Hydrogen in the Iron and Steel Industry: A Comprehensive Review

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Abstract:

The iron and steel industry plays a vital role in global economies but is also a significant contributor to greenhouse gas emissions. As the world seeks to transition to a low-carbon economy, hydrogen has emerged as a promising alternative to reduce emissions in this sector. Within the steelmaking sector, hydrogen presents an alternative to carbon in a significant chemical process responsible for 5-7% of the world's greenhouse-gas emissions and 11% of carbon dioxide emissions. By utilising hydrogen to heat iron oxide and eliminate oxygen, the steelmaking industry could witness a dramatic decline in its carbon emissions. Hydrogen, as a versatile and eco-friendly energy carrier, emerges as a promising solution to revolutionise the steelmaking landscape. Hydrogen acts as an ideal substitute, yielding pure iron and water as byproducts, effectively eliminating carbon emissions and reducing the sector's environmental footprint. Such an approach could lead to a substantial reduction in the industry's carbon emissions, making a significant contribution to global efforts to combat climate change. This review paper provides a comprehensive overview of the current state of hydrogen utilisation in the iron and steel industry, highlighting its potential, challenges, and future prospects. Various aspects, including hydrogen production methods, steelmaking processes, and hydrogen's impact on steel properties, are explored. The paper further compares the chemistry of steel making through two different routes and analyses how replacing the use of coal with hydrogen reduces carbon emission. Additionally, this paper examines the role of policy frameworks and technological advancements in fostering hydrogen integration within the industry.

Keywords: Green House Gases (GHG), Hydrogen, Steel Industry, net zero, CO2 emissions, sustainability

I. Introduction

The iron and steel industry is a cornerstone of global infrastructure, providing essential materials for construction, manufacturing, and transportation. However, it is also one of the most energy-intensive sectors and a significant contributor to greenhouse gas emissions. Day-by-day India is in a process of setting up its ambitious goals in terms of steel production (i.e. 300 million tons by 2030), Electricity production (i.e. 830 Giga Watt by 2030), 50 per cent of country's energy production to be met by non-fossil fuels, and by 2070 the pledge of 'Net Zero' emissions. [1-3] In a recent article, it was quoted that by 2050 if we meet the net zero the country could boost an annual GDP to 7.3% and could also create more than 20 million jobs. [2] Understanding the environmental impact of the iron and steel industry is crucial for developing sustainable solutions and transitioning to a low-carbon economy. The steel industries are adopting newer paths in reducing the green-house gases (GHGs) since every ton of steel produced normally emits on average 1.85 tons of carbon dioxide. The main cause for energy inefficiency and environment pollution are due to the outdated steel production technology in use. The production of iron and steel involves various processes, primarily starting with the extraction of iron ore from mines. The iron ore is then processed in conventional blast furnaces, where it is heated with coke (a form of carbon) and limestone to produce molten iron. Subsequently, the molten iron is further refined and transformed into steel through different methods, including basic oxygen furnaces (BOFs) and electric arc furnaces (EAFs). [1] The environmental impact of the iron and steel industry arises from multiple sources. Firstly, the primary production process relies heavily on fossil fuels, particularly coal and coke, leading to significant emissions of carbon dioxide (CO2). These emissions result from both the combustion of fuels and the chemical reactions involved in reducing iron ore in the form of sinter or pellets to liquid pig iron. Most iron ores are hematite Fe_2O_3 and the reduction of an iron oxide to Fe by C or CO produces CO_2, as shown below.

1. $Fe_2O_3 + 32\ C = 2\ Fe + 23\ CO_2$ or
2. $Fe_2O_3 + 3\ CO = 2\ Fe + 3\ CO_2$

The basic concept of using hydrogen ironmaking is to replace C or CO with H_2

$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$ thus releasing harmless H_2O instead of CO_2 in the reduction process. [10]

Additionally, the iron and steel industries are associated with other environmental concerns, such as air pollution, water consumption, and waste generation. The combustion of fossil fuels releases pollutants like sulphur dioxide (SO2) and nitrogen oxides (NOx), contributing to air pollution and acid rain. The water-intensive nature of steel production requires substantial amounts of freshwater, potentially depleting local water resources. [2] Moreover, waste by-products, such as slag and dust, can have environmental implications if not properly managed. Recognising the need to address these environmental challenges, the iron and steel industry has been exploring various strategies to reduce its carbon footprint and overall environmental impact. One promising avenue is the integration of hydrogen as an alternative feedstock and energy carrier. [3] By substituting fossil fuels with hydrogen, carbon emissions can be significantly reduced, leading to a more sustainable and environmentally friendly steel production process. Moreover, hydrogen also shows promise as an alternative heat source for various steelmaking processes. Traditional methods, such as blast furnaces, require high-temperature heat sources, are currently provided by burning fossil fuels. By utilising hydrogen as a clean energy source for heat generation, the steel industry can further minimise its carbon footprint and enhance its sustainability credentials.

