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Comment

How green will the green-steel production be?

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Abstract
The steel industry is undergoing a significant transformation driven by the urgent need to decarbonize the global economy. This transition aims to reduce CO_2 emissions substantially, impacting key sectors such as automotive, construction, transportation, and energy. The shift towards green steel production involves overcoming technological challenges, particularly the reliance on green electricity and hydrogen. This paper explores the technological pathways to achieving net-zero emissions in the steel sector, highlighting the potential for emissions reductions in other industries through the use of steel co-products. It discusses the primary and secondary steel production routes, the generation and utilization of by-products, and the integration of carbon capture and storage technologies. The paper also addresses the challenges of scrap availability and quality, the role of hydrogen in decarbonization, and the economic and regulatory factors influencing the industry's transition. Despite significant efforts, achieving net-zero emissions by 2050 remains uncertain, necessitating rapid implementation of low-carbon technologies and supportive policies to ensure the competitiveness of green steel production.

Keywords Green steel · Steel transformation · Technological pathway · Steelmaking routes · Scrap · Net-zero emissions

Abbreviations

BF	Blast furnace
BOF	Basic oxygen furnace
CCS	Carbon capture and storage
CCS	Carbon capture and storage
CCSU	Carbon capture sequestration and utilization
CCU	Carbon capture usage
CDA	Carbon direct avoidance
CE	Circular Economy
CO	Carbon monoxide
CO_2	Carbon dioxide
DR	Direct reduction
DRI-EAF	Direct reduced iron-electric arc furnace
EF	Electric Furnace
EoL	End of life
EU	European Union

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EU-WFD	EU Waste Framework Directive
GHG	Greenhouse gas
H2	Hydrogen
SCU	Smart carbon usage
SDS	Sustainable Development Scenario
SR	Smelting reduction
STEPS	Stated Policies Scenario
TRL	Technology Readiness Levels

1 Introduction

The steel and iron industry is an energy-intensive industrial activity, accounting for 20% of the industrial final energy consumption. It is also a significant contributor to the global anthropogenic CO_2 emissions, accounting for 7–9% of global CO_2 emissions [1, 2]. The principal sources of energy input are coal, electricity and natural gas [2]. Despite its significant contribution to CO_2 emissions, steel is an indispensable material in the modern society. Its key role in the development of modern society and every technological and global economic advance cannot be overstated. Indeed, the transition towards renewable energy production is inextricably linked to steel, as it is vital in the construction of wind turbines and solar farms. Steel is one of the most widely traded commodities in the world [2] and can be considered as a critical material, given its fundamental role in the economic development of the European Union (EU), particularly in the context of the transition to the production of renewable energies [2].

In order to achieve the goals set out in the Paris Climate Agreement [3], steel companies must implement drastic measures to reduce their emissions by more than 50% by 2050 (relative to 2019) [1, 2]. With this objective in focus, the steel sector has been implementing a number of strategies based on energy efficiency improvements and the switching of high-carbon fossil fuels for less carbon-intensive energy sources in order to achieve emissions reduction. Nevertheless, these measures appear to be inadequate for achieving the anticipated levels of CO_2 reduction. The steel industry is characterized by a certain degree of inertia and a tendency to resist change, which could make reaching the emissions target more challenging [2]. In order to achieve the ambitious scenario of zero emissions in the steel production process, the implementation of low-carbon technologies and strategic investment decisions must be taken to transform the sector. These operations must be jointly discussed between governments, energy sectors [2], and other industries [1, 4].

Due to its capacity to be subjected to eternal recycling cycles, steel is a permanent resource that benefits the exploitation of the concept of circular economy (CE) at different levels of the value chain. This represents another route in the pathway to more sustainable steel production [5].

A relative steel dematerialization has been seen in the last decades, represented by the development of a variety of steels with increased performance, thus translating into an overall reduction in weight or increased longevity [6]. The continuous development of high-quality, high-strength steels has resulted in a reduction in the amount of material required, as evidenced for example by the Eiffel Tower, which, if constructed today, would require only one-third of the steel originally used for its construction [6]. This reduction in material also implies a reduction in the necessary raw materials and consequently in energy consumption. Although steelmaking generates high quantities of emissions, steel products are considered to have a restoring function, i.e., the impact generated by steel production is counteracted by its use in renewable energy development, such as wind farms. Despite the highly energy demand of steel production, the energy systems require steel, especially for the transition to clean energy generation [2].

Despite the considerable efforts, strategies, and technological developments that have been made in the pursuit of green steel, it is possible that the pathway to zero emissions may not be achievable and that the objective of net-zero may not be met within the stipulated timeframe. The implementation of low-carbon technologies must be rapidly accelerated in order to reduce the emission intensity [7]

The objective of this paper is to present a perspective on the technological pathway to net-zero emissions. This will be done by describing the diverse aspects related to actions, implementation of technologies, and strategies in the pathway to zero emissions. Furthermore, this paper will point out the potential of the steel sector to influence emissions in other sectors, particularly the cement and construction sector through the use of steel co-products.

2 Steel production routes

In order to comprehend the origins of greenhouse gas (GHG) emissions, particularly of CO_2, and to debate potential strategies for their reduction, it is essential to differentiate between the steel industry´s iron production and steel production process. This distinction is crucial for defining the various pathways involved in steel production. Steel production can be divided into two categories: primary steel, which is manufactured from iron ore (the primary source) using fossil fuels as reductants, and secondary steel, which is derived primarily from scrap. Figure 1 shows

