Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

# Hydrogen-Based Ironmaking as a Cleaner Production Pathway toward Carbon-Neutral Steel: A Comparative Systems-Level Assessment

**[1] Arunansu Haldar, [2] Milan Samanta**

[1] Professor, Department of Mechanical Engineering, Suresh Gyan Vihar Univesity, Jaipur

[2] Research Scholar, C3WR, Suresh Gyan Vihar Univesity, Jaipur

**Abstract:-** The iron and steel industry is responsible for approximately 7–9% of global carbon dioxide ($CO_2$) emissions, making its decarbonization essential for achieving international climate targets. Among emerging solutions, hydrogen-based ironmaking has gained significant attention as a potential cleaner production pathway. This study presents a comprehensive, systems-level comparative assessment of conventional blast furnace–basic oxygen furnace (BF–BOF), natural gas–based direct reduction (NG–DRI), hydrogen-based direct reduction coupled with electric arc furnace ($H_2$–DRI + EAF), and hydrogen plasma smelting reduction (HPSR). The analysis integrates thermodynamic feasibility, lifecycle $CO_2$ emission intensity, total energy demand, technology readiness level (TRL), and infrastructure compatibility within a unified cleaner production framework. Results show that BF–BOF remains the most carbon-intensive route, emitting 1.8–2.2 t $CO_2$ per tonne of crude steel, while NG–DRI provides only partial mitigation. In contrast, $H_2$–DRI + EAF can reduce direct $CO_2$ emissions by up to 95–98% and achieve near-zero cradle-to-gate emissions when supplied with renewable electricity. However, these emission benefits are accompanied by a 25–30% increase in total energy demand, largely driven by electricity-intensive hydrogen production via electrolysis. Technology readiness assessment indicates that $H_2$–DRI has reached an advanced development stage (TRL 7–8), supported by large-scale pilot and early commercial projects, whereas plasma-based routes remain at lower maturity levels. The findings demonstrate that hydrogen-based direct reduction represents the most viable near- to mid-term pathway for deep decarbonization of primary steelmaking, provided that it is supported by large-scale renewable electricity deployment, cost-competitive green hydrogen supply, and enabling policy frameworks. Overall, this study highlights that effective cleaner production in the steel sector requires integrated coordination between process innovation, energy system transformation, and industrial policy to achieve durable and scalable emission reductions.

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

KEYWORDS: Steel industry emissions, $CO_2$ intensity, decarbonization of steel, energy-intensive industries, climate change mitigation, net-zero emissions, sustainable steel production, IEA Sustainable Development Scenario, emission reduction targets, Paris Agreement, low-carbon steel, energy efficiency, industrial decarbonization, crude steel production

## 1. Introduction

The steel industry significantly contributes to global $CO_2$ emissions, accounting for approximately 7-9% of total emissions, It releases around 2.6 gigatonnes of carbon dioxide each year, which underscores the urgent need for decarbonization strategies to meet climate targets like those set by the Paris Agreement (Speizer et al., 2023; IEA, 2023; Adhikari & Khanam, 2024; Skaf et. al., 2025). Current steel production methods, particularly those reliant on coal, are highly energy-intensive and environmentally damaging, necessitating a shift towards more sustainable practices (Vidyashree & Sheriff, 2024; Rippy et al., 2024). Emerging technologies such as hydrogen direct reduction and carbon capture are pivotal in reducing emissions, alongside increased recycling of steel scrap, which can save up to 80% of energy compared to primary production (Reck et al., 2024; Speizer et al., 2023). However, challenges remain, including technological dependencies and economic competitiveness, which must be addressed to facilitate a transition to low-carbon steelmaking (Vidyashree & Sheriff, 2024; Adhikari & Khanam, 2024). A comprehensive approach integrating efficiency improvements, alternative reductants, and enhanced recycling is essential for achieving sustainability in the steel sector.

### 1.1 Carbon Intensity of Conventional Iron and Steel Production

The blast furnace–basic oxygen furnace (BF–BOF) route remains the predominant method for steel production, accounting for approximately 70% of global output, yet it is highly carbon-intensive, emitting about 1.8–2.2 tonnes of $CO_2$ per tonne of steel produced due to the reliance on metallurgical coke as a reducing agent (Schneising et. al., 2024; Iron and Steel, n.d.). Despite advancements in energy efficiency, achieving a 20% reduction in energy use since 1990, the process's inherent dependence on carbon-based chemistry limits further improvements (Cavaliere, 2019). Alternative methods, such as natural-gas-based direct reduction (NG–DRI), only partially mitigate emissions, as fossil methane remains a primary reducing agent (Schneising et. al., 2024). Innovations like top gas recycling, hydrogen use, and alternative fuels, including biomass and plastic waste, are being explored to enhance sustainability and reduce greenhouse gas emissions (Cavaliere, 2019; Schmöle & Lüngen, 2005). The steel industry's significant energy consumption and $CO_2$ emissions underscore the urgent need for fundamental redesigns in ironmaking processes to achieve near-zero emissions.

### 1.2 Climate Commitments and Policy Drivers

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

The steel industry, responsible for approximately 7-10% of global greenhouse gas emissions, faces significant challenges in achieving the net-zero targets outlined in the Paris Agreement, necessitating a reduction in carbon intensity by over 90% by 2050 (Mokrzycki & Gawlik, 2024; Urban, 2023). Key strategies for decarbonization include transitioning from coal-based production methods, such as the blast furnace process, to hydrogen-based and electric arc furnace technologies, which utilize renewable energy sources (Mokrzycki & Gawlik, 2024; Urban, 2023). The integration of green hydrogen for direct reduction and enhanced recycling practices are critical to mitigating emissions (Algers et al., 2025; Rodriguez Diez et al., 2023). Additionally, supportive policies like the EU's Carbon Border Adjustment Mechanism and national hydrogen strategies are essential to incentivize low-carbon steel production and ensure competitiveness in a transitioning market (Algers et al., 2025; Bataille, 2020). Achieving these goals requires substantial investments in infrastructure and technology, alongside comprehensive policy frameworks tailored to regional contexts.