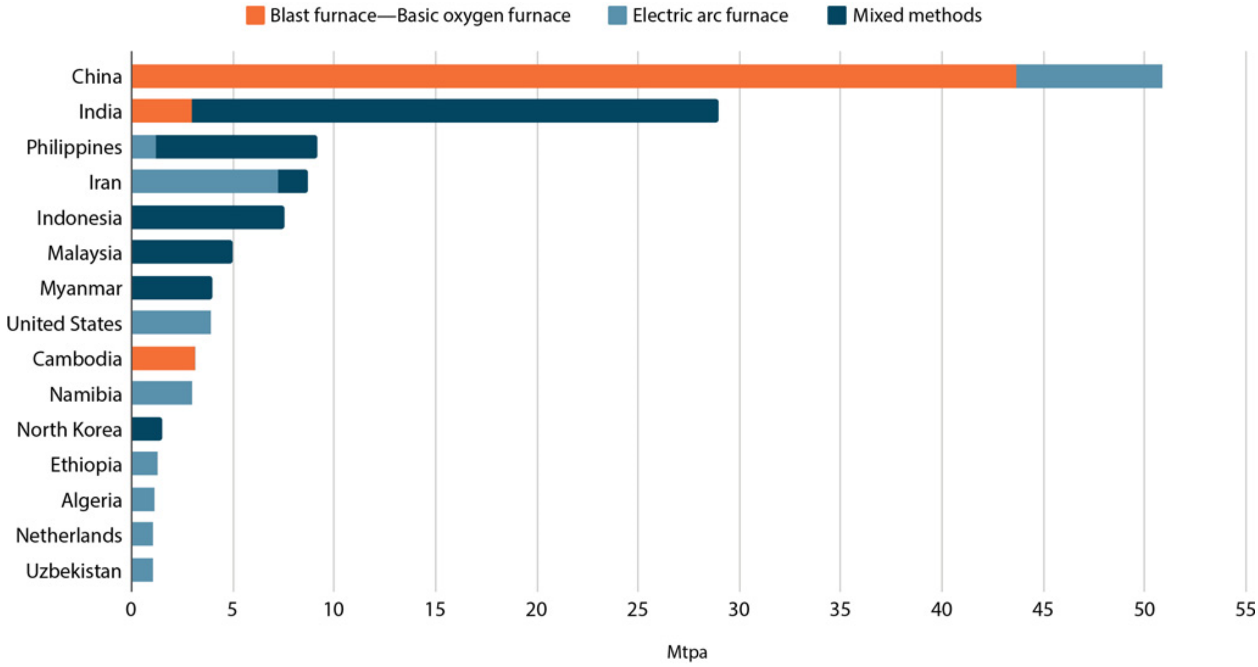

Figure 1: Proposed steel plants around the world, represents around 553 steel plants accounting to 80% of steel plants. Source: Global Steel Plant Tracker, Global Energy Monitor, February 2021. [4]

The extensive utilisation of BF-BOF technology is the key factor attributing to the responsibility of the 553 identified plants for an approximate 3 billion tonnes of CO2 (GtCO2) emissions. This amounts to around 9% of the total global CO2 emissions. [4]

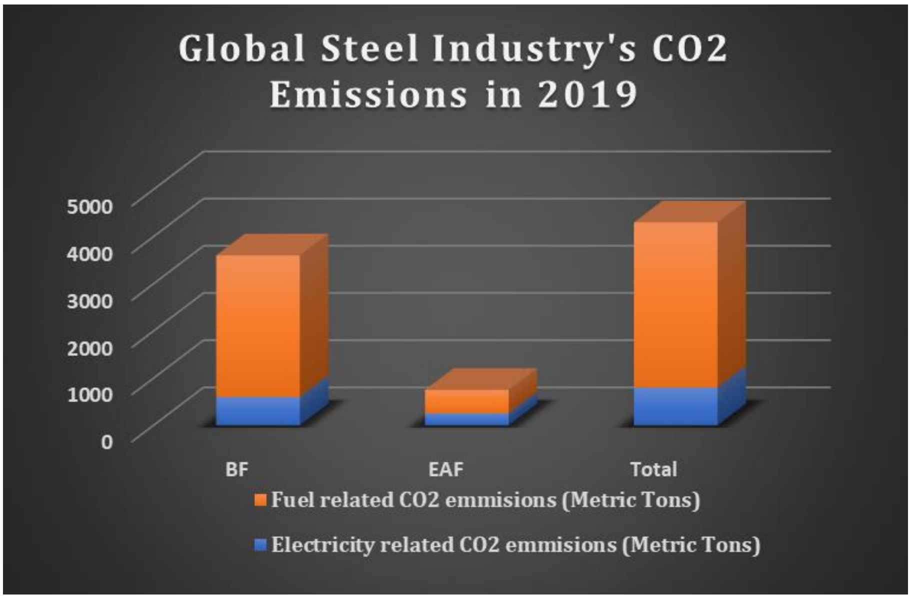

Figure 2: Graph showing both electricity related CO2 and fuel related CO2 emissions during steel making process. [3]

