CHAPTER 34

Clean Energy Transition using Hydrogen in Steel Industry

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ABSTRACT

This paper addresses the innovative potential of the hydrogen technology in driving the decarbonisation of the steel industry, responsible for almost 8% of global CO_2 emissions. It identifies the environmental issue with traditional processes, i.e., the blast furnace basic oxygen furnace (BF-BOF) process that is coke and coal-based. The study compares different hydrogen production routes, including steam methane reforming, partial oxidation, coal gasification, and water electrolysis, subject to their technical viability, economic feasibility, and environmental benefits. The study reveals that green hydrogen through renewable-fuelled electrolysis is the most environmentally friendly solution, and blue hydrogen from carbon capture as a bridging technology. The research addresses challenges to implementation through means of production costs, infrastructural requirements, and technical changes needed in applying hydrogen in steel production. Not despite the prevailing economic difficulties, technological advancements, economies of scale, and friendly policy frameworks would make use of hydrogen in steel-making exist in the future. Lastly, the study concludes that hydrogen is a crucial solution to align steel manufacturing with global climate goals while maintaining access to this significant content for the construction of new infrastructure. The transformation is needed for providing substantial reduction of emissions in one of the world's most carbon-intensive industries.

Keywords: Hydrogen steelmaking; Green hydrogen; Decarbonization; Clean energy transition; Direct reduced iron; Carbon emissions reduction; Blast furnace alternatives; Renewable energy integration; Climate change mitigation; Industrial sustainability.

1.0 Introduction

The transition to renewable energy has become a necessity in the context of climate change and the need to cut greenhouse gas emissions. While the world's industrial economies scramble in order to achieve global climate objectives, the steel sector is particularly hard-pressed because of its environmental load. Steel manufacturing takes up about 8% of total global carbon dioxide emissions, one of the single biggest sources of industrial greenhouse gases in the international context.

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Conventional ironmaking where coal is both when reduced agent and source of energy combine, they end up producing about 2.2 kg of CO_2 for every kilogram of produced liquid steel—an unreliable ratio under carbon-restricted forthcoming years. Steel manufacturing is also one of the most carbon-emitting industrial processes and is accountable for approximately 7-9% of all anthropogenic CO_2 emissions. This vast carbon footprint is mainly supplemented by the widespread application of the blast furnace-basic oxygen furnace (BF-BOF) process that involves heavy dependence on coke and coal. Carbon monoxide, which is used to reduce iron ore produces CO_2 as a by-product. Steel production, other than the release of greenhouse gas, also release other pollutants like sulfur dioxide, nitrogen oxides, and particulate matter, which deteriorate air quality and pose health risks to surrounding communities. The extraction and transportation of raw materials also lead to environmental degradation through land disturbance and water management. Satisfying these sophisticated environmental requirements requires a shift to more environmentally friendly steel production processes that reduce emissions and pollution but still meet the growing need for steel worldwide.

1.1 Drivers for change in the steel industry

The steel sector is experiencing unparalleled demands for transformation in response to ambitious climate policies and market demands for low-carbon goods. The Paris Agreement encourages nearly complete industrial process decarbonization by the middle of this century, compeling steel producers to cut reduction of carbon intensity by as much as 90%, from 1.8 tonnes CO_2 to 0.2 tonnes CO_2 per tonne of steel. This cutback is required in view of the increased world demand for steel, which is set to increase from 1.6 billion tonnes in 2025 to 2.5 billion tonnes in 2050. The addition of required cuts the increase in emissions accompanied by the increase in output levels presents a severe technological problem for the industry, which calls for basic changes in production methods, rather than additions to efficiency.

1.2 Hydrogen as a decarbonization solution

Hydrogen is one of the most promising options for transforming the steelmaking sector, while significantly lowering carbon emissions. Hydrogen, as a chemical element, has unique properties as a reducing agent in iron production. Hydrogen, upon reaction with iron oxide, produces metallic iron and water vapor in the reaction: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$. This underlying chemistry is rather the opposite of carbon-based reduction, which inevitably creates CO_2. By the replacement of hydrogen by carbon as the major reducing agent, steel manufacture There can be a potential for removing the principal source of the direct emissions from the process. The environmental advantages of hydrogen go beyond the mitigation of reduction-related CO_2 emissions. Hydrogen is a non-polluting fuel, not leaving behind impurities like sulphur in the metal product, and the possible advantage of better product quality and reduced environmental pollution. control equipment. Hydrogen, as a reducing agent and as a fuel, can satisfy more by addressing more than one of the problems of the environment at once, with a production path to carbon neutrality if hydrogen is from low-carbon feedstock.