Hydrogen is increasingly recognized as a crucial element in the decarbonization of the steel industry, particularly through hydrogen-based direct reduction processes that can significantly lower $CO_2$ emissions. The International Energy Agency highlights that transitioning from the traditional blast furnace-basic oxygen furnace (BF-BOF) route to hydrogen-based direct reduction could reduce emissions from approximately 1.9 t $CO_2$ per tonne of steel to below 0.1 t $CO_2$, contingent on the use of low-carbon electricity for hydrogen production (Skaf, 2025; Rechberger et al., 2020). This shift necessitates substantial renewable energy resources, with estimates suggesting that nearly 2,000 TWh of additional renewable electricity will be required annually by 2050 to meet hydrogen demands for steelmaking alone (Gielen et al., 2020). Furthermore, the integration of renewable hydrogen not only promises lower emissions but also presents economic opportunities, particularly in regions with abundant renewable resources, such as Australia (Algers et al., 2025; Elsheikh & Eveloy, 2023). Thus, the successful implementation of hydrogen-based steelmaking is closely tied to broader energy transition efforts and renewable energy availability.

### 1.3 Evolution of Hydrogen in Metallurgical Reduction

Hydrogen-based reduction of iron oxides presents a promising alternative to traditional carbon-intensive methods, significantly reducing $CO_2$ emissions in steel production. This process, which involves the reaction of iron ore with hydrogen to produce metallic iron and water, is thermodynamically favorable, particularly at elevated temperatures and hydrogen concentrations (Miškovičová et al., 2024; Skaf, 2025). Recent advancements in electrolyzer efficiency and the expansion of renewable energy sources have revitalized interest in hydrogen metallurgy, as demonstrated by successful pilot projects like HYBRIT in Sweden and SALCOS in Germany, which have achieved over 95% reductions in direct $CO_2$ emissions (Skaf, 2025; Tang et al., 2020). Life Cycle Assessments indicate that

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

hydrogen-based processes can emit as little as 0.16 kg$CO_2$-eq/kg iron when powered by renewable energy, showcasing a potential 74-82% reduction in emissions compared to conventional methods (Skaf, 2025). However, challenges remain, including the need for substantial infrastructure and cost-effective hydrogen production to facilitate widespread adoption.

### 1.4 Comparative Low-Carbon Ironmaking Pathways

Hydrogen-based direct reduction ($H_2$–DRI) combined with electric arc furnace (EAF) technology represents a promising low-carbon pathway for steelmaking, significantly reducing $CO_2$ emissions compared to traditional methods. While natural gas-based direct reduction (NG–DRI) can lower emissions by 30–50% relative to the blast furnace-basic oxygen furnace (BF-BOF) route, it still relies on fossil fuels, emitting approximately 1.9 t of $CO_2$ per ton of crude steel (Rechberger et al., 2020). In contrast, $H_2$–DRI can achieve emissions as low as 0.03–0.1 t per ton of steel when powered by renewable energy sources (Skaf, 2025; Elsheikh & Eveloy, 2023). However, this process demands substantial renewable electricity and electrolysis capacity, which poses challenges in terms of energy requirements and technological maturity (Elsheikh & Eveloy, 2023). Advanced methods like molten oxide electrolysis and hydrogen plasma smelting reduction promise near-zero emissions but are not yet fully developed (Skaf, 2025). While $H_2$–DRI with EAF offers a viable transition towards greener steel production, its success hinges on large-scale decarbonization of electricity sources.

### 1.5 Technological and Economic Constraints

Hydrogen-based ironmaking presents significant environmental advantages, notably a reduction in CO2 emissions by up to 90% compared to traditional blast furnace methods (Patisson & Mirgaux, 2020). However, the transition faces substantial economic and infrastructural hurdles. Upgrading existing facilities to hydrogen-compatible shaft furnaces requires investments estimated at US$1,000–1,200 per tonne of annual steel capacity. Additionally, the current cost of green hydrogen, ranging from *US$*3–6 per kilogram, is prohibitively high compared to fossil-based alternatives, although projections suggest a decrease to around US$1 per kilogram by the mid-2030s(Skaf, 2025; Zeng et al., 2025). Furthermore, the successful implementation of hydrogen-based processes necessitates advancements in hydrogen transport and storage, solutions to hydrogen embrittlement, and extensive workforce training (Skaf, 2025; Bhaskar et al., 2020). Thus, large-scale adoption hinges on technological improvements, coordinated policy support, and comprehensive long-term planning.

### 1.6 Research Gap and Contribution of This Study

Existing research provides valuable knowledge on topics such as hydrogen reduction behavior, reactor design, and cost analysis, but most studies examine these aspects separately. As a result, there is still a clear lack of integrated assessments that jointly evaluate thermodynamic feasibility, lifecycle emissions, energy demand, technology readiness, and policy

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

considerations within a single analytical framework. This study addresses this gap by offering a comprehensive comparative analysis of conventional BF–BOF, NG–DRI, $H_2$–DRI, and plasma-based ironmaking routes from a cleaner production perspective. By combining thermodynamic analysis, emission modeling, technology readiness assessment, and policy implications, this work identifies the most realistic pathways toward carbon-neutral primary steel production by 2040. The results provide practical guidance for industry stakeholders and policymakers seeking to align technological innovation with sustainable manufacturing and climate mitigation goals.