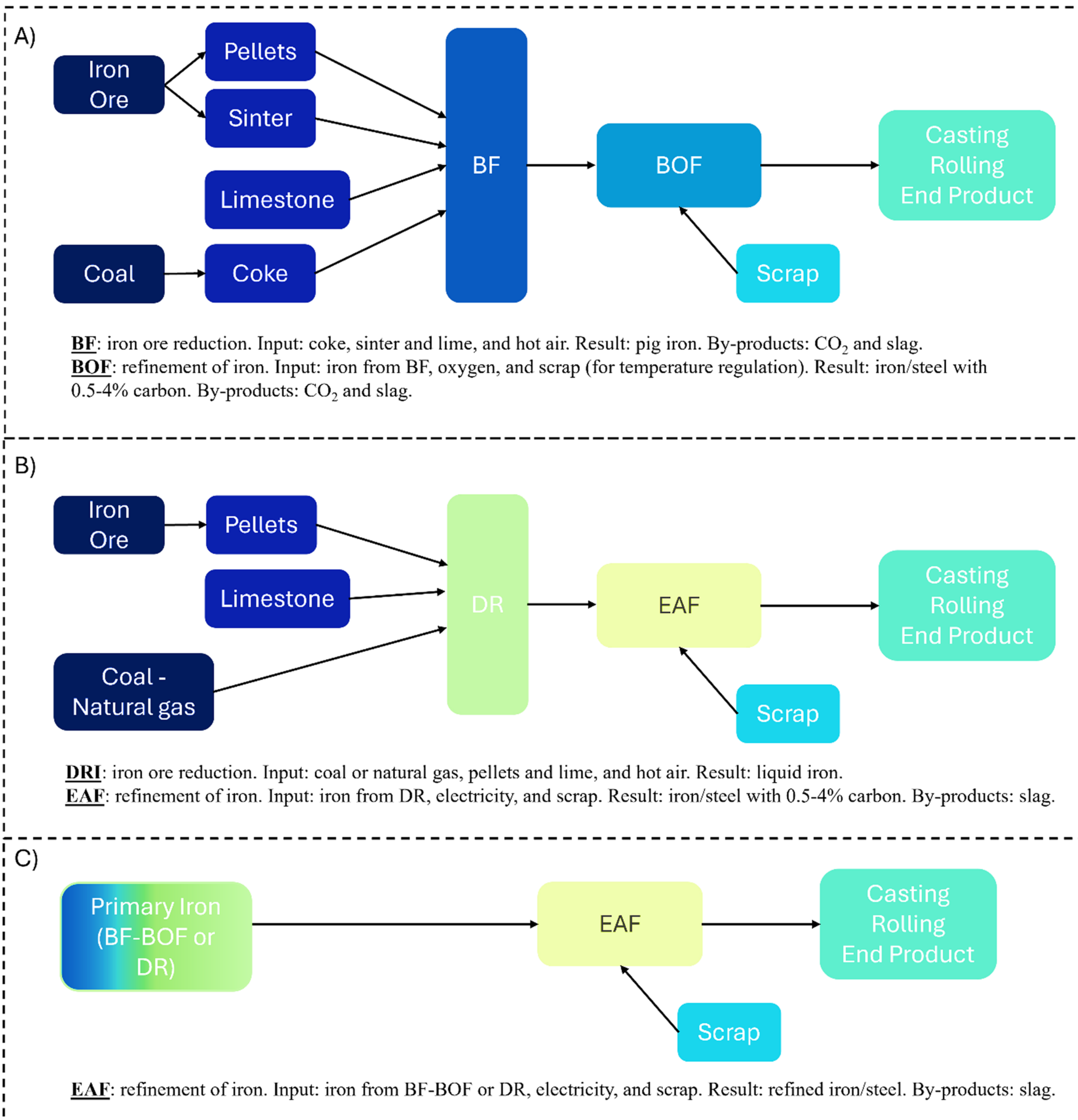


Fig. 1 Schematic representation of the different routes for steel production

schematically the different routes for produce steel, whereas Fig. 2 provides an overview of the emissions corresponding to the different steel production routes [2, 7].

As inputs, the steelmaking process requires: (i) iron ore, with a metallic concentration of 50–70%; (ii) energy to melt the metallic input and chemically reduce the iron ore (coal, natural gas and/or electricity); (iii) limestone (for control of impurities); and (iv) steel scrap with a metal content of > 95% [2]. The different process routes require varying amounts and sources of energy inputs, as well as different raw materials.

Iron ores are reduced in blast furnaces (BF) using carbon monoxide (CO) and hydrogen (H_2), which are generated principally from fossil fuel energy to remove the oxygen [1, 8]. This process is currently operating at close to its maximum efficiency [2, 4].

The **primary production** process includes the preparation of raw materials, ironmaking, and steelmaking. Approximately 90% of **primary production** is performed using BF followed by a basic oxygen furnace (BOF), which accounts for approximately 70% of global steel production [1, 2]. The BF is fed with coke and iron ore, and simultaneously, hot air and pulverized coal or natural gas are injected in counterflow. An alternative method for primary steel production is the direct reduced iron-electric arc furnace (DRI-EAF), which differs from BF-BOF process in terms of the type of iron ore that is used, the state of the material when it is reduced, the main reduction agents, and the balance of energy inputs, described in Fig. 1.

Secondary steel production is done by two principal routes (Fig. 2): (i) BOF, which uses molten iron from the BF and steel scrap, and (ii) electric furnace (EF), which can use up to 100% of steel scrap, generating the other 30% of the demanded steel [2]. Secondary steel production requires large amounts of electricity.

Primary production (i.e., the BF-BOF route) is much more energy demanding than secondary routes and is therefore more sensitive to energy prices. The generation of emissions is higher for the primary production since the energy input is based on coal and natural gas. However, the off-gases from BF-BOF production still contain sufficient energy, with large potential to be re-used in other processes such as heating furnaces in rolling mills, preheating air for blast furnaces, or energy production, as will be detailed later [2]. The energy consumption, in form of electricity, of steel production from scrap (secondary production) is eight times lower than from iron ore [2]. As the majority of the consumed electricity is derived from the grid, the emissions generated by secondary routes are contingent upon of electricity production [2, 9].

Before steel production, the raw material needs certain levels of preparation (pellets or sinter are done from fines using heat and pressure), where the iron content in the ore and pellet/sinter will determine the level of energy required for raw material preparation, as well as for the further iron- and steel-making steps. The coke and scrap also need certain