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1.3 Types of hydrogen and their use

Hydrogen Type	Production Method	Carbon Intensity	Key Considerations
Green Hydrogen	Electrolysis using renewable electricity (solar, wind, hydro)	Zero emissions	Most sustainable options require large-scale renewable energy infrastructure
Blue Hydrogen	Steam Methane Reforming (SMR) + Carbon Capture and Storage (CCS)	Lower emissions (compared to gray hydrogen)	Intermediate solution: still relies on fossil fuels but mitigates CO_2 through CCS
Gray Hydrogen	Steam Methane Reforming (SMR) without CCS	High emissions	Most widely used today, offers limited climate benefits
Brown/Black Hydrogen	Gasification of coal	Very high emissions	Least sustainable; produces significant CO_2 emissions
Pink Hydrogen	Electrolysis using nuclear power	Low emissions	Low carbon but dependent on nuclear energy availability
Turquoise Hydrogen	Methane pyrolysis (produces solid carbon byproduct)	Moderate emissions	Produces solid carbon instead of CO_2; emerging technology

2.0 Literature Review

2.1 Introduction

The literature on the use of hydrogen in steel making has significantly expanded in recent decades, reflecting expanding interest in the decarbonization of heavy industry sectors. This review consolidates key findings in previous research addressing the use of hydrogen in the steelmaking industry, such as technical feasibility, economic cost, environmental impact, and implementation impediments. There is a new generation of technology, legislation, and market regimes in literature that collectively impact the ability of hydrogen to transform steelmaking technology.

2.2 Review of past research done

Hydrogen-based steelmaking research exists back for a number of decades with early publications examining the underlying chemistry for hydrogen reduction of iron oxides. The last decade, however, has witnessed accelerated momentum fueled by climate necessity and developments in hydrogen production and use. Literature can be broadly grouped into a number of major streams of research: Studies on hydrogen-based steelmaking have changed dramatically, spurred by climate needs and innovation in hydrogen technologies. Prominent fronts include hydrogen-based direct reduction (H-DRI), whereby near-total CO_2 emissions abatement is facilitated using hydrogen levels higher than 95% in pilot plants. The process maximizes reduction efficiency and energy performance using cutting-edge modeling of heat

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and mass transfer phenomena. Blast furnace hydrogen injection has also been studied, with 20-30% CO_2 reductions at rates of up to 40 kg H_2 per tonne of hot metal, although the stability of the furnace still relies on coke. Advanced routes such as hydrogen plasma smelting, flash ironmaking, and suspension reduction are developed to overcome drawbacks of traditional techniques but suffer scale-up issues. Economical analyses put the price of hydrogen as the deciding factor with cost parity of conventional steel production when green hydrogen drops to less than \$2/kg and the carbon price hits more than \$50-100/tonne CO_2. Life cycle evaluations verify 80-95% greenhouse gas reduction through green hydrogen but alert toward trade-offs in terms of added water usage. Policy structures and integrating the energy system are key to speeding up adoption and making it economically viable.

3.0 Methodology

3.1 Introduction

This study utilized an in-depth methodological framework to assess hydrogen production routes and their use in steelmaking. The method centered on examining different hydrogen production routes, their efficiency, cost, environmental effect, and scalability. This framework offers a basis for the technical viability and economic feasibility of switching to hydrogen steelmaking. The research investigated both fossil fuel and renewable energy-based methods of hydrogen production, acknowledging that alternative routes can be suitable in different situations depending on the availability of resources, prevailing infrastructure, and local policy structures. Every method of production was assessed against its technical nature, process conditions, and product parameters. Hydrogen production routes to determine their potential in a decarbonized energy system.

Hydrogen use in Steelmaking	Efficiency	Cost (\$/kg H_2)	Advantages	Challenges	Future Prospects
Direct Reduced Iron (DRI) with Hydrogen	~60-70%	4-6	Zero CO_2 emissions, improves sustainability	High hydrogen demand, infrastructure modifications needed	Scaling up green hydrogen production, policy support for adoption
Blast Furnace Hydrogen Injection	~50-60%	3-5	Reduces coke consumption, lowers CO_2 emissions	Partial replacement, requires process adaptation	Gradual transition to full hydrogen-based reduction
Hydrogen Plasma Smelting	~70-85%	6-8	High efficiency, potential carbon-free steel production	High energy requirement, still in research phase	Further technological development and pilot-scale implementation

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3.2 Hydrogen in the steel industry

The steel industry is one of the largest carbon emitters globally, primarily due to its reliance on coal-blast furnaces to smelt iron ore. Hydrogen provides a hopeful alternative as a green reducing agent, substituting carbonaceous coke in direct reduction processes.