Figure 2 depicts the total GHG emissions from 1900 to 2015 extracted from nature communications. [5] The rise in emissions signals that the global steel sector has fallen behind in the competition between rising consumption and efficiency improvements. The growth in demand is strongly connected to both national and global advancements in urbanisation and industrialisation since steel is the essential metal for modern society. As a result, the most significant increase in production has taken place in recent years, driven by the rapid demand growth in emerging economies such as China and India. [6]

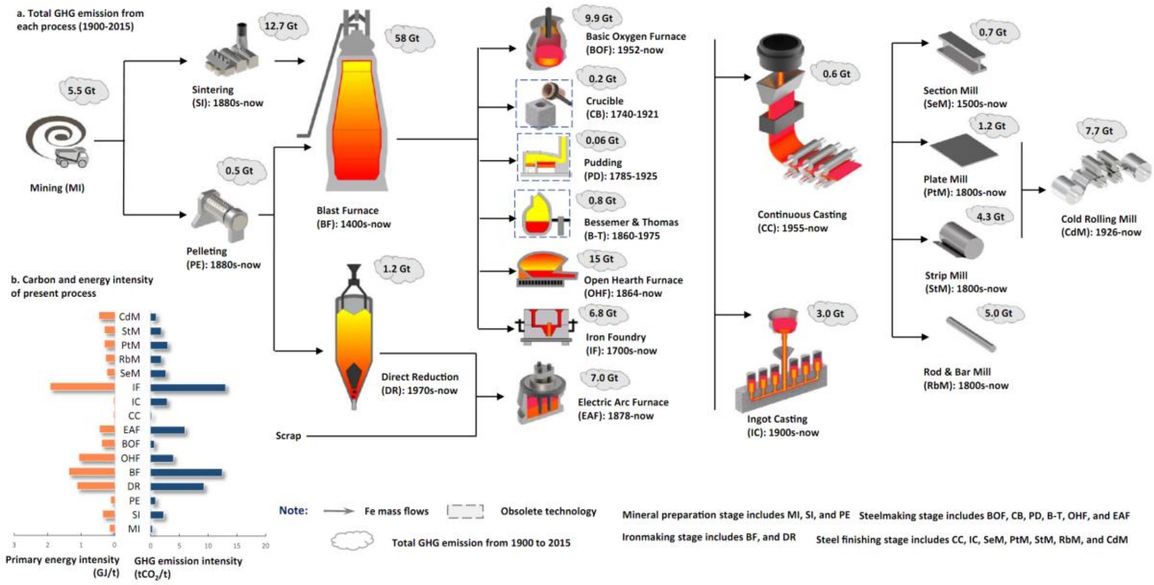

Figure 3: Steel manufacturing methods and total GHG emissions from 1900-2015 [5]

It's worth noting that as there is no commercial level steel plant using hydrogen at a large scale currently, experimental data is not accessible. Therefore, theoretical data from various sources have been used to analyse.

II. Rationale for hydrogen integration

The integration of hydrogen in the steel industry offers several compelling rationales, driven by the need to mitigate climate change, reduce carbon emissions, and enhance sustainability. [1,2] The primary drivers for hydrogen integration are as follows:

- **Decarbonisation:** Hydrogen is a clean and versatile energy carrier that, when produced from renewable or low-carbon sources, emits no carbon dioxide during combustion. [7] By replacing fossil fuels with hydrogen in steelmaking processes, significant reductions in greenhouse gas emissions can be achieved, aligning with global decarbonisation goals.
- **Energy Efficiency:** Hydrogen has the potential to enhance energy efficiency in steel production. [8] When used as a reducing agent in direct reduced iron (DRI) processes or injected into electric arc furnaces (EAFs), it can facilitate more efficient steelmaking, leading to lower energy consumption per unit of steel produced. [1,5,8]
- **Product Quality and Performance:** The incorporation of hydrogen in steelmaking processes can impact the properties and performance of steel. It offers the potential for improved material properties, such as increased strength, reduced brittleness, and enhanced corrosion resistance, depending on the specific application and steel composition. [9]

- **Diversification of Feedstock:** The integration of hydrogen as a feedstock in steel production allows for diversification away from carbon-intensive inputs such as coal and coke. [3] This diversification can enhance the resilience of the steel industry, reduce supply chain risks, and promote resource efficiency. [5]

These rationales are driving increased research, pilot projects, and industry collaborations to explore the technical and economic feasibility of hydrogen integration in the steel sector.

III. Hydrogen Production methods:

Hydrogen can be produced through various methods, each with its own advantages and challenges. The selection of hydrogen production method depends on factors such as cost, energy source availability, and environmental considerations.

