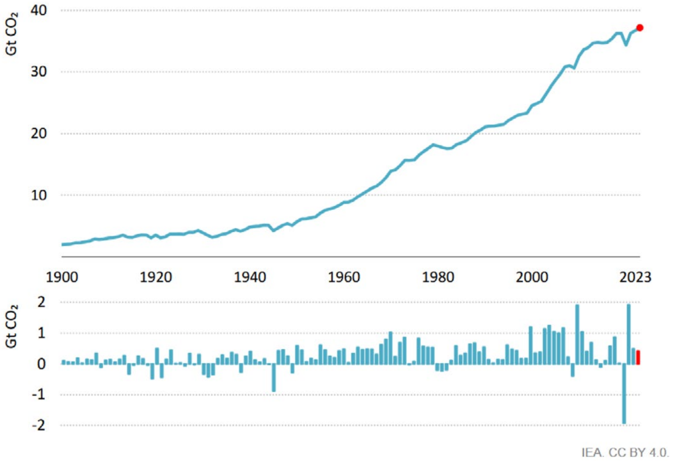

Fig. 8. Global energy-related CO$_2$ emissions and their annual change, 1900-2023 (IEA 2024)

The steel industry is responsible for approximately 7–9% of global CO2 emissions. This substantial impact has prompted the implementation of various regulatory frameworks and the adoption of circular economy practices to drive decarbonization efforts within the sector. Carbon pricing mechanisms, such as CO2 taxes and emissions trading schemes (ETS), have emerged as critical tools to incentivize decarbonization. The European Union's Emissions Trading System (EU ETS), for instance, imposes escalating costs on steelmakers for each ton of CO2 emitted, while the Carbon Border Adjustment Mechanism (CBAM) seeks to level the playing field by taxing imports based on their embedded carbon (Hasanbeigi et al. 2025, Shuai et al. 2024). These policies aim to mitigate carbon leakage—where production shifts to regions with laxer regulations—and accelerate investments in low-carbon technologies like hydrogen-based direct reduction (H-DRI) and carbon capture, utilization, and storage (CCUS). In China, the national ETS initially excluded steel but is expected to expand coverage by 2025, reflecting growing regulatory urgency (European Commission 2024; World Steel Association 2022).

Complementary policies, such as the EU's Innovation Fund and the U.S. Inflation Reduction Act, provide subsidies for green steel projects, while stricter emissions standards (e.g., EPA's New Source Performance Standards) mandate operational upgrades. Internationally, the Paris Agreement's Sectoral Decarbonization Approach emphasizes sector-specific targets, urging steel producers to adopt science-based pathways (IEA 2020; Wang and Li 2021). Circular economy strategies further underpin sustainability efforts. Steel's inherent recyclability—global scrap recycling rates exceed 85%—positions it as a leader in material efficiency. Electric arc furnaces (EAFs), which use scrap as feedstock, emit 70–80% less CO2 than traditional blast furnaces. However, maximizing the benefits of steel recycling necessitates robust policy support, including standardized scrap certification systems and incentives for secondary steel production (Ellen MacArthur Foundation 2024; Wang and Li 2021).

Despite progress, challenges persist. In developing economies, informal recycling sectors lack regulation, leading to environmental and labor abuses. Meanwhile, uneven global carbon pricing risks fragmenting markets. A "smart" carbon tax system, incorporating process efficiency metrics (e.g., <1.3 tons ore/ton steel) and raw material quality, could accelerate adoption of green technologies (Mission Possible Partnership 2024; IPCC 2022). Hydrogen-based metallurgy is increasingly being considered as a long-term solution, with significant efforts to replace carbon-intensive blast furnace operations with hydrogen reduction technologies. While hydrogen-based direct reduction iron (DRI) presents a promising pathway for deep decarbonization, its widespread adoption depends on the availability of low-carbon hydrogen and supportive regulatory frameworks. Meanwhile, carbon trading systems, such as those implemented in China and the European Union, are pushing steel producers toward emission reduction strategies. However, as global steel demand continues to grow, particularly in developing economies, achieving significant reductions in emissions will require coordinated policy actions, investment in clean technologies, and fundamental shifts in energy sourcing.