3.3 Hydrogen production methods

Production Method	Efficiency	Cost ($/kg H_2)	Challenges	Future Prospects
Steam Methane Reforming (SMR)	~65-75%	1.3-2.3	High CO_2 emissions (~9-12 kg CO_2/kg H_2), reliance on natural gas, limited suitability for fluctuating energy inputs	Integration of carbon capture and storage (CCS) to produce "blue hydrogen," development of enhanced catalysts for efficiency improvements
Partial Oxidation of Hydrocarbons	~60-70%	N/A	Requires oxygen separation, generates CO_2, complex setup	Improved carbon capture technologies and efficiency optimization
Coal Gasification	~45-55%	2-3	Highest CO_2 emissions (~19 kg CO_2/kg H_2), high water consumption, high capital costs	Carbon capture integration for "blue hydrogen" production, process optimizations to enhance efficiency
Methane Pyrolysis ("Turquoise Hydrogen")	~40-50%	N/A	High energy input, limited commercialization	Industrial-scale implementation, integration with renewable energy sources
Alkaline Electrolysis	~60-70%	4-6	High electricity cost, materials durability	Cost reductions through technological advancements and increased renewable energy adoption
PEM Electrolysis	~55-65%	5-7	High material costs, limited scalability	Technological improvements to reduce costs and enhance efficiency
SOEC Electrolysis	~70-85%	N/A	Pilot-phase development, durability concerns	Large-scale deployment with integration of industrial waste heat sources
Thermochemical & Photocatalytic Splitting	<5%	N/A	Low efficiency, scalability issues	Research into advanced catalysts and solar energy utilization

3.4 Comparative analysis

From above discussion, we reached the conclusion that Fossil fuel-based technologies (SMR, coal gasification) are the leaders in terms of cost and scalability but need carbon capture to avoid environmental damage. Electrolysis and methane pyrolysis offer cleaner options but are

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limited by cost and infrastructure scalability. New technologies, including thermochemical and photocatalytic hydrogen production, are still in the initial research phase but have long-term sustainability potential. For the steel sector, hydrogen-based options offer a real route to decarbonization but need breakthroughs in hydrogen production and storage at scale.

4.0 Future Scope of Hydrogen in the Steel Industry: Pathways to Decarbonization and Sustainable Growth

4.1 Escalating global demand for green steel

The demand for low-carbon or "green" steel has been spurred by more stringent climate policies and business sustainability objectives. Sectors like automobile, construction, and consumer products are increasingly looking for materials with lower carbon footprints, presenting market opportunities for green steel manufacturers. This demand is anticipated to increase exponentially, with the global market possibly reaching $300-500 billion by 2050. Early adopters in high-end sectors such as luxury products and premium automotive are prepared to pay a premium, setting the stage for wider market acceptance as production volumes scale and costs reduce. The competitive environment is becoming more severe, with established producers, new players, and cross-industry consortia cutting costs and increasing efficiency through innovation, reflecting patterns in renewable energy technologies.

4.2 Advancements in hydrogen production and storage

Improvements in the technology of hydrogen production and storage are critical to the economic feasibility of hydrogen steelmaking. Electrolysis technology, for instance, developed More efficient and less expensive electrolysers have the potential to lower capital expenses. by 50-70% over a ten-year timeframe. Technologies such as high-temperature co-electrolysis and water splitting have further efficiency enhancement but entail continuing research spending. Storage materials like metal hydrides and liquid organic Hydrogen carriers solve problems of energy efficiency and operational complexity. These Technological development enables greater use of renewable energy sources combined with secure hydrogen. demand, thus making steel production from hydrogen more economic.

4.3 Storage and transportation breakthroughs

Effective hydrogen storage and transportation are necessary to scale up hydrogen-based steelmaking, particularly for plants distant from renewable sources. Improvements in liquefaction, compression, and carrier molecules such as ammonia or liquid organic hydrogen carriers (LOHCs) may cut transport costs by 30-50%. Materials science breakthroughs that overcome hydrogen embrittlement in pipelines and storage tanks are important for mass application. Demonstration projects are proving these technologies, with commercial operations set to scale up after 2025, making cost-effective long-distance hydrogen transport possible.

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4.4 Infrastructure development and investment landscapes

Hydrogen-based steelmaking depends on sturdy infrastructure growth. Over $500 billion in investments worldwide is being allocated to production, storage, and transport systems. Regional hydrogen hubs are becoming dominant models, aggregating production with industrial uses such as steelmaking to drive economics of scale. Hubs promote synergies among industries like chemicals and transportation and minimize system costs. Such infrastructure initiatives will have a profound impact on the adoption level of hydrogen in steelmaking.