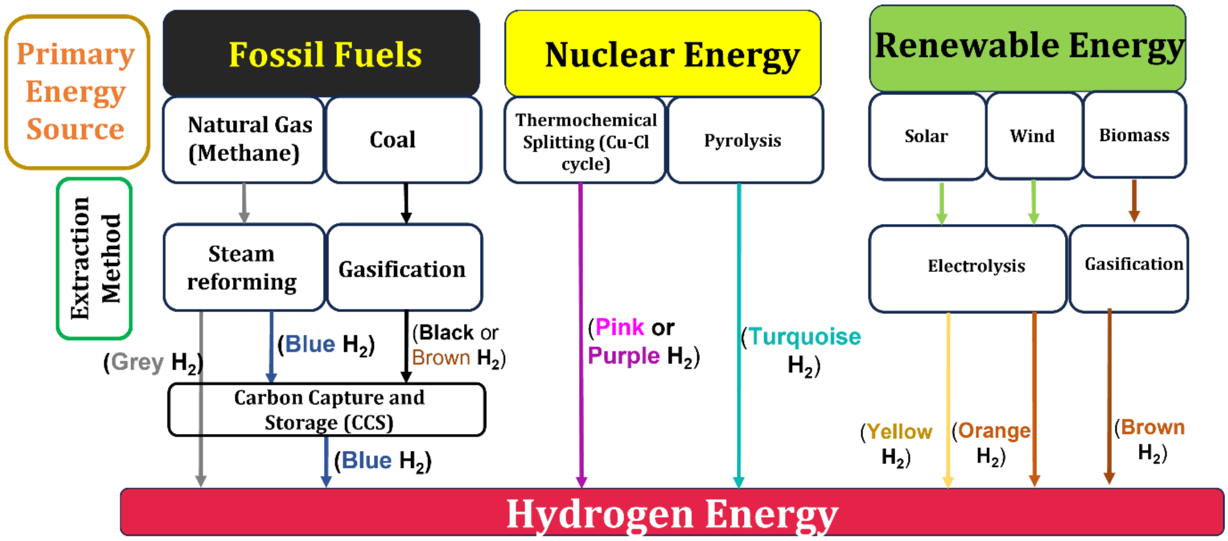

Figure 4: Hydrogen production methods [9]

Some commonly used hydrogen production methods are:

- **Steam Methane Reforming (SMR):** SMR is the most prevalent method for hydrogen production, accounting for the majority of industrial-scale production. It involves reacting natural gas (methane) with steam at high temperatures, yielding hydrogen and carbon dioxide as by-products. Although widely used, SMR is associated with carbon emissions due to reliance on fossil fuels like natural gas. Carbon capture and storage technologies are required to reduce its environmental impact. Additionally, SMR is energy-intensive and may face competition from cleaner hydrogen production methods like electrolysis using renewable energy sources. [9,10]
- **Water Electrolysis:** Electrolysis splits water into hydrogen and oxygen using an electric current. The reactions considered in the electrolyser and the reduction shaft are shown in the equation H20 = H2 + ½ O. This method can utilise renewable energy (Wind/Solar), making it a low-carbon option. Two types of electrolysis are commonly employed: alkaline electrolysis, which has a long history of commercial use, and proton exchange membrane (PEM) electrolysis, which offers faster response times and greater flexibility. Alkaline Electrolysis functions by the transfer of hydroxide ions from the cathode to anode while hydrogen is forming at cathode. Hydrogen then get removed from the cathode to combine in gaseous form. This operates at a temperature of about

30ºC to 80ºC with an aqueous solution of KOH or NaOH as the electrolyte. Asbestos diaphragm and nickel materials are used as the electrodes. PEM electrolyzers are specialty plastic material. Water reacts at anode to produce oxygen and positively charged hydrogen ions - protons - which then move through the membrane to the cathode where they combine with electrons flowing through an external circuit forming hydrogen gas. Water electrolysis challenges include the high energy input required for the process, making it dependent on affordable and abundant renewable electricity. Scaling up electrolysis for large-scale hydrogen production remains costly. Improving the efficiency of electrolysis cells and developing cost-effective electrocatalysts are critical for widespread adoption of this green hydrogen production method. [9,10]