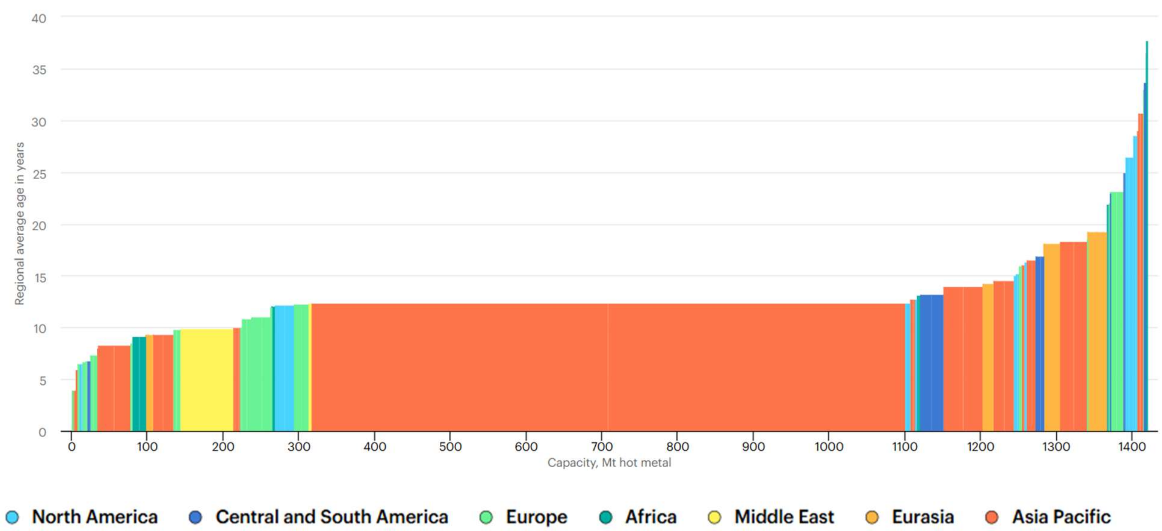


**Figure 1**. Age profile of global production capacity for the steel sector (blast furnaces and DRI furnaces)

*Source:* https://www.iea.org/reports

## 2. Methodology and Analytical Framework

### 2.1 Research Design and Analytical Scope

This study uses a comparative, systems-based approach to evaluate different ironmaking pathways from a cleaner production perspective. The analysis combines thermodynamic feasibility, lifecycle $CO_2$ emissions, energy demand, and technology readiness level (TRL) to assess both environmental performance and practical feasibility of emerging ironmaking technologies. This integrated approach is important because it considers not only potential emission reductions, but also technology maturity and system-level constraints that affect real industrial deployment (ISO, 2006; IEA, 2023).

Four ironmaking routes were selected for comparison:
(i) conventional blast furnace–basic oxygen furnace (BF–BOF),
(ii) natural-gas-based direct reduction with electric arc furnace (NG–DRI + EAF),
(iii) hydrogen-based direct reduction with

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

electric arc furnace ($H_2$–DRI + EAF), and (iv) hydrogen plasma smelting reduction (HPSR).

These routes represent different stages of steelmaking decarbonization, ranging from well-established carbon-intensive processes to emerging near-zero-emission technologies. Their selection allows a clear comparison between incremental improvements and transformative cleaner production pathways (Vogl et al., 2018; IEA, 2023).

## 2.2 System Boundaries and Functional Unit

The assessment uses a cradle-to-gate system boundary, covering iron ore preparation, iron reduction, primary steel production, and all related energy inputs up to the plant gate. Downstream stages such as rolling, finishing, and steel use were excluded because they are largely independent of the ironmaking route and do not significantly affect comparisons between primary production technologies. In contrast, upstream emissions from electricity generation and hydrogen production were included to avoid shifting environmental impacts and to remain consistent with cleaner production and lifecycle assessment principles (ISO, 2006; IEA, 2023).

The functional unit for this study is one tonne of crude steel produced at the plant gate. All material inputs, energy use, and carbon dioxide emissions were normalized to this unit to allow consistent comparison across the different ironmaking routes. Lifecycle emissions were divided into direct emissions from reduction reactions and on-site fuel use, and indirect emissions from electricity consumption and hydrogen production. Emissions from raw material extraction and transport were considered qualitatively, as they are similar across the assessed technologies and involve higher uncertainty in available data.

## 2.3 Thermodynamic and Process Feasibility Assessment

The thermodynamic feasibility of iron oxide reduction was evaluated using well-established reaction equilibria and Gibbs free energy ($\Delta G°$) relationships. For conventional carbon-based reduction, the main reaction involves carbon monoxide reducing iron oxide to metallic iron while forming carbon dioxide. In hydrogen-based reduction, hydrogen reacts with iron oxide to produce iron and water, a reaction that becomes more favorable at higher temperatures but requires additional energy input due to its endothermic nature. Thermodynamic data such as reaction enthalpies, equilibrium constants, and temperature effects were obtained from established thermodynamic databases and published literature, and Ellingham-type diagrams were used to compare the reduction potential of carbon monoxide and hydrogen across relevant temperature ranges (Sohn & Fruehan, 2006; Turkdogan, 1980).

Process feasibility was assessed qualitatively by reviewing operating temperature ranges, required gas compositions ($H_2/H_2O$ ratios), and metallization levels reported in laboratory and pilot-scale studies. This approach allows evaluation of whether favorable thermodynamic conditions can be practically achieved in real processes and whether hydrogen-based reduction can deliver reliable cleaner production performance under

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

industrially relevant conditions (Vogl et al., 2018).

### 2.4 Energy Demand and Hydrogen Supply Modeling

The total energy demand was calculated as the combined thermal and electrical energy required to produce one tonne of crude steel. For the BF–BOF route, energy use includes coke production, blast furnace operation, and basic oxygen furnace processing. For DRI-based routes, energy demand comes mainly from shaft furnace operation, electric arc furnace melting, and supporting systems (IEA, 2023).