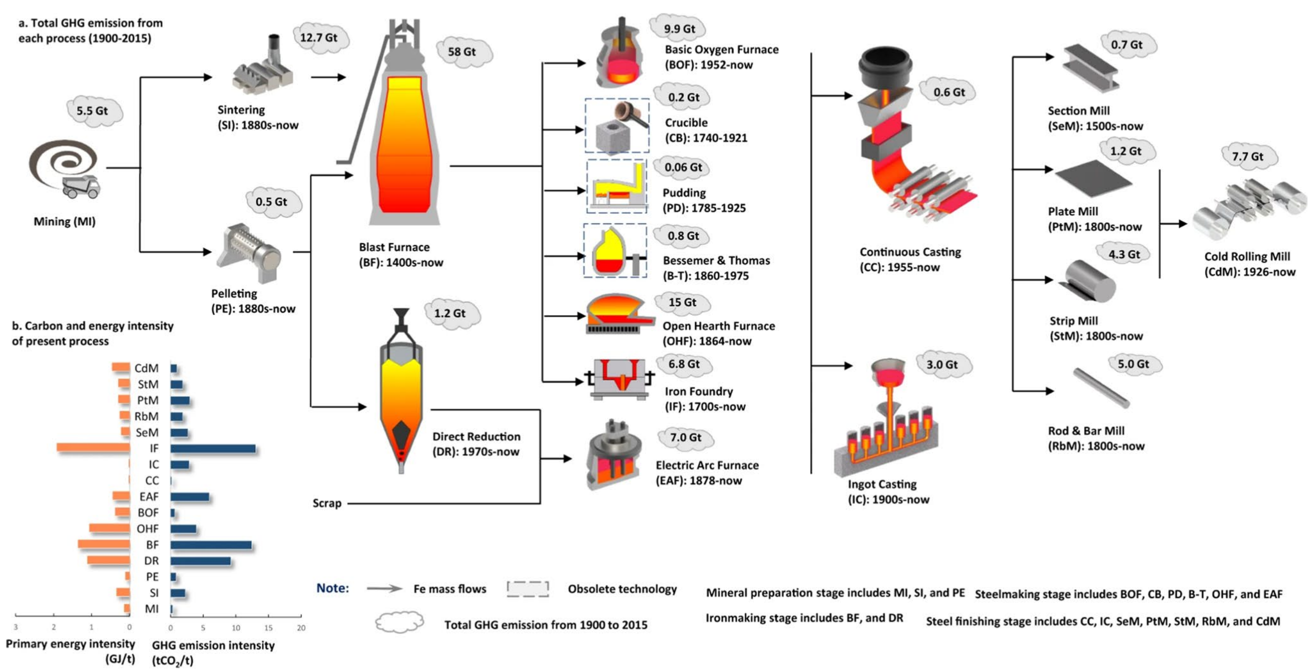


Fig. 2 Steel production routes. Primary production, that compose ~ 90% of produced steel, is done using Blast Furnace followed by Basic Oxygen Furnace (BF-BOF). The total GHG emissions from 1900 to 2015 are indicated for each individual production route [7]

level of preparation. Coke is heated in absence of air to remove its volatile components, while scrap should be separated from other materials [2]. Scrap is also sometimes used in primary production and iron in secondary production. From there, it is necessary to estimate the share of scrap in total metallic inputs, since it will affect the final energy input and emissions output [2]. Lime fluxes are used at various stages of the steelmaking process for the removal of impurities such as sulphur, phosphorous and silica.

3 Waste generation and use of by products

During the steel production process, several by-products are produced [8, 10, 11]. By-products are defined by the EU Waste Framework Directive (EU-WFD) as a "*substance or object, resulting from a production process, the primary aim of which is not the production of that item*" [12]. By-products can have different impacts on the environment and therefore, their correct classification is important to avoid environmental damage.

The main by-products in the steel industry are slag [10], process gases, dust (from coke and coal) and sludge, and chemicals [11, 13]. Apart from slag, solid waste such as mill scale, scrap, fly ash, refractory waste, etc., are also generated in the steel industry. These originate from the coke oven by-product plant, sinter plant, refractory materials plant, BF, BOF, steel melting shop, and rolling mill [14]. Unless these by-products are utilized elsewhere, they must be stored, disposed of, or released (in the case of process gases), which can result in significant costs, potential safety hazards, or environmental concerns [2].

On the other hand, co-products are defined as *planned and desirable outputs form the manufacturing process*, and therefore, the internal use of by-products, or as virgin materials input to other industries (e.g., the cement industry), prevents them from transforming into waste and simultaneously helps in the reduction of emissions [8]. Consequently, the importance of the co-products[1] is twofold: from the economic perspective, they contain a significant economic value; and from a sustainability perspective, they reduce waste and emissions. Their utilization should therefore be considered as a vital step in achieving the ambitious *zero-waste* goal. Despite considerable efforts to decarbonize the steel sector, expanding the use of steel sector co-products in other industries, such as cement and chemicals, has the potential to further reduce global GHG emissions. Furthermore, the recycling and reuse of co-products from steelmaking engenders a symbiotic relationship with other industrial sectors, simultaneously creating new business opportunities that would otherwise be destined for disposal as waste.

3.1 Slag production and its use as co-product

The major waste by-product resulting from the iron and steelmaking processes is slag, representing 90% by mass of the total by-products produced. On average, the production of one tonne of steel results in 200 kg (in an EAF) to 400 kg (BF / BOF) of by-products, where the main fraction corresponds to slags, and the rest to dusts, sludge and other materials [15].

Slags are a mixture of silica, calcium oxide, magnesium oxide, aluminium and iron oxides. This by-product results from extracting impurities from the steel, where lime fluxed combines with sulphur, phosphorus, and silica [2]. The separation of slag from the production cycle is easy, due to its light weight. Slag is partially recycled internally or used as a substitute for virgin materials in many applications, such as fertilizer, construction, and bulk material industries [11], preventing their disposal in landfills and resources exploitation. Several types of slag find applications in concrete, roofing, railway ballast, insulation, bricks and construction. Iron and steel slag are valuable raw material sources, vital to the cement industry as a substitute for clinker and help to reduce the global carbon footprint in the cement industry (down ground in the value chain) [2]. Slag coming from different processes e.g., BOF slag or EAF slag, have different chemical compositions and properties and thus, they have different applications. BF slags are mainly used as cement replacement in concrete, whereas steel slags, due to their low hydraulicity, are used as filler materials in embankment construction [11].

A detailed knowledge about the composition and physical properties is fundamental for increasing the use of slags [10]. Slags rich in sulphur cannot be used or recycled in the metallurgical circuit and are therefore usually disposed of in a landfill [16]. Since slags usually contain precious elements such as zinc (Zn), chromium (Cr), iron (Fe), nickel

[1] Co-products are, in contrast to by-products, planned and desirable outputs from the manufacturing process that have a commercial value.

(Ni), silicon (Si), aluminium (Al), and vanadium (V) and are considered a secondary source of many metals, there is a huge potential for metal recovery for conserving metal supplies and environmental protection [14].

An illustrative example is the utilization of granulated BF slag as a substitute for clinker in blended cements [2, 8], which circumvents further environmental impact due to raw material extraction for cement production.

3.2 Dust and gas emissions

As previously described, CO_2 emissions from the steel industry are energy-related emissions (from fuel combustion), process emissions (primary emissions from the use of lime fluxes and ferroalloy production, i.e., to remove impurities), and indirect emissions (related to electricity generation, on site or imported) [2].

Other gases than CO_2 are generated during steel production like sulphur oxides (SOx) or nitrous oxide (NOx), especially from the sinter process, which is highly pollutant [2, 17]. Emission levels of these gases are highly dependent upon raw material and coke quality. Additionally, diffuse dust is generated from non-point sources, e.g., material handling, stockpiling and transport, and escapes from valves and evaporation of solvents, which are quite difficult to control [2].

The emissions associated to the diverse production routes, i.e., BF-BOF, scrap-based EAF and natural gas-based DRI-EAF, vary as a function of the different amount of energy consumed. The most energy is consumed by the BF-BOF (~ 21 GJ/t), followed by the natural gas-based DRI-EAF (~ 18 GJ/t) and scrap-based EAF (2–5 GJ/t) routes. The coupled emissions are 2.2 t CO_2/t (BF-BOF), 1.4 t CO_2/t (natural gas-based DRI-EAF), and 0.3 t CO_2/t (scrap-based EAF), according to the values reported by the *worldsteel association* [2].