- **Biomass Gasification:** Biomass gasification involves the conversion of organic materials, such as agricultural waste or dedicated energy crops, into hydrogen-rich syngas through high-temperature reactions. This method offers the potential for carbon-neutral hydrogen production since the carbon dioxide emissions from syngas combustion can be offset by the biomass carbon capture process. Biomass gasification challenges include the variable composition of biomass feedstock, leading to inconsistent gas quality. The process also generates tar and other impurities that can damage gasification equipment. Efficient gas cleaning and upgrading technologies are necessary to produce a clean and reliable syngas suitable for various applications, including hydrogen production. [10,11]
- **Coal gasification:** Coal gasification is a process that converts coal into syngas, a mixture of hydrogen, carbon monoxide, and other gases. Despite its potential for producing hydrogen and cleaner fuels, coal gasification faces several challenges. One major concern is the high carbon emissions associated with coal usage, contributing to climate change. Additionally, the process generates toxic byproducts, such as coal ash and heavy metals, necessitating effective waste management. Furthermore, coal gasification requires significant water usage, which can strain water resources. To overcome these challenges, advancements in gasification technologies, carbon capture and storage (CCS) implementation, and a shift towards cleaner feedstocks are essential for sustainable coal gasification applications.[10]
- **Thermochemical water splitting by nuclear Cu-Cl cycle:** Thermochemical water splitting by the nuclear Cu-Cl cycle is an innovative hydrogen production method. It involves a series of high-temperature chemical reactions driven by nuclear heat to extract hydrogen from water. This promising cycle has the potential to offer a clean and efficient pathway for large-scale hydrogen generation, contributing to a greener energy future. This method produces minimal air emissions and total carbon dioxide emissions. Unlike fossil fuel-based approaches, a nuclear power plant does not emit carbon dioxide during operation, significantly reducing total carbon dioxide emissions. [9,11]
- **Solid oxide electrolysis cells (SOECs):** Solid oxide electrolysis cells (SOECs) are cutting-edge devices used for hydrogen production through high-temperature electrolysis of water. They offer a promising solution for efficient and sustainable hydrogen generation. SOECs operate at elevated temperatures, enabling faster ion mobility and reduced electrical resistance. However, challenges remain, such as the high operating temperatures requiring specialised materials, affecting cell durability and cost. Furthermore, gas crossover and electrode degradation can limit the efficiency and lifespan of SOECs. Overcoming these challenges necessitates continuous research

and development to improve materials, increase efficiency, and optimise system design, making SOECs a key player in the transition towards a low-carbon hydrogen economy. [11-13]

- **Photobiological Processes:** This emerging method utilises microorganisms or algae to produce hydrogen through photosynthesis or other biological processes. Although still in the research and development phase, photobiological processes have the advantage of being renewable and potentially more sustainable.[14]

It is worth noting that using renewable energy as the primary source of energy is important ingredient of green hydrogen production and is most carbon efficient.

- **Types of Hydrogen:**

Hydrogen can be classified into various types based on its production methods and associated carbon emissions. The three main types of hydrogen are: [13, 15]

- ✓ **Grey Hydrogen/Brown Hydrogen:** Grey hydrogen is produced from fossil fuels, primarily through steam methane reforming (SMR) or coal gasification. It is the most common type of hydrogen but generates CO2 emissions during production, making it a carbon-intensive option.
- ✓ **Blue Hydrogen:** Blue hydrogen is produced from fossil fuels, similar to grey hydrogen, but incorporates carbon capture and storage (CCS) technologies to capture and store the CO2 emissions. This process reduces the carbon footprint of hydrogen production compared to grey hydrogen.
- ✓ **Green Hydrogen:** Green hydrogen is produced through water electrolysis using renewable energy sources, such as solar or wind power. It has no associated carbon emissions during production, making it the cleanest and most sustainable form of hydrogen.
- ✓ **Turquoise Hydrogen:** Turquoise Hydrogen is generally produced during thermochemical methods.
- ✓ **Orange Hydrogen:** Orange Hydrogen is mostly used for biomass gasification.

In steel industry, green hydrogen is considered the most desirable option due to its potential for carbon neutrality. Utilising green hydrogen can significantly reduce carbon emissions and support the industry's transition towards a low-carbon future. Green hydrogen provides an opportunity for the steel industry to align with climate goals and contribute to global decarbonisation efforts.

IV. Hydrogen utilisation in iron and steel making

The iron and steel industry is exploring various ways to integrate hydrogen into its processes to reduce carbon emissions and enhance sustainability. Hydrogen can be utilised in different stages of steel production, including blast furnace-based processes, direct reduced iron (DRI) production, and electric arc furnace (EAF) operations. The potential benefits and challenges of hydrogen utilisation in these processes are as follows: [3-5,16-18]

- **Blast Furnace-Based Processes:** The traditional ironmaking process relies on blast furnaces, which use coke as a reducing agent. One option for hydrogen integration is to partially replace coke with hydrogen injection, resulting in the production of hot metal with lower carbon intensity. This approach, known as hydrogen injection in blast furnaces, can reduce carbon emissions significantly. However, it requires modifications to the blast furnace design and careful control of operating parameters to maintain stable operation and achieve desired performance. One of the raw materials fed into the blast furnace is limestone – an almost pure form of calcium carbonate. It decomposes in the blast furnace to give a base – calcium oxide: CaCO3 = CaO + CO2. The calcium oxide then joins with silica – one of the most abundant impurities in iron ores – to make calcium silicate, a salt which is formed as molten slag: CaO + SIO2 = CaSIO3.

- **Direct Reduced Iron (DRI) Production:** DRI, also known as sponge iron, is produced by reducing iron ore using a reducing gas, typically derived from natural gas or coal. By replacing fossil-based reducing gases with hydrogen, the carbon emissions associated with DRI production can be substantially reduced. Hydrogen-based DRI processes offer the advantage of producing "green" iron with lower carbon footprints and can serve as a feedstock for subsequent steelmaking processes. [17, 18]
- **Electric Arc Furnace (EAF) Operations:** EAFs are widely used in steel production, particularly for recycling scrap steel. Hydrogen injection in EAFs can enhance energy efficiency, increase productivity, and reduce specific energy consumption. The injection of hydrogen gas into the EAF can help improve combustion and temperature control, resulting in faster melting and reduced energy requirements. Additionally, hydrogen injection can lead to lower carbon emissions compared to using natural gas or other fossil-based fuels.