For hydrogen-based pathways, hydrogen production through water electrolysis is the largest source of energy use. Based on current industrial benchmarks, electrolysis requires about 50–55 kWh of electricity per kilogram of hydrogen, and hydrogen demand for $H_2$–DRI was assumed to be 50–60 kg per tonne of steel, consistent with data from pilot and demonstration projects (Vogl et al., 2018; Skaf et al., 2025). To reflect the cleaner production impact of energy supply, electricity-related emissions were evaluated under two scenarios: (a) a renewable electricity scenario with emissions below 50 g $CO_2$/kWh, and (b) a fossil-dominated grid scenario exceeding 600 g $CO_2$/kWh. This scenario-based approach highlights the strong dependence of hydrogen-based steelmaking on power sector decarbonization and prevents overestimation of emission reduction benefits (IEA, 2023).

### 2.5 Technology Readiness Level (TRL) Assessment

Technology maturity was evaluated using the Technology Readiness Level (TRL) framework, adapted from classifications commonly used by the International Energy Agency. TRL values range from 1, where basic scientific principles are observed, to 9, where a technology is fully commercialized and widely deployed (IEA, 2023). Based on reported operating status, pilot-scale demonstrations, and announced industrial projects, BF–BOF and NG–DRI were classified as TRL 9, reflecting full commercial maturity, while $H_2$–DRI was assigned TRL 7–8 due to successful large-scale pilot plants and early commercial deployment. In contrast, hydrogen plasma smelting reduction remains at TRL 4–5, as development is still limited to laboratory and pilot-scale studies (Vogl et al., 2018; IEA, 2023). Including TRL in the analysis allows a clear distinction between theoretical cleaner production potential and near-term industrial feasibility, which is often overlooked in studies focused only on emission performance.

### 2.6 Comparative Evaluation Framework

The final comparison combines results across four key dimensions: (i) $CO_2$ emission intensity (t $CO_2$ per tonne of steel), (ii) total energy demand (MWh per tonne of steel), (iii) technology readiness level (TRL), and (iv) infrastructure compatibility and scalability. These factors were assessed together to identify trade-offs between emission reduction potential and practical implementation. Instead of ranking technologies using a single indicator, this study focuses on balanced cleaner production performance, recognizing that the most

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

environmentally efficient option may not yet be ready for large-scale industrial deployment (ISO, 2006; IEA, 2023).

### 2.7 Methodological Limitations

Several limitations should be noted. First, this analysis is based on secondary data from pilot studies and publicly available sources, which introduces uncertainty due to differences in operating conditions and reporting methods. Second, future cost trends for hydrogen and renewable electricity remain uncertain and were not explicitly modeled in this section. Finally, regional differences in electricity grid carbon intensity and resource availability were not considered in detail, even though they are likely to strongly influence real-world implementation (ISO, 2006). Despite these limitations, the integrated analytical framework provides a solid basis for comparison of ironmaking pathways and helps identify the most promising cleaner production options under realistic industrial constraints.

## 3. Results and Discussion

The comparative analysis shows clear differences between ironmaking routes in terms of carbon dioxide emissions, energy use, and technology maturity. These differences highlight the key trade-offs involved in moving from conventional carbon-based ironmaking to hydrogen-based cleaner production pathways. The following discussion brings together thermodynamic behavior, lifecycle emissions, energy requirements, and industrial readiness to provide an overall interpretation of the results.

### 3.1 Thermodynamic and Kinetic Performance of Hydrogen-Based Reduction

Thermodynamic analysis confirms that hydrogen is an effective reducing agent for iron oxides at high temperatures. Hydrogen reduction of hematite becomes increasingly favorable above about 800 °C, as shown by Gibbs free energy trends derived from Ellingham-type diagrams. Although this reaction is endothermic and requires external heat, the absence of carbon means that no carbon dioxide is formed during reduction, effectively separating iron production from fossil carbon emissions (Turkdogan, 1980; Sohn & Fruehan, 2006). Results from laboratory and pilot-scale studies consistently show metallization levels above 95% under hydrogen-rich conditions when suitable temperatures and gas compositions are maintained. At lower temperatures, reaction rates are mainly controlled by chemical reactions, while at higher temperatures gas diffusion through the porous iron layer becomes the limiting factor. These findings highlight the importance of pellet structure, porosity, and gas flow control for stable and efficient hydrogen-based reduction. From a cleaner production perspective, the strong thermodynamic performance of hydrogen reduction provides a solid basis for deep decarbonization, provided that sufficient low-carbon energy is available to supply heat and hydrogen (Vogl et al., 2018; IEA, 2023).