The combustible hot gases produced during steel fabrication can be valorised in different equipment of integrated steel mills, serving as energy sources for heat and energy production. This is due to the high levels of carbon monoxide, carbon dioxide, and methane contained in these gases, which vary depending on the production route, e.g., coke gas (hydrogen & methane), blast furnace gas (hydrogen & carbon monoxide), and converter gas (carbon monoxide).These by-product gases are primarily utilized internally, within manufacturing setups (e.g., reheating furnace), as an alternative power source to operate various processes, thereby reducing reliance on natural resources, minimizing fuel costs and carbon emissions [13, 17]. The challenge lies in the management of the constant variations in composition and physical characteristics of the by-product combustible gases [17]. Consequently, digital solutions employing deep learning algorithms are under development to predict the energetic content of the off-gases produced by the BF [18].

Additionally, the re-use of BF top gases can reduce the demand for coke and energy, since the CO_2 is removed from the top gas, whereas the CO and H_2 are recycled in the BF [17, 19]. Moreover, gases from coke oven, BF, or BOF contain sufficient energy content that can be internally recirculated and used to produce steam and electricity, which could provide up to 60% of the plant power [2, 17, 19], saving fossil fuel and energy resources.

4 Technology pathways towards zero emissions in the steel industry

Development of new technologies is fundamental to achieving the zero-emission goal in the steel industry. The technologies under development can be grouped into two main strategic technological pathways: i) **smart carbon usage (SCU),** and ii) **carbon direct avoidance (CDA)** [4, 20]. A SCU approach, also called CO_2 management, proposes modifications on the existing iron- and steelmaking processes for reducing the use of fossil fuels and the CO_2 emissions. It includes the integration of off-gases into the process, together with carbon capture sequestration and utilization (CCSU) and carbon valorisation, which uses fume gases as raw materials to produce valuable products. On the other hand, a CDA approach relies on the use of renewable electricity in basic steelmaking and H_2-based metallurgy i.e., carbon is replaced by H_2 as iron ores reduction agent [4, 21].

Several innovation efforts are aiming to lower emissions from conventional BF production. Technologies that are already mature or in early stages of adoption will play the greatest role in reducing emissions [2, 21].

There are some technologies that possess an advanced status in terms of technology readiness levels (TRL5) that look promising for optimizing conventional BF/BOF production routes, or for the transition to EAF or DRI steelmaking process and having high potential of being implemented by 2030 [2, 8].

4.1 SCU

4.1.1 Reduction of use of fossil fuels

Optimization of steelmaking process includes full or partial substitution of coal (or fossil energy) by e.g., natural gas or bioenergy, which leads to fewer CO_2 emissions [2]. As an alternative to BF steelmaking, the smelting reduction (SR) process has been developed, which eliminated the pre-processing steps for the iron ore (required for BF). Therefore, the direct smelting reduction process allows CO_2 emission reduction of up to 85% when scrap is included in the process. When combined with carbon capture and storage, the process can be even more sustainable [21]. Moreover, SR presents a promising option for applying carbon capture, given that the off-gases have a very low nitrogen content (compared to a relatively high nitrogen content in typical blast furnace off-gases), making the separation considerably more cost-efficient [2]. Furthermore, the production of steel using a natural gas-based DRI-EAF results in about 20% fewer direct emissions than the production of steel using a coal-based BF-BOF [2]. However, to reach near-zero emissions, the process should be combined with carbon capture and storage (CCS).

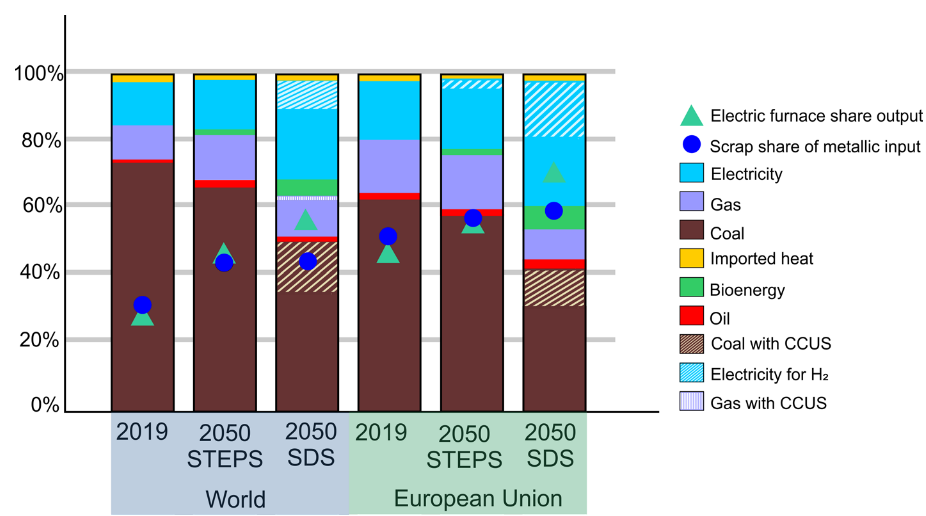
Other strategies focus on the substitution of fossil materials for by-products coming from other industries, such as biomass, residues from companies, rubber wastes, etc. These by-products are usually landfilled and could be used as alternative carbon sources that could lead to CO_2 emission reductions of up to 30% [22, 23]. The use of biomass as partial coke or coal substitution might help in the global emission release. However, due to the diverse nature and origin, not all types of biomasses are suitable for direct injection [2, 22]. Therefore, its chemical and physical properties should be well established before being used in the iron-make processing. Studies showed that biomass can replace only up to a maximum of 25% coke or coal, based on the productivity of the BF. The potential of biomass to reduce BF emissions will depend on the availability of sustainable biomass in the neighbourhood of the plant [11, 22, 23].

According to the data provided by the IEA [2], coal will remain being a key input to the iron and steel sector (Fig. 3). In the proposed sustainable development scenario (SDS), ironmaking global consumption of coal is projected to drop by almost 30% by 2050, relative to 2019, due to the switch to other fuel sources. However, in the stated policies scenario (STEPS) the reduction of coal demand seems to vary.

4.1.2 Carbon capture

Carbon capture systems are a promising technology for reducing the amount of CO_2 released into the atmosphere. These systems capture CO_2 at all three points of generation from the BF/BOF process, including off-gases from BF and coking ovens. There are various CO_2 capture technologies, including post-combustion, pre-combustion, and oxy-fuel capture systems. The capture of CO_2 can be achieved through various methods, including absorption, adsorption, membrane separation, and cryogenic separation, whose principles of functioning are well described in [24, 25]. The captured CO_2 can then be stored or used to create value in manufacturing processes or converted into chemicals [19, 25].