5. Best Available Technologies (BAT) in Iron and Steel Production - – A European Perspective

The European steel industry stands among the most advanced in the world, setting global standards for energy efficiency and environmental performance. Over the past decades, the sector has halved its CO2 emissions and energy use per tonne of steel compared to 1960 levels, and it aims for an 80–95% reduction in emissions by 2050 (relative to 1990). Achieving this goal requires substantial investment in novel technologies, upgraded energy infrastructure, and reliable access to high-quality raw materials such as iron ore and scrap. The potential for emissions reduction varies significantly among nations, depending on infrastructure, equipment conditions, application of best available technologies (BAT), and raw material quality. Given that China accounts for nearly half of the global steel output, its energy efficiency advancements play a crucial role in shaping global emission trends.

Within the EU-27, steel is predominantly produced via two routes:

- Blast Furnace/Basic Oxygen Furnace (BF/BOF) - Steel is produced from iron ore in a multi-step process, incorporating sintering, cokemaking, and reduction of iron ore in the blast furnace, followed by steel refining in the BOF.
- Electric Arc Furnace (EAF) using Scrap - Steel is produced by melting recycled scrap (preferable with DRI) in an EAF. This route generally has lower direct CO2 emissions and aligns more closely with circular-economy principles.

With the European Green Deal's emphasis on carbon neutrality by 2050, there is a notable shift toward the EAF route (OECD 2025). EAF-based steelmaking reduces fossil fuel use and leverages scrap recycling, easing the industry's transition to lower-carbon processes. Many European producers are expanding EAF capacity and modernizing existing facilities to accelerate decarbonization.

In 2008, the EU produced 198 Mt of crude steel (14.9% of global output), a decline from its 24.6% share a decade earlier—mainly due to China's fourfold increase in steel production. Though the 2009 financial crisis severely impacted EU steel output (down by ~30%), moderate growth is anticipated, potentially reaching 260 Mt by 2030 (a 1.18% annual increase). Between 2009 and 2030, finished steel consumption in the EU-27 is projected to grow at around 2% annually. Even so, consumption levels by 2030 are expected to remain about 8% lower than in 2007 due to structural market adjustments. Newer Member States may see faster growth (2.1% CAGR) compared to the EU-15 (1.0% CAGR). Long-standing trends suggest the EU will progressively reduce its net steel exports, becoming mostly self-sufficient by 2030 as competition from non-EU producers intensifies and domestic demand absorbs much of Europe's production.

5.1. Scrap Availability

Scrap metal is an essential raw material in steelmaking, competing with primary iron produced from mined ore. Given its flexibility and alignment with decarbonization goals, scrap use is projected to rise—driven by:

- An increase in the BOF scrap rate from 18% to 20% by 2030.
- Growth the EAF share in overall production from 41% to 47% by 2030.
- Higher scrap recovery rates (from 50% to 58%), adding ~14 Mt of scrap annually.

Despite the growing emphasis on steel scrap as a key component in decarbonization and resource efficiency, its increased utilization faces a major constraint due to the presence of tramp elements such as Cu, Sn, Cr, Ni, and Mo. A projected surplus of low-purity scrap—rising from 20 Mt/yr in 2020 to 43 Mt/yr by 2050—highlights the challenge of quality limitations in secondary steel production. Without improved sorting, dilution strategies, or advanced refining processes, the scrap rate may stagnate at around 55%, far below its theoretical potential of 75% (Dworak et al., 2022).

5.2. Pathways to a CO_2-Neutral European Steel Industry

Achieving deep decarbonization requires coordinated efforts in technology and policy. Two overarching technological pathways guide current research and deployment:

- Smart Carbon Usage (SCU): Enhancing existing BF/BOF operations to use less carbon and optimize energy flows.
- Carbon Capture and Usage (CCU): Capturing CO, CO_2, and hydrogen-rich off-gases for conversion into valuable by-products or chemicals.
- Carbon Direct Avoidance (CDA): Substituting hydrogen for carbon during iron ore reduction, contingent on affordable, low-carbon hydrogen availability; increasing reliance on clean electricity for iron ore reduction, emphasizing renewables.