### 3.2 Comparative Carbon Dioxide Emission Intensity

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

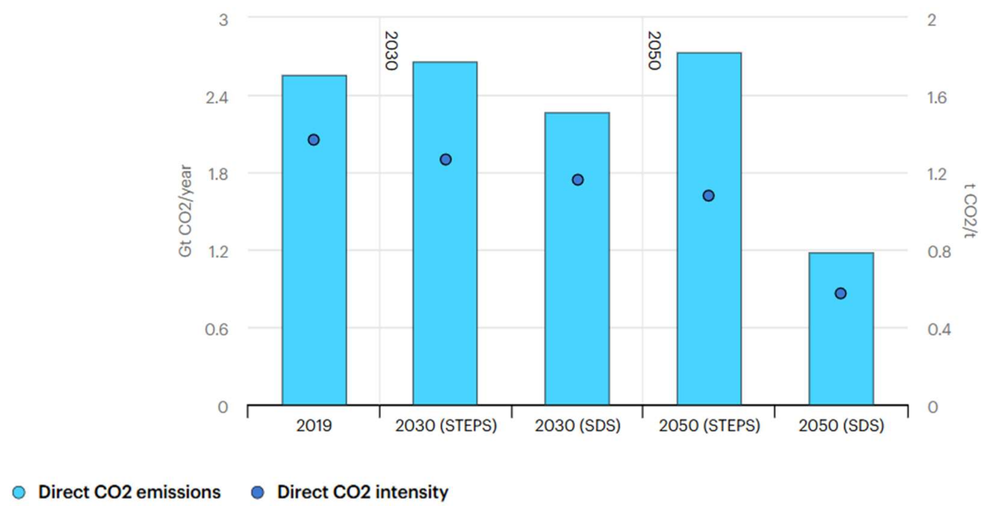


**Figure 2**. Direct CO2 emissions in the iron and steel sector by scenario, 2019-2050.

*Source:* https://www.iea.org/reports

Lifecycle emission results show that hydrogen-based ironmaking can significantly reduce carbon dioxide emissions compared to conventional blast furnace routes. The BF–BOF process has the highest emission intensity, typically producing 1.8–2.2 tonnes of $CO_2$ per tonne of crude steel, due to both direct reduction reactions and supporting processes. Natural-gas-based direct reduction lowers emissions by about 30–50%, but its benefits are limited because it still relies on fossil methane and related upstream emissions (Vogl et al., 2018; IEA, 2023). In comparison, hydrogen-based direct reduction can reduce direct $CO_2$ emissions by approximately 95–98% relative to BF–BOF systems. When hydrogen is produced using renewable electricity, total cradle-to-gate emissions can fall below 0.1 tonnes of $CO_2$ per tonne of steel, approaching near-zero emission production. However, these benefits strongly depend on electricity sources, as emissions from hydrogen electrolysis increase sharply when fossil-based grids are used. This confirms that hydrogen-based ironmaking can only deliver true cleaner production outcomes when combined with a highly decarbonized power system (Skaf, 2025; IEA, 2023). All quantitative values are presented as representative ranges derived from peer-reviewed literature, pilot studies, and international roadmaps, and are subject to system boundaries, regional conditions, and energy supply assumptions.

**Table 1.** Lifecycle $CO_2$ emission intensity of major ironmaking routes.

| **Ironmaking Route** | **Direct $CO_2$ Emissions (t $CO_2$/t steel)** | **Lifecycle $CO_2$ Emissions (t $CO_2$/t steel)** | **Emission Reduction vs. BF–BOF** |
|---|---|---|---|

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

| | | | |
|---|---|---|---|
| BF–BOF | 1.8–2.2 | 2.1–2.4 | — |
| NG–DRI + EAF | 1.1–1.4 | 1.2–1.6 | 30–50% |
| $H_2$–DRI + EAF (renewable $H_2$) | 0.02–0.1 | <0.1 | 95–98% |
| $H_2$–DRI + EAF (fossil grid) | ~0.02 | 0.6–1.2 | Highly grid-dependent |

*Source:* Data synthesized from International Energy Agency (2023), Vogl et al. (2018), and Skaf (2025).

### 3.3 Energy Demand and System-Level Trade-Offs

Although hydrogen-based ironmaking greatly reduces carbon emissions, it requires significantly more energy than conventional steelmaking. The total energy demand of hydrogen-based direct reduction is about 25–30% higher than that of the blast furnace route, mainly because producing hydrogen through water electrolysis is electricity-intensive. This higher energy requirement is one of the main challenges for large-scale deployment and raises concerns about whether future energy systems can supply sufficient low-carbon electricity (Vogl et al., 2018; IEA, 2023). These results show that the environmental benefits of hydrogen-based steelmaking are closely linked to the broader energy transition. Widespread adoption would require a major expansion of renewable electricity generation, which could add pressure to power systems that are already undergoing decarbonization. From a cleaner production perspective, this highlights that emission reduction strategies in heavy industry must be assessed as part of integrated energy–industrial systems, rather than as isolated technological changes (IEA, 2023).

**Table 2**. Energy Demand Comparison across Ironmaking Routes (Hydrogen routes shift energy demand from thermal → electrical, explaining system-level trade-offs.)

| Ironmaking Route | Thermal Energy (MWh/t steel) | Electrical Energy (MWh/t steel) | Total Energy Demand (MWh/t steel) |
|---|---|---|---|
| BF–BOF | 4.5–5.0 | 0.4–0.6 | 5.0–5.6 |
| NG–DRI + EAF | 3.0–3.5 | 1.0–1.2 | 4.0–4.7 |
| $H_2$–DRI + EAF | 1.5–2.0 | 3.5–4.0 | 5.2–6.0 |
| HPSR | — | 6.0–7.5 | 6.0–7.5 |

*Source:* Compiled from International Energy Agency (2023), Vogl et al. (2018), and Turkdogan (1980).

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

### 3.4 Technology Readiness and Industrial Feasibility

An assessment of technology readiness levels shows clear differences between ironmaking pathways. Conventional blast furnace and natural-gas-based direct reduction technologies are fully mature and widely used, placing them at the highest readiness levels. Hydrogen-based direct reduction is at an advanced stage of development, supported by large pilot plants and early commercial projects. Initiatives such as HYBRIT in Sweden and SALCOS in Germany demonstrate that hydrogen-based direct reduction can operate reliably at industrially relevant scales (Vogl et al., 2018; IEA, 2023). In contrast, hydrogen plasma smelting reduction remains at a lower readiness level, with most work still limited to laboratory and pilot-scale testing. Although plasma-based processes could eliminate coke ovens and sinter plants, their very high electricity demand and unresolved technical challenges limit near-term use. Overall, these findings indicate that hydrogen-based direct reduction is the most practical cleaner production option in the short to medium term, while plasma-based technologies may become relevant later as electricity systems and process efficiencies continue to improve (IEA, 2023).

**Table 3**. Technology readiness level (TRL) and deployment status of ironmaking technologies.

| Technology | TRL | Current Status | Representative Projects |
|---|---|---|---|
| BF–BOF | 9 | Fully commercial | Global |
| NG–DRI + EAF | 9 | Fully commercial | MIDREX, HYL |
| $H_2$–DRI + EAF | 7–8 | Pilot / early commercial | HYBRIT, SALCOS |
| HPSR | 4–5 | Lab / pilot | SuSteel, SIDERWIN |

*Source:* Based on classifications reported by International Energy Agency (2023) and Vogl et al. (2018).