Fig. 3 Regional energy demand for steelmaking and electric furnace and scrap shares by scenario, adapted from[2]. Note: *STEPS* Stated Policies Scenario, *SDS* Sustainable Development Scenario



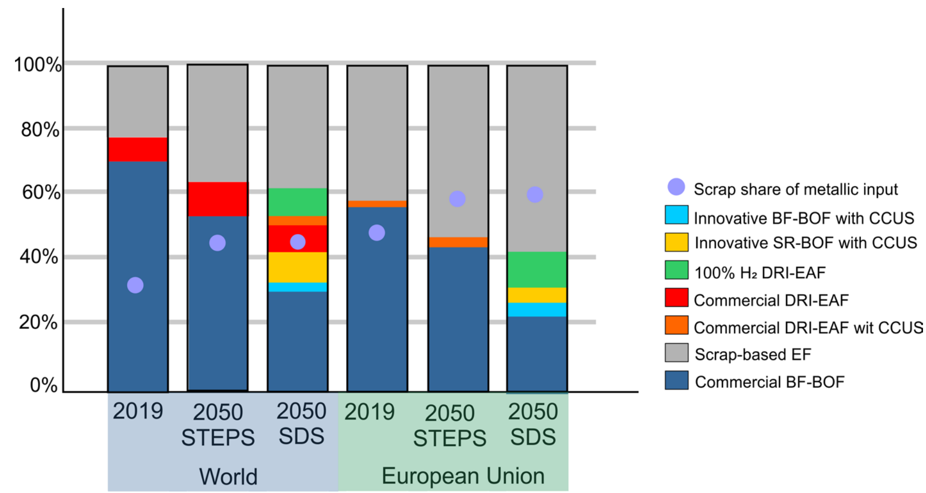


Fig. 4 Crude steel production by process route and scenario in major steel-producing regions, adapted from[2]. *Note: STEPS = Stated Policies Scenario, SDS = Sustainable Development Scenario*

CCS is a relatively expensive process, consisting of capturing CO_2 before it reaches the atmosphere, transporting it, and storing it in geological storages, ocean storage, or mineralization. Typical storage sites include saline aquifers or depleted oil and gas reservoirs. However, the lack of sufficient capacity for transport and storage of CO_2 can become an important bottleneck in the use of these technologies. The current quantity of CO_2 undergoing geological storage in the European Economic Area is less than 2 million tonnes. It is estimated that the demand for annual storage services may increase up to 80 million tonnes by 2030 [26]. Statistical data indicates that a mere 6 MT out of the 240 MT of CO_2 captured by a single installation (~ 2.5%) have been sequestered, while 114 MT (47%) were utilized for enhanced oil recovery [27]. It can thus be argued that CCS linked to fossil fuel extraction, use or production may in fact prove to be of little benefit in terms of addressing climate change. Consequently, given that not all countries possess the requisite capacity for CO_2 storage, there is a growing concern regarding the accessibility of storage sites when required.

Apart from availability of storage sites, concerns persist regarding their safety and potential environmental risks. According to the stipulations from the European Commission (EC), a geological formation may only be selected as a storage site if there is no substantial risk of leakage under the proposed conditions and no significant environmental or health hazards [28]. One key requirement for CO_2 storage is minimising its environmental impact, as stored CO_2 must remain securely contained for at least 10,000 years to prevent adverse climate effects. While the scientific community hypothesises that the geological storage is unlikely to result in leakage for the next 100 years and is expected to remain sealed for 1000 years [29, 30], the potential consequences of leakage must be addressed.

Leakage into subterranean water sources could reduce drinking water quality due to the acidification of potable groundwater, potentially leading to the dissolution of heavy metals. Additionally, geological CO_2 sequestration may disrupt the original local stress equilibrium within rock formations, increasing the risk of microearthquakes due to the crack formation and propagation [24, 31]. Similarly, large-scale CO_2 injection into marine environments can cause water acidification, leading to harmful bio-alterations that negatively impact marine ecosystems and biodiversity [32].

The process becomes economically more effective when is further used (CCU) to produce high-value chemicals like ethanol [33, 34]. Post-combustion capture, for example, uses chemical absorbents to separate CO_2, resulting in high-purity CO_2 that can be used in enhanced oil recovery, urea production, or the food and beverage industry. In pre-combustion systems, syngas (composed of CO and H_2) is produced by gasification of the fuel. The H_2 is then combusted in the plant. Finally, oxyfuel combustion is performed using pure oxygen instead of air. The process has the advantage of producing combustion products H_2O and CO_2, but the separation of O_2 and N_2 is expensive [24, 25, 35]. Although the post-combustion capture system is the most favoured strategy in the industry, it requires large equipment, a large volume of solvent, and a significant amount of energy for solvent regeneration. However, it is advantageous for plants that have already been constructed [11, 21]. The CO_2 collected from coke ovens, BF, and BOF is separated from a dilute gaseous stream and concentrated for its use as a fuel source in a combined heat and power plant (CHP), improving resource efficiency and contributing to the circular economy while reducing emissions [20].

4.2 CDA

CDA strategies are based principally in the secondary EAF steel production and the transition to iron ore reduction using H_2 instead of carbon. CDA strategy bases on the use of renewable electricity in basic steelmaking and H_2-based metallurgy. Furthermore, EAF steelmaking is well integrated in the EU circular economy scenario. Different scenarios as shown in Fig. 4.

4.2.1 Moving from BF to EAF

Secondary steel production, i.e., scrap-based EAF production uses primarily electricity as an energy source and has a much lower GHG emission intensity compared to ore-based primary steel production. For each tonne of scrap used, 1.5 tonnes of CO_2 are emitted and the consumption of other resources (such as coal, iron ore, limestone) are avoided [1, 2]. This recycling strategy can be applied since steel can be submitted to eternal cycles of recycling without a loss in quality and performance and therefore, it can be considered as a permanent resource [7, 36].

The available scrap can be classified as: i) home scrap, generated from failures in the steelmaking, rolling and finishing processes. It is recycled immediately since it does not leave the plant [2]; ii) prompt scrap, is of high quality and near zero contamination and is generated during the manufacture of steel products; iii) end-of-life (EoL) scrap, generated at the end of a steel-containing product´s lifetime.

The major problem of the EAF strategy is the limited scrap availability, since it is linked to the number of products reaching their end-of-life (vehicles, buildings, infrastructure, etc.). The average life of steel products is considered 40–100 year in construction, 10–30 years for transportation, and 10–40 years for machinery [6]. Around 75% of all steel ever produced is estimated to be still in service [36]. Furthermore, the extension of the lifespan of steel products through the implementation of CE measures results in a reduction in the quantity of scrap that reach the EoL, thereby reducing the overall amount of scrap available for recycling [37].