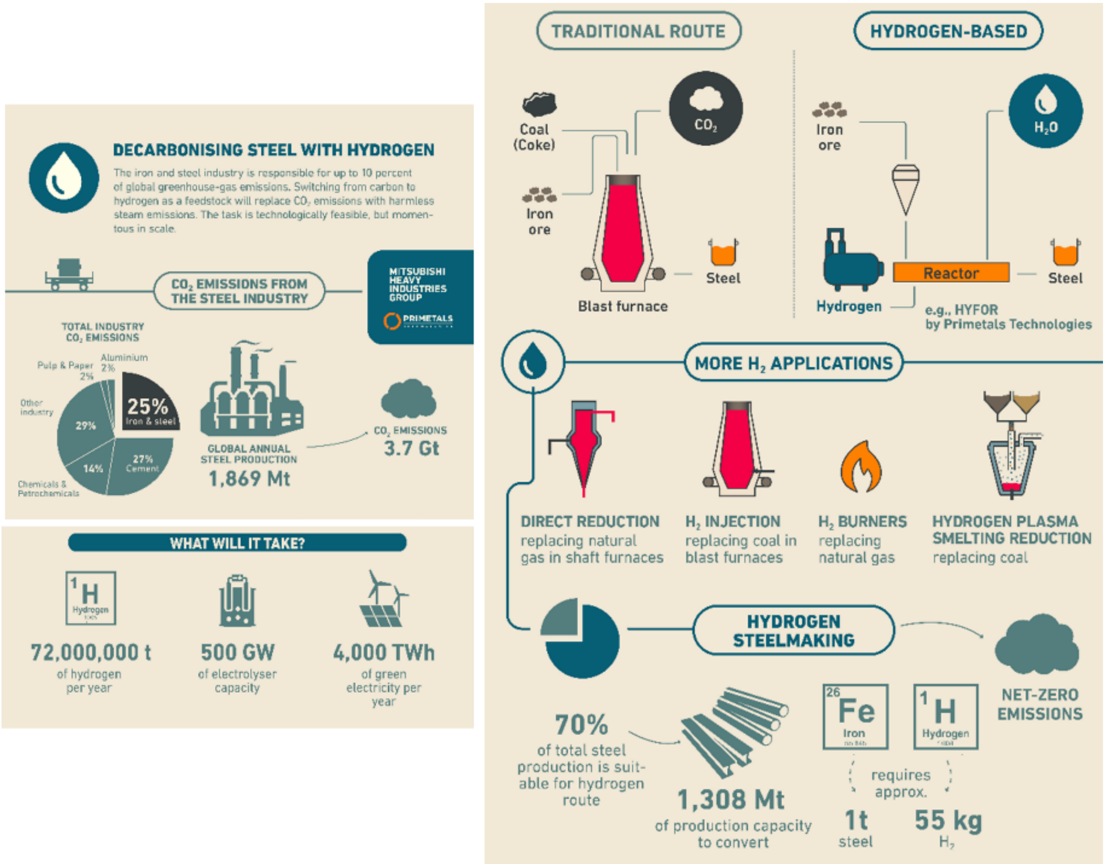

Figure 5: Decarbonisation through hydrogen during steel making, difference between the traditional route and hydrogen route for steel making in steel industry, global CO_2 emissions and amount of hydrogen to be required. [17]

The possibilities and process efficiencies are much ahead by using hydrogen and it can be clearly depicted in Figure 5. The integration of hydrogen into iron and steelmaking processes requires careful consideration of safety, process compatibility, equipment modifications, and infrastructure development. Collaborative efforts between governments, industries, and research institutions are crucial to addressing these aspects and accelerating the widespread integration of hydrogen technologies, ushering in a cleaner and more environmentally friendly future for steel production. [19, 20]

V. Case Studies on Hydrogen usage in Iron and Steel Making

Several case studies and pilot projects have been conducted worldwide to explore the potential of hydrogen utilisation in the iron and steel industry. [21-27] These initiatives demonstrate the feasibility, challenges, and opportunities associated with integrating hydrogen into various steelmaking processes. Here are notable case studies showcasing hydrogen use in iron and steel technology:

- **HYBRIT Project (Sweden):** The HYBRIT (Hydrogen Breakthrough Ironmaking Technology) project, a collaboration between SSAB, LKAB, and Vattenfall, aims to replace fossil fuels with hydrogen in the steelmaking process. The project employs a direct reduction process using hydrogen produced from renewable sources, resulting in "green" hydrogen-based sponge iron (DRI). This approach has the potential to significantly reduce carbon emissions, as demonstrated in pilot-scale trials. [21] Challenges faced by the project include the high cost of green hydrogen production, the need for large-scale infrastructure, and ensuring a stable and cost-effective supply of renewable energy. [21]
- **H2Future Project (Austria):** The H2Future project, led by Voestalpine and partners, focuses on hydrogen-based DRI production. It utilises hydrogen generated from renewable energy sources to produce high-quality DRI. H2Future utilises hydrogen produced via electrolysis using renewable energy sources. The project aims to develop an innovative and sustainable process that can serve as a blueprint for transitioning to low-carbon steel production. [22]
- **Steelanol Project (Belgium):** The Steelanol project, led by ArcelorMittal, Lanzatech and Primetals Technologies, explores the use of hydrogen and carbon capture and utilization (CCU) technologies to convert waste gases from steelmaking into low-carbon chemicals, including ethanol. The project focuses on capturing CO_2 emissions from steel production and utilizing Lanzatech's gas fermentation technology to convert them into bioethanol. This process reduces the carbon footprint of the steel industry and produces a valuable biofuel. Challenges faced by the project include optimizing the efficiency and scalability of the gas-to-ethanol conversion process, managing the economics of large-scale implementation, and ensuring the long-term viability and competitiveness of the Steelanol solution in the biofuel market. The project aims to demonstrate the technical and economic viability of producing sustainable chemicals from steel mill emissions. [23]
- **Salzgitter Hydrogen Steelmaking (Germany):** Salzgitter AG is actively involved in several hydrogen-related steelmaking initiatives. The company is developing a hydrogen-based direct reduction plant to produce DRI using hydrogen from renewable energy sources. Additionally, Salzgitter AG is working on a project to inject hydrogen into blast furnaces to reduce carbon emissions and improve energy efficiency. [24,25]

Challenges include the high cost of green hydrogen production, the development of efficient hydrogen-based technologies, and the establishment of a reliable and sustainable hydrogen supply chain.

- **HIsarna Pilot Plant (Netherlands):** The HIsarna process, developed by Tata Steel and partners, combines ore smelting and pre-reduction in a single step, using hydrogen as a reducing agent. The project specifically aims to revolutionize the traditional blast furnace process bypassing the need for coke. This process significantly reduces carbon emissions and improves energy efficiency. However, challenges include optimizing the process for consistent and efficient iron production, addressing operational issues for stable and reliable operations, and ensuring the availability and sustainability of the powdered coal supply. Additionally, scaling up the technology for commercial production and cost competitiveness are critical challenges for its widespread adoption. [26]

These case studies highlight the ongoing efforts and progress in implementing hydrogen-based solutions in the iron and steel industry. They provide valuable insights into the technical feasibility, environmental impact, and economic viability of hydrogen utilization in different steelmaking processes. While these projects demonstrate the potential of hydrogen in the iron and steel sector, several challenges must be addressed for widespread adoption. These include the availability and cost of hydrogen, development of suitable infrastructure, and ensuring safety in handling and storage of hydrogen. [22, 26]

- **Indian scenario:**

One notable Indian case study highlighting the role of hydrogen in the iron and steel industry is the joint initiative between Indian Oil Corporation Limited (IOCL) and the National Thermal Power Corporation (NTPC). [27] This collaborative project aims to establish a pilot-scale plant for the production of green hydrogen and its utilization in the steelmaking process. The project involves setting up a green hydrogen generation unit at the IOCL's Mathura refinery. [27] The hydrogen produced will be utilised in the NTPC's gas-based power plant and also supplied to nearby steel plants for their steelmaking processes. This integration of hydrogen in steel production is expected to reduce carbon emissions and contribute to the decarbonisation of the iron and steel sector.

The Indian government is also actively supporting the adoption of hydrogen in the iron and steel industry through policy frameworks and initiatives. [27] The National Hydrogen Energy Mission, launched in 2021, aims to promote the production, storage, and utilization of hydrogen in various sectors, including iron and steel. [28] This mission provides a roadmap for the widespread adoption of hydrogen technologies in India and supports research, development, and demonstration projects. The role of hydrogen in the Indian iron and steel industry is significant as it offers a pathway to decarbonise the sector and reduce reliance on fossil fuels. By embracing hydrogen, Indian steelmakers can enhance their environmental performance, improve energy efficiency, and meet the country's ambitious climate targets. However, there are challenges to overcome, including the development of infrastructure for hydrogen production, storage, and transportation. Additionally, ensuring the cost competitiveness of hydrogen-based processes and addressing safety considerations are crucial for successful implementation. The recent launch of Kalyani FERRESTA by the Kalyani group has made a significant move towards the green steel among many steel industries in the nation. [29] TATA

Steel, Jindal Steel, SAIL and other players in the market has already taken initiative towards coal gasification and imparting hydrogen usage in the steel industry. [29-30] Overall, the Indian case study exemplifies the growing recognition of hydrogen's potential in the iron and steel industry and highlights the country's commitment to transitioning towards a more sustainable and low-carbon steel production sector.