### 3.5 Hydrogen versus Ammonia as Reduction Pathways

Using ammonia as a carrier for hydrogen adds extra complexity to steel decarbonization pathways. Ammonia has advantages for storage and long-distance transport, which could support hydrogen-based steelmaking in regions without direct access to renewable hydrogen. However, converting ammonia back into hydrogen requires additional energy and can lead to energy losses of around 30% compared to direct hydrogen use, while also posing risks of nitrogen oxide formation if not properly controlled (Valera-Medina et al., 2018; IEA, 2023). These findings suggest that ammonia is better suited as a transitional or niche option rather than a main cleaner production route for ironmaking. Direct use of hydrogen remains more attractive in terms of energy efficiency and emission reduction, especially in regions with growing renewable electricity supply and developing hydrogen infrastructure (Vogl et al., 2018; IEA, 2023).

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

### 3.6 Integrated Interpretation from a Cleaner Production Perspective

When considered as a whole, the results show that hydrogen-based direct reduction is currently the most balanced cleaner production option for primary steelmaking. It can almost completely eliminate direct carbon emissions while remaining technically feasible within existing industrial systems. However, its success depends on factors beyond the steel plant itself, including the availability of renewable electricity, the development of hydrogen infrastructure, and strong policy support (Vogl et al., 2018; IEA, 2023). The analysis highlights that cleaner production in heavy industry is not achieved simply by adopting new technologies, but by aligning process innovation with energy system transformation and regulatory frameworks. Hydrogen-based ironmaking clearly demonstrates this interdependence and shows that integrated planning is essential to deliver long-term and meaningful emission reductions (IEA, 2023).

## 4. Policy Implications and Strategic Outlook

The shift toward hydrogen-based ironmaking is not only a technical challenge but also a broader policy and governance challenge that goes beyond individual steel plants. The results show that hydrogen-based direct reduction can achieve near-zero direct emissions only when supported by low-carbon electricity, affordable green hydrogen, and supportive regulatory frameworks. As a result, public policy plays a key role in determining whether hydrogen-based steelmaking moves from small-scale demonstrations to a widely adopted cleaner production pathway (IEA, 2023; Vogl et al., 2018).

Carbon pricing is one of the most important tools for accelerating this transition. Conventional blast furnace routes benefit from existing infrastructure and lower short-term costs despite high emissions. Introducing meaningful carbon prices—especially above US$100 per tonne of $CO_2$—can significantly reduce the cost gap between carbon-intensive and hydrogen-based steelmaking. Policy instruments such as emissions trading systems, carbon taxes, and carbon border adjustment mechanisms can therefore improve the competitiveness of low-carbon steel by accounting for environmental costs (IEA, 2023; European Commission, 2023).

In addition to carbon pricing, direct support for green hydrogen is essential. Hydrogen cost remains the main factor limiting the economic viability of hydrogen-based ironmaking. Policies that encourage large-scale renewable electricity deployment, electrolyzer expansion, and hydrogen infrastructure development are therefore critical. Financial tools such as investment subsidies, contracts for difference, and long-term offtake agreements can lower risk and support early commercial projects. Without such support, hydrogen-based steelmaking is likely to remain limited to pilot-scale deployment (IEA, 2023).

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

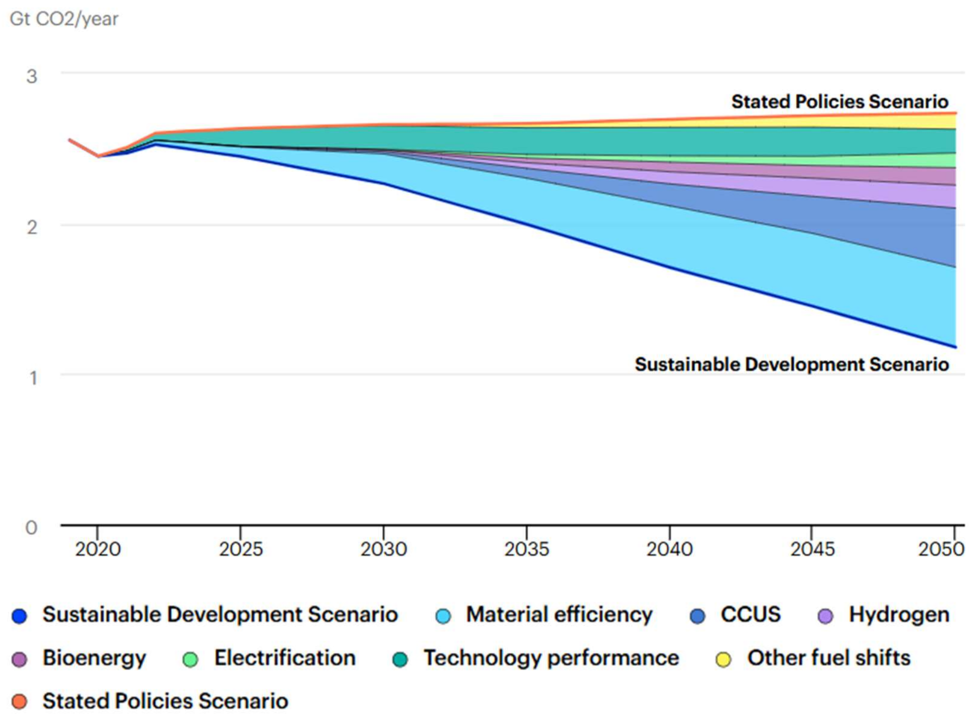


**Figure 3**. Iron and steel sector direct CO2 emission reductions in the Sustainable Development Scenario by mitigation strategy, 2019-2050. *Source:* https://www.iea.org/reports

Industrial clustering and infrastructure coordination can further improve policy effectiveness. Placing hydrogen-based steel plants within industrial hubs allows shared use of hydrogen pipelines, renewable power supply, and storage systems, which can reduce overall costs and improve system efficiency. These clusters also create synergies with other hydrogen users, increasing infrastructure utilization. From a cleaner production perspective, such system-level planning is as important as improving individual process efficiency (Vogl et al., 2018).