Steel recycling rates are high, with an average of 85% globally, which might be higher depending on the sector, consequently providing limited opportunities for improvement [1, 38]. The amount of prompt scrap and home scrap generated is expected to maintain their proportion in relation to the levels of steel production [2, 20]. Although EoL scrap is estimated to increase, its availability is defined by the past production, the ongoing recycling rate, and average life for the produced steel products [20]. In the EU the availability of scrap is expected to remain almost constant, with a share of total metallic inputs of 60% in 2050 compared to 50% in 2019 [2], whereas the scrap demand is expected to increase drastically as a consequence of the strategies for CO_2 reduction. The generation and availability of scrap is, therefore, an increasing concern for steel producers. Some studies show scenarios where the EoL scrap generation increases [39] and it might be sufficient to satisfy the demand [40]. However, it is worth noting that the availability and demand of EoL steel scrap depends on the economic development scenarios presented and evaluated at the global level.

The transition to secondary steel production also faces the problematic of scrap quality, which is linked to its chemical composition and contamination with other elements and somehow determines towards which steel grades the scrap will be used. Currently, more than 3000 different steel grades can be found in the market, each with specific chemical composition and properties [38]. The complex composition of modern steel products is not aligned with the level of current scrap processing practices in the recycling industry [38]. As a result of the mixed steel scrap, the impurity elements tend to accumulate in the recycled steel. Scrap characteristics are expected to worse as a result from the complexity and heterogeneity of available ferrous materials and repeated recycling cycles [20].

Although most undesired elements can be removed through metallurgical processes, copper for example, cannot be easily removed from molten steel due to its high solubility and thermodynamic stability [41, 42]. The increasing amount of copper in steel is detrimental during the steel manufacturing process.

4.2.2 H_2-based options

Different scenarios show the use of hydrogen as a key player in the decarbonization of the steel industry [43]. The implementation of H_2-enriched direct reduction, i.e., where hydrogen is used as an auxiliary reduction agent replacing up to 80% of natural gas, would work as a transition phase until the H_2-based DRI technology is fully developed [43]. The most sustainable scenarios rely on the use of fully electrolytic H_2-based DRI as the route for a net-zero steel production [2].

In comparison with BF, the DRI occurs in a solid state, giving as a result sponge iron without carbon content. Scientific and operational challenges remain, since the endothermic nature of the H_2 reduction reaction might signify a different heat balance than for natural gas configuration [41, 43]. Therefore, questions about diffusion, effective kinetic, morphology of iron ore particles, or heat transfer, among others should be carefully answered [44, 45].

The changes in the production process should be addressed. Coking plants, sinter plants, BF, and BOF have to be replaced. H_2-DR technology relies on iron ore pellets, and since in most EU steelmaking plants, pelletizing plants are not available, they would have to build [43].

5 Discussion

The steel industry, particularly in Europe, has demonstrated a considerable degree of commitment to the implementation of measures and new technologies with the objective of achieving near-zero emission steel production. The developed technologies are aligned with the EU´s ecological transition impulse, which aims to achieve a net-zero carbon emissions economy [46]. The reduction of CO_2 emissions, enhancement of energy efficiency, and advancement of the circular economy represent the core areas of focus.

It must be acknowledged that there is no single solution or single technological pathway that will lead to a more sustainable steel production process. The European steel industry has a diverse range of available technologies, with numerous additional technologies currently in development [43]. These encompass material efficiency technologies designed to reduce steel demand, as well as carbon avoidance and carbon management options. While hydrogen has garnered much attention in the field of emerging technologies, there are other pathways that have reached a more advanced stage of development. These include energy-saving technologies for existing process routes, such as top-gas recovery turbines on blast furnaces [47]; the transition from coal to natural gas and biomass [48]; the expansion of EAF-based production [49]; and the use of DRI with CCUS [50]. The viability of their implementation is contingent upon regional and local circumstances. These include local regulations and the availability of specific low-CO_2 energy sources at competitive prices, as well as the deployment of carbon capture and storage (CCS) technologies, and regulations that ensure the competitiveness of EU steel industries in the face of competitor from regions with less strict environmental regulations [2]. Nonetheless, one of the primary uncertainties associated with these technologies is their projected future costs. Energy prices, for instance, exert a significant influence on the cost of disparate production routes, thereby rendering the competitiveness of distinct technologies contingent upon the prevailing energy price context, among other factors [2, 51].

One of the strategies for promoting sustainability and enhancing resource efficiency in the steel sector is focused on the reduction of waste and emissions, by the incorporation of by-products into both the steel production process and subsequent downstream applications. The utilisation of steel industry co-products as a substitute for an equivalent product will lead to enhanced resource efficiency and contribute to the development of a circular economy. For instance, the utilisation of BF-slag as a valuable input to the cement and fertiliser industries, and the valorisation of steel off-gases through their transformation into other products including ethanol, are illustrative examples of this [52]. The expansion of EAF-based production or a complete transition to EAF will affect the symbiosis between the steel industries and other sectors, since the EAF-slag has not current use in cement factories [43]. Consequently, research and development initiatives should concentrate on establishing new applications for this by-product. The implementation of more sustainable practices offers a dual benefit: firstly, it has a positive impact on the environment, and secondly, it also yields a positive financial impact in return. The enhancement of by-products utilisation rates can be achieved through the advancement of co-product quality, ensuring the development of products with consistent and superior characteristics for utilisation by other industries [15].

The lack of a uniform legal definition of co-products across countries creates challenges in regulation and utilization, making it essential to clearly distinguish between by-products (residual valuable materials) and co-products (planned outputs) [16, 53]. Proper classification in legislation is crucial to improving the perception and use of co-products while ensuring that by-products derived from waste comply with strict waste management regulations, whereas co-products follow product commercialization rules [54, 55]. Since the steel industry influences emissions in other sectors through co-product utilization, these contributions should be accounted for in the sector's overall emissions balance [56, 57].

The technological pathways associated with the two main strategies, SCU and CDA, present both challenges and opportunities, which will be explored in the following discussion. Achieving net-zero targets by 2050 will require substantial investments, along with the urgent resolution of critical technological hurdles within the next decade to ensure feasibility, scalability, and competitiveness.

The SCU pathway continues using fossil carbon as a reduction agent in ironmaking while simultaneously reducing CO_2 emissions through CO_2 management. Shifting the fuel sources from coal to natural gas can reduce carbon emissions by up to a 20% [1, 2, 9]. Consequently, regions possessing abundant, low-cost natural gas, have a competitive advantage, particularly if it is supported by soft environmental regulations and low prices for CO_2 emissions. The utilization of carbon capture facilities is another promising method for and rapid emissions reduction, and the implementation of CCS is crucial in achieving this objective [58]. Regulations governing the management of captured CO_2 are pivotal for effective implementation of CCS [43]. Geological sequestration of CO2 is widely accepted as the most effective and economical technology for permanent CO_2 storage, utilizing reservoirs such as depleted oil and gas fields, saline aquifers, and unamenable coal seams [24, 35].