As illustrated in EU roadmaps, these pathways are expected to coexist, with breakthrough hydrogen and electricity-based processes gradually taking market share alongside optimized BF/BOF technologies. The transformation will be iterative—requiring infrastructure upgrades, policy support (e.g., carbon pricing), and wide-scale demonstration projects.

5.3. Potential Energy Savings – BAT Recommendations in the EU

Table 2 (adapted from Steel Institute VDEh data) shows specific energy consumption for current EU production pathways. The blast furnace route remains the most energy-intensive, whereas electric arc furnaces, especially when paired with direct reduced iron (DRI) or high-quality scrap, consume less direct energy. Upstream energy savings also matter, indicating opportunities for improving system-wide efficiency (e.g., power generation, heat recovery).

A ranking of potential energy-saving Best Available Techniques (BATs) in the EU highlights several high-impact measures (Figure 9):

- Power Plant Improvements: Over 200 PJ of potential savings.
- Coke Dry Quenching: ~60 PJ potential savings.
- BOF Waste Heat and Gas Recovery: ~40 PJ potential savings.
- Optimized Sinter–Pellet Ratios: ~14 PJ potential savings.

Lesser but still significant savings come from techniques like Top Gas Pressure Recovery Turbines (TRT) and district heating integration. Together, these BATs serve as a roadmap for immediate efficiency gains while the industry advances toward novel low-carbon processes.

Table 2. Estimated specific energy consumption per tonne of product of the current pathways for the Iron & Steel production in Europe[1] (Pardo et al, 2025)

Processing Unit	Primary energy2 (GJ/t)	Direct energy3 (GJ/t)
Coke plant	6.827	6.539
Sinter plant	1.730	1.549
Pellet plant	1.204	0.901
Blast furnace	12.989	12.309
BOS plant	-0.253	-0.853
Electric Arc Furnace	6.181	2.505
Bloom, slab and billet mill	2.501	1.783
Hot strip mill	2.411	1.700
Plate Mill	2.642	1.905
Section Mill	2.544	1.828
Pickling line	0.338	0.222
Cold mill	1.727	0.743
Annealing	1.356	1.086
Hot dip metal coating	2.108	1.491
Electrolytic metal coating	4.469	2.619
Organic coating	1.594	0.758
Power plant	12.173	12.173

1 Adapted from Steel Institute VDEh, Statistics of the European Iron & Steel sector

2 Primary Energy: This value represents the total energy content, considering the lower heating value, along with the upstream energy required to produce the material. This includes, for example, the energy used to generate the electricity consumed during the production process.

3 Direct Energy: This value refers to the energy consumed directly by a specific installation during the production process, without accounting for the upstream energy used to produce the input materials.

6. Conclusions and Recommendations

The iron and steel industry remains a foundation of global economic development, yet it faces growing challenges from resource constraints, environmental regulations, and evolving market dynamics. Over the past decade, iron ore production has experienced significant shifts, with pricing mechanisms transitioning from annual benchmarks to index-linked systems, amplifying volatility. Geopolitical tensions and supply chain vulnerabilities, particularly in regions heavily reliant on imports, have further complicated the landscape. While the dominance of China, India, and emerging producers such as Indonesia and Vietnam continue to reshape global production patterns, traditional steelmaking hubs in Europe and North America have witnessed a gradual decline, driven by stricter environmental policies and industrial restructuring.

The demand for high-grade iron ore has increased, reflecting a broader shift toward sustainability and energy-efficient production. The presence of gangue elements remains a critical concern, necessitating advancements in beneficiation technologies and raw material optimization. Meanwhile, the push for specialized steel grades underscores the industry's pursuit of higher-performance materials while balancing cost considerations. Microalloyed steels, in particular, have emerged as a viable alternative to expensive alloying strategies, offering improved mechanical properties through optimized processing techniques rather than reliance on costly alloying elements.