**Table 4**. Indicative capital cost, hydrogen cost, and infrastructure requirements for ironmaking routes. (Cost values represent indicative ranges based on recent literature and policy roadmaps; actual costs vary by region, scale, and financing conditions)

| Parameter | BF–BOF | NG–DRI | $H_2$–DRI |
|---|---|---|---|
| CAPEX (US$/t annual capacity) | 800–1,000 | 900–1,100 | 1,000–1,200 |
| Hydrogen cost (US$/kg) | — | 1–2 | 3–6 (current) |
| $CO_2$ price sensitivity | Low | Medium | High |

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

| | | | |
|---|---|---|---|
| Infrastructure needs | Coke, sinter | Gas pipelines | Renewable power + $H_2$ |

*Source:* Synthesized from International Energy Agency (2023), World Steel Association (2023), and Skaf (2025).

To stay on track with global energy and climate targets, emissions from the steel industry need to drop sharply. By 2050, they must be reduced by at least half, with continued efforts to move toward near-zero emissions in the years that follow. The International Energy Agency's Sustainable Development Scenario outlines a clear pathway toward a net-zero energy system by 2070. Even with better material efficiency lowering overall steel demand, major changes in production are still required. In practical terms, the average direct $CO_2$ emissions from steelmaking must fall by about 60% by 2050, decreasing from today's level of around 1.4 tonnes of $CO_2$ per tonne of crude steel to roughly 0.6 tonnes per tonne (IEA, 2023).

Finally, green steel certification and demand-side policies can help create market demand for low-carbon steel. Public procurement rules, sustainability reporting, and voluntary certification schemes can signal long-term demand and provide investment confidence for producers. These measures are especially important for sectors such as construction and automotive manufacturing, where material sustainability is becoming a key purchasing criterion (IEA, 2023).

## 5. Conclusions and Future Outlook

This study presents a comprehensive evaluation of hydrogen-based ironmaking as a cleaner production pathway toward carbon-neutral steelmaking by combining thermodynamic analysis, lifecycle emissions, energy demand, and technology readiness. The results show that hydrogen-based direct reduction combined with electric arc furnace steelmaking is the most realistic near- to mid-term option for deeply reducing emissions from primary steel production. When powered by renewable electricity, this pathway can lower direct carbon dioxide emissions by up to 98% compared with conventional blast furnace routes, achieving near-zero lifecycle emissions (Vogl et al., 2018; IEA, 2023).

At the same time, the analysis highlights that these emission reductions come with a significant increase in energy demand, mainly due to hydrogen production through electrolysis. This confirms that industrial decarbonization is closely linked to the wider energy transition. Hydrogen-based steelmaking cannot function as an isolated solution, as its environmental benefits depend strongly on the availability of low-carbon electricity and affordable green hydrogen. Without parallel progress in power sector decarbonization, the emission advantages of hydrogen metallurgy are greatly reduced (IEA, 2023).

From a technology perspective, hydrogen-based direct reduction has reached an advanced level of maturity, supported by large pilot projects and early commercial deployment. In contrast, hydrogen plasma smelting reduction is still at an early development stage, with high electricity demand and operational challenges limiting its short-term use. These differences

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

emphasize the need to align decarbonization strategies with realistic timelines for technology development (Vogl et al., 2018).

Looking ahead, the transition to hydrogen-based steelmaking will require coordinated progress across technology, economics, and policy. Continued innovation is needed to improve process efficiency, reduce hydrogen consumption, and integrate advanced digital control systems. At the same time, strong policy signals—such as carbon pricing, hydrogen incentives, and green material standards—are essential to support investment in cleaner production infrastructure. Future research should focus on regional deployment strategies, system-level energy integration, and the long-term potential of emerging technologies such as molten oxide electrolysis.

In summary, hydrogen-based ironmaking offers a transformative opportunity to balance the steel industry's critical societal role with urgent climate goals. When supported by a decarbonized energy system and effective policy frameworks, hydrogen metallurgy can become a key pillar of sustainable and resilient industrial production in a carbon-constrained world.

**Reference:**

1. Adhikari, N., & Khanam, S. (2024). Toward Sustainable Production: Emerging Trends in Iron and Steel Making. *ChemBioEng Reviews*. https://doi.org/10.1002/cben.202300055
2. Algers, J., Åhman, M., & Nilsson, L. J. (2025). Steel Decarbonization—from Optimization to Transformation. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-111523-101851
3. Bataille, C. G. (2020). Physical and policy pathways to net-zero emissions industry. *Wiley Interdisciplinary Reviews: Climate Change*, *11*(2), e633. https://doi.org/10.1002/wcc.633Digital Object Identifier (DOI)
4. Bhaskar, A., Assadi, M., & Nikpey Somehsaraei, H. (2020). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies*, *13*(3), 758. https://doi.org/10.3390/en13030758
5. Cavaliere, P. (2019). *Blast Furnace: Most Efficient Technologies for Greenhouse Emissions Abatement* (pp. 167–273). Springer, Cham. https://doi.org/10.1007/978-3-030-21209-4_4
6. Elsheikh, H., & Eveloy, V. (2023). Renewable hydrogen based direct iron ore reduction and steel making with grid assistance. *Energy Conversion and Management*. https://doi.org/10.1016/j.enconman.2023.117544
7. European Commission. (2023). *Carbon Border Adjustment Mechanism (CBAM)*. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en
8. Gielen, D., Saygin, D., Taibi, E., & Birat, J.-P. (2020). Renewables-based decarbonization and relocation of iron and steel making: A case study. *Journal of Industrial Ecology*, *24*(5), 1113–1125. https://doi.org/10.1111/JIEC.12997