In addition to the necessity of storage sites, a primary concern regarding CCS technologies pertains to the uncertainty surrounding the security of geological CO_2 storage over the span of 10,000 years [29, 30]. The European Commission has stipulated that CO_2 storage must meet strict safety and environmental criteria, with the objective of mitigating risks such as leakage, which could bear severe consequences for human health and ecosystems [28]. Potential hazards include groundwater acidification, heavy metal dissolution, microearthquakes from geological disturbances, and marine biodiversity loss due to CO_2-induced water acidification [32] [24, 31]. It is reasonable to hypothesise that the implementation of CCS may create the impression of environmentally friendly production, potentially delaying the development and implementation of measures and technologies to address CDA. Given these uncertainties, future generations may encounter challenges similar to those currently experienced with the storage of nuclear fuel from nuclear power plants.

In consideration of the **CDA** pathway, the decarbonization of the steel industry through the utilization of H_2 as a reduction agent (H_2-DR) is regarded as the pinnacle of technological advancement. The replacement of coke with hydrogen in the reduction of iron ore results in the production of pure iron and gases containing H_2O in lieu of CO_2. Although hydrogen appears to be a potentially transformative technology for industrial decarbonization, the implementation of this technology is associated with a number of technical, logistical, and economic uncertainties that require further investigation and resolution.

The H_2-DR route requires significantly more electricity than the BF-BOF or EAF processes, in addition to the energy required for hydrogen production. Currently, most of the global hydrogen production (95[2] MtH_{2eq}) is derived from fossil fuels, with grey hydrogen (from natural gas) and brown or black hydrogen (from coal gasification) generation of more than 1 Gt of CO_2 emissions annually—comparable to the entire aviation sector. As an interim step, combining natural gas-based technologies with carbon capture (blue hydrogen) could reduce direct CO_2 emissions by up to a 95%.

Replacing the BOF with H_2-DR + EAF route will further increase in electricity consumption and alter the iron metal mix used in steel production. Producing one tonne of green steel via this route requires at least 3.0 MWh of renewable electricity, compared to the 0.1 MWh for the BF-BOF process [59]. When considering CO_2 emissions from electricity generation and downstream emissions, H_2-DR emits approximately 1.09 t CO_2/t steel—lower than the BF-BOF and EAF routes (1.4–2.2 t CO_2/t steel) but still falling short of net-zero [2, 6, 8]. The adoption of H_2-DRI + EAF technology will increase the scrap demand due to higher scrap proportions in primary steelmaking and secondary steel production [60]. While scrap availability in the EU is expected to increase marginally by 2050 [37], it will not meet total demand, since scrap availability is influenced by products reaching the end-of-life [41, 44]. In a growing market, the volume of scrap becoming available from historical levels will inevitably fall short of meeting the total current demand [1, 2, 8]. This underscores the continued importance of primary steel production. The increase in the efficiency of steel production, will minimize the generation of home scrap and prompt scrap, further reducing the scrap available.

The generation and availability of scrap is an increasing concern for steel producers, especially in Europe. In practice, it is not feasible to achieve a recycling rate of 100% due to the limitations in collection, sorting, and separation in the recycling stage, as well as metal recovery in the production stage. Consequently, the collection of end-of-life scrap should be optimized. Therefore, ferrous scrap plays a pivotal role in meeting the EU's ambitious climate and circularity targets, serving as a valuable source of secondary raw materials. The European Steel Association (EUROFER) has put forth the

[2] It is estimated that for 2030, 170 MtH_{2eq} will be needed, whereas the demand might increase up to 600 MtH_{2eq} by 2050 [63].

proposal that metallic scrap should be included in the list of critical raw materials, since millions of tonnes of ferrous metal scrap—19.5 million tonnes in 2021—are exported yearly outside the EU, being Turkey the primary destination [61]. This is expected to facilitate the achievement of circular economy and climate objectives as well as ensuring the EU's strategic autonomy and social standards. Furthermore, this would guarantee the long-term competitiveness of European steelmakers and prevent the growth of carbon emissions [1, 2].

Beyond availability, scrap quality represents a significant challenge due to its heterogeneity and potential contamination, requiring pre-treatment prior to remelting to meet physical and chemical standards for specific steel grades [38]. End-of-life scrap may contain contaminants, which must be managed through the implementation of appropriate operational techniques for environmental quality assurance, particularly in the production of specific steel grades [38, 62]. The term "high quality" is a relative and refers to specific, well-defined scrap grades. To guarantee the production of superior-quality steel via secondary routes, regulations governing the separation of end-of-life materials should be implemented. These regulations should include detailed guidance on the demolition and dismantling of structures, as well as improved sorting and separation techniques to reduce contamination. Furthermore, these policies should extend to other sectors, such as the automotive and construction industries To achieve this, improvements in collection and separation centres are necessary, enhancing the scrap management process from the initial collection to the selection and classification.

Ensuring high-quality steel production requires precise scrap blending and contamination control, as removing problematic elements after melting is challenging, often requiring dilution with virgin steel [38]. The improvement of scrap quality can be performed from different perspectives, namely:

i) *Technical perspective:* ensuring material purity through proper identification and sorting of ferrous scrap allows steel mills to optimize resource allocation and expand their scrap usage [38].Improved scrap information enables higher scrap fractions and a broader range of scrap types, while lower quality scrap is often re- or downcycled into construction steel [40].
ii) *Economical perspective:* high costs of collection, separation, and removal of undesired alloy elements, which require energy-intensive interventions. Additionally, valuable elements like niobium, cobalt, tungsten, and vanadium, listed in the EU's Critical Raw Materials[38], risk being lost when blended into steel products, making them inaccessible for future use.
iii) *Operational perspective:* the availability of high-quality scrap reduces the need for virgin materials, as better information on scrap composition allows for more precise melt adjustments.

The steel industry is becoming increasingly reliant on the energy sector, with long-term success relying on the availability of cost-competitive, low-carbon electricity and hydrogen (and, temporarily, natural gas) [59]. While hydrogen prices are set locally, green hydrogen currently costs between US$2.5 an US$58.0 per kilogram (90–150 US$/MWh), significantly higher than grey hydrogen, which costs around US$1.5 per kilogram (10–15 US$/MWh). However, prices are expected to become more competitive over time due to economies of scale and cheaper renewable energy sources [63]. The large-scale production of green hydrogen may face challenges in highly industrialised and densely populated countries (European countries, Japan and South Korea), which could struggle to generate sufficient low-cost hydrogen to meet demand [63]. Regions with abundant renewable resource endowment and extensive land availability may produce cost-competitive green hydrogen beyond domestic needs, but costs for storage and transportation must be considered. Several companies have expressed their intent to use green hydrogen when becomes available and cost-effective, though this is unlikely in the near term, meaning grey hydrogen will be used interim. German steel producers plan to connect to a national hydrogen pipeline network [64], and the expansion of hydrogen production will depend on the availability of renewable electricity for electrolysis, ensuring that both hydrogen and electricity are sourced from renewable sources to achieve genuine carbon avoidance [1, 8].