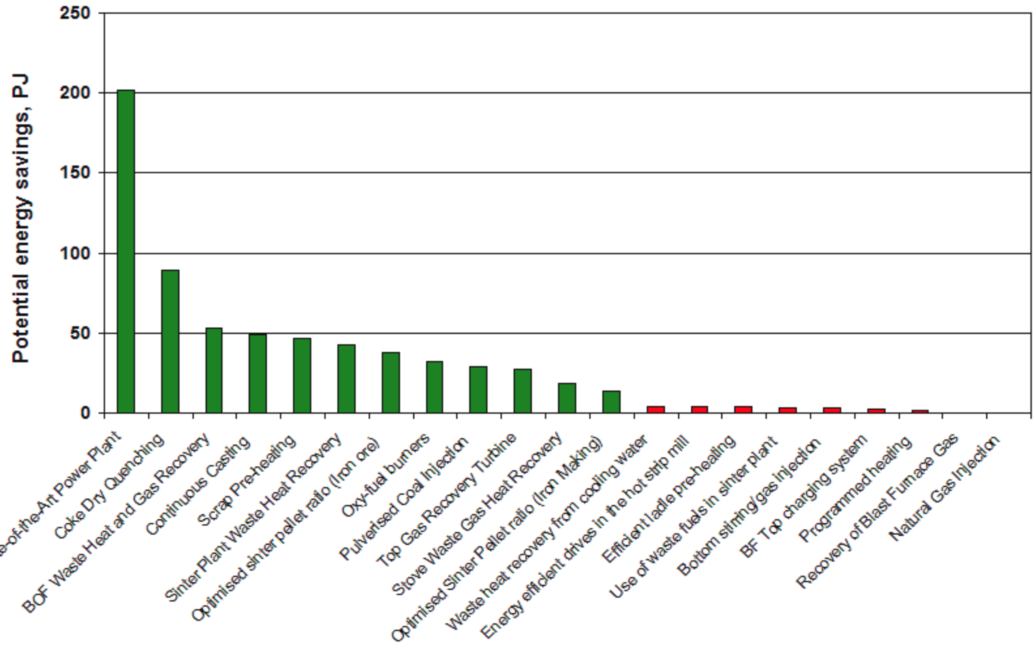

Fig. 9. Ranking of the potential energy savings for BATs considered in EU 27 (Pardo et al, 2025)

Environmental and regulatory frameworks continue to exert significant influence on industry practices. The European Union's stringent emissions targets, embodied in the Emissions Trading System (ETS) and the Carbon Border Adjustment Mechanism (CBAM), have accelerated the transition toward low-carbon steel production (Shuai et al. 2024). Hydrogen-based direct reduction (H-DRI) and carbon capture technologies are gaining traction, though their widespread adoption hinges on cost reduction and infrastructure readiness. Scrap availability is another pivotal factor in the decarbonization of steelmaking, with electric arc furnaces (EAFs) playing a growing role in achieving sustainability targets. However, constraints related to tramp elements in recycled steel necessitate improvements in sorting and refining processes to maximize scrap utilization without compromising quality.

The adoption of Best Available Technologies (BAT) offers promising pathways for energy efficiency and emissions reduction in European steel production. Strategic measures, including increased process electrification, waste heat recovery, and digital process optimization, can drive significant energy savings while maintaining competitiveness. The transition to CO_2-neutral steel production will require coordinated efforts from policymakers, industry leaders, and research institutions to align technological advancements with economic feasibility.

Moving forward, industry should embrace a multi-faceted approach that integrates technological innovation, regulatory compliance, and resource efficiency. Strengthening supply chain resilience, investing in cleaner production technologies, and fostering international cooperation on climate policies will be instrumental in ensuring a sustainable and economically viable future for iron and steel manufacturing. While challenges persist, the sector's ability to adapt and innovate will ultimately define its role in the evolving industrial landscape.

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