VI. Challenges in usage of hydrogen in steel industry and future prospects

The usage of hydrogen in the iron and steel industry brings several challenges that need to be addressed for successful implementation. These challenges include: [21, 22]

- **Hydrogen Supply and Infrastructure:** Establishing a reliable and cost-effective hydrogen supply chain is essential. This involves ensuring sufficient hydrogen production capacity, developing storage and transportation infrastructure, and integrating hydrogen into existing steelmaking processes and equipment. Current hydrogen production methods mostly rely on fossil fuels, defeating the purpose of emissions reduction. [23]
- **Cost Considerations:** Hydrogen production, especially from renewable sources, can be expensive compared to conventional fossil fuel-based processes. The high capital and operational costs associated with hydrogen production, storage, and distribution need to be addressed to make hydrogen economically viable for widespread adoption in the iron and steel industry. The retrofitting or development of new infrastructure to accommodate hydrogen-based processes requires significant investments. [22, 24, 25]
- **Safety Concerns:** Hydrogen is highly flammable and requires special handling and safety measures. Ensuring the safe storage, transportation, and usage of hydrogen in industrial settings is crucial to mitigate the risks associated with its utilization.
- **Technological Challenges:** Adapting steelmaking processes to effectively utilise hydrogen can pose technical challenges. For example, the injection of hydrogen into blast furnaces or its integration into direct reduction processes requires modifications to equipment and operating parameters to maintain stable and efficient operations. These transitioning from conventional coke-based methods to hydrogen-based processes demands adjustments in operational practices and workforce skills. [26]

Overcoming these challenges requires concerted efforts from stakeholders, technological advancements, and supportive policies Addressing these challenges requires concerted efforts and collaboration among stakeholders, including policymakers, steel manufacturers, technology providers, and research institutions, to develop innovative solutions, improve efficiency, drive down cost and to realise hydrogen's full potential in making steel production greener and more sustainable.

Table 1: Green hydrogen and renewable capacities required for annual steel production [38]

Steel Production Source	Annual Steel Production	Green Hydrogen Required	Electrolyser Capacity Required	Total Renewables Capacity Required
Base Reference	1 Mt	50 kT	0.56 GW	0.7 GW
U.S.	85.8 Mt	4.3 Mt	48 GW	60 GW

Europe	103 Mt	5.2 Mt	58 GW	72 GW
China	1032.8 Mt	51.6 Mt	581 GW	726 GW
Global	**1951 Mt**	**97.6 Mt**	**1,097 GW**	**1,371 GW**

The requirements for green hydrogen and associated renewable energies are depicted in Table 1. The data is shown for three developed countries where the requirement of H_2 and the capacity of renewable energy is matter of concern. The real requirements of such hue capacities of renewable energy will merely depend upon major factors such as land availability for installing the renewable energy stations, improving efficiencies, proper transfer of energy without many losses to grid, economic issues and policies. The future prospects of hydrogen usage in the steel industry are promising, driven by the global imperative to reduce carbon emissions and transition to a low-carbon economy. [41-46] Hydrogen offers the potential for significant decarbonisation, improved energy efficiency, and enhanced sustainability in steel production. [11, 43] The integration of hydrogen technologies, such as hydrogen injection in blast furnaces, direct reduction processes, and hydrogen-based electric arc furnaces, holds the potential to transform the steel industry and contribute to a greener and more sustainable future. [8, 48-49]

The difference in carbon emission during various steelmaking routes were analysed and have been summarised in the table below.

Table 2 (Abbreviations – BF: blast furnace; BOF: basic oxygen furnace; HRC: hot rolled coil; EAF: electric arc furnace; LS: liquid steel) [10]

Route	Energy Needed	CO_2 Emission
Standard BF-BOF route	18.8 GJ/t_{HRC} (mostly coal)	1850 kg_{CO2eq}/t_{HRC}
Direct reduction + EAF	15.6 GJ/t_{HRC} (gas and electricity)	970 kg_{CO2eq}/t_{HRC}
Hydrogen-based route	15.4 GJ/t_{HRC}	196 kg_{CO2eq}/t_{HRC}
	14.7 GJ/t_{LS} (mostly electricity)	25 kg_{CO2eq}/t_{LS}
	13.3 GJ/t_{LS}	53 kg_{CO2eq}/t_{LS}

The energy consumption in Hydrogen based route is similar to that of Direct reduction + EAF route. Within Hydrogen based routes, three different data are presented basis three different studies. The variations are dependent on boundary conditions and assumption of three different studies. While DR + EAF emits ~50% CO2 compared to BF-BOF route, Hydrogen based steel production can reduce CO2 by 90% or more compared to BF-BOF route.

In conclusion, hydrogen emerges as a beacon of hope for the steel industry, offering a green pathway to significantly reduce its carbon emissions and environmental impact. While challenges remain, continuous research, development, and collaboration can pave the way for a sustainable future where hydrogen plays a central role in reshaping the steelmaking industry. Embracing this transformative potential of hydrogen is not only an economic opportunity for the industry but also a crucial step towards achieving global climate goals.

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