The global transition from coal to green hydrogen will significantly affect the geographical distribution of the steel industry, given that the location of steel mills has historically been determined by the availability of domestic coal or efficient shipping facilities. With the shift to green hydrogen, the availability of low-cost renewable electricity and hydrogen transport infrastructure, such as pipelines and ports, is poised to become a pivotal factor in determining the competitiveness of the steel industry. Investments in renewable energy and a rapid transition towards a hydrogen economy in Europe could offer the European steel sector long-term competitive advantages. The energy demands associated with green ironmaking may lead to new steel production facilities in regions with low energy costs [59, 65].

Conversely, the presence of divergent carbon tax rates across nations – ranging from less than one US dollar to over $150 per ton of CO2 in Sweden and Uruguay – impedes global climate mitigation initiatives [66, 67].

Decarbonizing the steel industry is a major challenge due to rising steel demand, the difficulty of replacing carbon-based resources for high-temperature processes, and the carbon lock-in effect of long-lived production assets [7]. Blast and DRI furnaces are the primary sources of emissions and capital-intensive assets with a service life of around 40 years, meaning their associated CO_2 emissions will persist for decades [68]. Consequently, investment decisions must account for this lock-in, but strategic actions can help mitigate emissions, including: i) early assets retirement due to policies or market shifts; ii) refurbishment through emission-reduction technologies like fuel switching (coal by natural gas by hydrogen) or CCUS, and iii) material input changes, such as increasing scrap usage or using higher-quality iron ore.

The transition to a green steel industry requires substantial investment in technology and green energy, significantly increasing production costs, especially for primary steel [4]. Companies must invest heavily to convert their plants into green technologies. The level of investment undertaken by individual companies will be contingent upon available resources, local policies, and financial capacity [48]. A supportive regulatory framework is crucial to maintaining competitiveness against producers in regions with lower environmental standards [2]. Capital expenditures (CAPEX) for decarbonizing steel and iron production are estimated at €2-€3 trillion, with a similar investment needed for green energy infrastructure. The steel industry, particularly in Europe, will encounter challenges pertaining to competitiveness [69]. European steelmakers, including those in Germany, are seeking public funding, with the German government allocating €7 billion to support decarbonization efforts [70, 71].

Projections of GHG emissions suggest that achieving the 1.5°C climate target is unlikely without a significant reduction in emissions intensity (0.85 tCO2eq/t steel per decade) or a 34% [7] decrease in steel demand [39]. Despite this, steel demand is expected to continue growing, with global demand for low-carbon steel projected to increase tenfold from 15 million metric tons in 2021 to over 200 million metric tons by 2030 [59].

It could be concluded that none of the scenarios for transformation presented by the European Steel Industry Association [4] would be capable of reaching the zero-emission target. In the most favourable of the scenarios presented, a 95% reduction in emissions compared to 1990 levels could be achieved. Nevertheless, this objective can only be achieved if CO_2-free energy and H_2 are available at the time. It is noteworthy that even in the sustainable development scenario, the consumption of coal for ironmaking remains at approximately 30%, representing a consequence of the reduction in the proportion of primary production within the total steelmaking process, coupled with a transition towards natural gas, biomass, electricity and hydrogen. Some have proposed that the carbon problem could be mitigated through an increased use of renewable energy sources. Nevertheless, even if renewable energy sources become more cost-competitive, the time required for them to become widely adopted will necessitate the continued significant use of fossil fuels [72].

6 Conclusions

It is reasonable that the steel industry should be the main focus of decarbonisation efforts due to its carbon-intensive nature, with the potential to significantly reduce the carbon footprint of key sectors such as automotive, construction, transport, and energy. This manuscript has described and analysed the technological pathway and the main problematic facing the transformation, leading lead to the following conclusions:

- Achieving zero-emissions in steel production will require significant technological advances, given the absence of a single pathway to achieving emission reduction targets in the iron and steel industry.
- The primary objective of the steelmaking technological pathway is to reduce emission to achieve the ambitious target of zero emissions, with a secondary focus on zero-waste steelmaking. and improved by-product reuse to reduce the environmental impact of steel companies and increase their competitiveness.
- The optimal technology combination for decarbonisation remains uncertain, influenced by regional factors such as the availability of low-carbon energy and local regulations, with investments dependent on resources and specific local policies.
- The transition to a new steelmaking route will impact the entire value chain, with the generation and transport of green electricity and hydrogen playing a pivotal role. Over the next decade, efforts will focus on advancing hydrogen technology, increasing the use of low-carbon energy, and implementing CCS and CCU to support this transformation.

- Reducing emissions by increasing the use of metallic scrap utilization is contingent upon the availability and quality of the scrap, as well as the efficient transmission of information between traders and steel mills. The enhancement of scrap quality is best achieved through the prioritisation of cost-effective end-of-life material separation techniques, with the objective of minimising contamination. Furthermore, the implementation of supportive policies is a requirement to facilitate the sorting of scrap and the production of diverse steel grades through the secondary route.
- The transition to green steel production will require substantial investment in hydrogen capacity and advanced technologies, which will lead to an increase in steel production costs. However, the current supply of renewable energy is insufficient to produce green hydrogen at a competitive cost. In order to mitigate these challenges and ensure the competitiveness of primary steel production—the largest emitter of greenhouse gases—robust supportive policies are imperious, particularly in comparison to producers in regions with lower environmental standards.
- The steel industry's contribution to reducing emissions extends beyond its own sector, influencing other industries, such as the cement and construction industries, through the utilisation of steel co-products. Achieving net-zero targets by 2050 will require accelerated investment, the adoption of renewable energy, and strong policy support.
- Achieving a maximum emission reduction of 95% by the year 2050 (in comparison to 1990 levels) is feasible under the most optimistic scenario, providing that CO2-free energy is utilised. However, attaining 100% zero emissions remains a considerable challenge.
- Combating global warming and limiting temperature rise to 1.5°C above pre-industrial levels require a collective global effort rather than the responsibility of a single country or region. However, the lack of uniformity in regulations and climate goals worldwide presents a significant challenge. While the EU has demonstrated a commendable commitment to decarbonization, many economically and industrially developed nations have not exhibited a comparable level of dedication. To ensure the continued competitiveness of the European steel industry, it is of utmost importance that the EU enforces measures to guarantee that imported steel is either carbon neutral or subject to taxation.

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