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

9. "Iron and Steel," in *Transactions of the American Institute of Electrical Engineers*, vol. 47, no. 4, pp. 1275-1275, Oct. 1928, 10.1109/T-AIEE.1928.5055135
10. International Energy Agency. (2023). *Iron and steel technology roadmap: Towards more sustainable steelmaking*. https://www.iea.org/reports/iron-and-steel-technology-roadmap
11. International Organization for Standardization. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. https://www.iso.org/standard/37456.html
12. Miškovičová, Z., Legemza, J., Demeter, P., Buľko, B., Hubatka, S., Hrubovčáková, M., Futáš, P., & Findorák, R. (2024). An Overview Analysis of Current Research Status in Iron Oxides Reduction by Hydrogen. *Superalloys*. https://doi.org/10.3390/met14050589
13. Mokrzycki, E., & Gawlik, L. (2024). Decarbonisation determinants of the steel industry. *Gospodarka Surowcami Mineralnymi-Mineral Resources Management*, 71. https://doi.org/10.24425/gsm.2024.152719
14. Patisson, F., & Mirgaux, O. (2020). *Hydrogen Ironmaking: How It Works*. *10*(7), 922. https://doi.org/10.3390/MET10070922
15. Rechberger, K., Spanlang, A., Sasiain Conde, A., Wolfmeir, H., & Harris, C. (2020). Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. *Steel Research International*, *91*(11), 2000110. https://doi.org/10.1002/SRIN.202000110
16. Reck, B. K., Zhu, Y., Althaf, S., & Cooper, D. R. (2024). *Assessing the Status Quo of U.S. Steel Circularity and Decarbonization Options*. 211–221. https://doi.org/10.1002/9781394214297.ch17
17. Rippy, K. C., Bell, R., & Leick, N. (2024). Chemical and electrochemical pathways to low-carbon iron and steel. *Npj Materials Sustainability*, *2*(1). https://doi.org/10.1038/s44296-024-00036-6
18. Rodriguez Diez, J., Tomé-Torquemada, S., Vicente, A., Reyes, J., & Orcajo, G. A. (2023). Decarbonization Pathways, Strategies, and Use Cases to Achieve Net-Zero CO2 Emissions in the Steelmaking Industry. *Energies*. https://doi.org/10.3390/en16217360
19. Schmöle, P., & Lüngen, H.-B. (2005). Ecological hot metal production using the coke plant and blast furnace route. *Revue De Metallurgie-Cahiers D Informations Techniques*, *102*(3), 171–182. https://doi.org/10.1051/METAL:2005140
20. Schneising, O., Buchwitz, M., Reuter, M., Weimer, M., Bovensmann, H., Burrows, J. P., & Bösch, H. (2024). Towards a sector-specific CO/CO 2 emission ratio: Satellite-based observation of CO release from steel production in Germany. *EGUsphere*, *2024*, 1-17.
21. Skaf, A., Ahmadi, A., & Tiruta-Barna, L. (2025). Toward Cleaner Ironmaking Routes: Energy and Environmental-Evaluation of Hydrogen-Based

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*

Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
**SGVU International Journal of Convergence of Technology and Management**
E-ISSN: 2455-7528
Vol.12 Issue 1 Page No 413-429

Ironmaking. In *8th World Conference on Chemistry and Chemical Engineering*. https://doi.org/10.62422/978-81-981865-7-7-004

22. Sohn, H. Y., & Fruehan, R. J. (2006). *The metallurgical processing of iron and steel*. Metallurgical and Materials Transactions B, 37(5), 689–699.
23. Speizer, S., Durga, S., Blahut, N., Charles, M., Lehne, J., Edmonds, J., & Yu, S. (2023). Rapid implementation of mitigation measures can facilitate decarbonization of the global steel sector in 1.5°C-consistent pathways. *One Earth*. https://doi.org/10.1016/j.oneear.2023.10.016
24. Tang, J., Chu, M., Feng, L., Feng, C., Liu, Z., & Yusheng, Z. (2020). Development and progress on hydrogen metallurgy. *International Journal of Minerals Metallurgy and Materials*, *27*(6), 713–723. https://doi.org/10.1007/S12613-020-2021-4
25. Turkdogan, E. T. (1980). *Physical chemistry of high temperature technology*. Academic Press.
26. Urban, F. (2023). *Decarbonizing energy-intensive industries: the case of the steel sector* (pp. 237–245). Edward Elgar Publishing. https://doi.org/10.4337/9781800882119.00024
27. Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W.I.F. and Bowen, P.J. (2018) Ammonia for Power. Progress in Energy and Combustion Science, 69, 63-102. https://doi.org/10.1016/j.pecs.2018.07.001
28. Vidyashree, V., & Sheriff, A. M. (2024). Environmental impact of steel production and its challenges in achieving sustainability. *ShodhKosh Journal of Visual and Performing Arts*, *5*(6). https://doi.org/10.29121/shodhkosh.v5.i6.2024.3402
29. Vogl, V., Åhman, M., & Nilsson, L. J. (2018). *Assessment of hydrogen direct reduction for fossil-free steelmaking*. Journal of Cleaner Production, 203, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279
30. World Steel Association. (2023). *Steel's contribution to a low carbon future*. https://worldsteel.org
31. Zeng, L., Zhang, J., Li, K., Shao, L., Liu, Z., Yang, Z., Jiang, C., Ren, S., & Conejo, A. N. (2025). Fully Electric Hydrogen-Driven Direct Reduction Process for Zero-Carbon Green Steel Production. *Green Chemistry*. https://doi.org/10.1039/d5gc00279f

*Correspondence to: Milan Samanta, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur, India*
*Corresponding author. E-mail addresses: president@mygyanvihar.com*