4.5 Public-private funding models

New financing instruments are meeting the capital-hungry nature of hydrogen-based steelmaking. Green bonds, sustainability-linked loans, public-private partnerships, and carbon contracts for differences (CCfD) are becoming increasingly popular. CCfDs reduce the risk of revenues by assuring minimum carbon prices for emissions cuts to help invest in projects that are still in development. International financial institutions are also coming into play by offering funding, risk mitigation instruments, and policy support to promote faster adoption among both developed and emerging economies.

4.6 High production costs

Hydrogen-based steelmaking faces cost premiums of 30-80% compared to conventional methods due to high hydrogen production expenses. Cost reductions depend on technological advancements in electrolysis, transport infrastructure, and equipment optimization. Carbon pricing policies and market differentiation for low-carbon products can further bridge this cost gap by internalizing environmental costs.

4.7 Energy intensity and efficiency concerns

Hydrogen-based processes require significant energy inputs, particularly for electrolysis-driven hydrogen production. Transitioning global steel production entirely to hydrogen would demand 2,500-3,000 TWh annually—10% of current global electricity generation. Research into hybrid processes combining biomass or fossil fuels with carbon capture could mitigate energy intensity while achieving substantial emission reductions.

4.8 Infrastructure and supply chain limitations

Scaling up hydrogen adoption necessitates expanding electrolyzer manufacturing capacity and renewable electricity generation. Current electrolyzer output meets less than 5% of projected 2030 needs. Supply chain bottlenecks for critical minerals such as iridium and platinum must be addressed through alternative material research and cross-sector collaboration among industries like energy, mining, and chemicals.

4.9 Need for policy support and market signals

Policy frameworks play a decisive role in accelerating hydrogen adoption in steelmaking. Carbon pricing mechanisms remain insufficient in many regions to drive rapid

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transformation. Stable policies that incentivize low-carbon products through procurement standards and certification systems are essential to create market differentiation for green steel.

4.10 Long-term environmental and economic impacts

Hydrogen-based steelmaking could reduce global greenhouse gas emissions by 5-7%, offering significant climate benefits alongside improved air quality by eliminating pollutants from conventional processes. Economically, the transition could revitalize industrial regions with abundant renewable resources while creating jobs across the value chain—from renewable energy development to steel production—despite challenges faced by coal-dependent regions during this shift.

5.0 Result

Innovative funding models are responding to the capital-hungry nature of hydrogen-based steel production. Carbon contracts for difference (CCfD), green bonds, sustainability-linked loans, and public-private partnerships are becoming more popular. CCfDs mitigate the risk of revenues by assuring minimum carbon prices for carbon reductions, making investments into first-mover projects more attractive. International financial institutions also have a key role to play by offering funding, risk management instruments, and policy assistance to drive adoption in developed and emerging economies.

The steel industry faces an urgent need to reduce its substantial carbon footprint while maintaining production capacity. Traditional steelmaking through blast furnace processes generates approximately 2 kg of CO_2 per kg of liquid steel produced, along with other pollutants affecting air quality. Hydrogen presents a promising pathway for transformation, producing only water vapor as a byproduct when used as a reducing agent. This transition is being accelerated by converging economic forces, stringent climate policies, and growing market pressure from consumers demanding lower-carbon materials.

Regional approaches vary, with the EU implementing mechanisms like the Carbon Border Adjustment Mechanism, while the US provides funding through the Inflation Reduction Act1. Significant progress is evident in hydrogen adoption for steelmaking globally. India, the world's second-largest steel producer, has launched ambitious initiatives including a National Green Hydrogen Mission with an initial outlay of ₹19,744 crore. Approximately ₹455 crore is dedicated to pilot projects for hydrogen use in iron and steel production. In October 2024, the Ministry of Steel awarded projects to produce Direct Reduced Iron using 100% hydrogen and to inject hydrogen into existing blast furnaces. India is also developing a dedicated 'Green Steel Mission' with an estimated budget of ₹15,000 crore, which includes production-linked incentives, financial support for renewable energy, and preferential purchasing mandates for government agencies. The shift to hydrogen steelmaking is vital for the decarbonization of a carbon-intensive sector while maintaining the production of critical materials. This study

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identifies a number of important conclusions. Hydrogen offers a feasible solution for decarbonization, with different implementation routes depending on regional circumstances. Hydrogen direct reduction and electric arc furnace steelmaking can lower emissions by 80-95% when green hydrogen is used. The environmental gains vary by hydrogen production pathway; green hydrogen has the largest climate benefits, with blue hydrogen achieving significant but partial emission cuts. Economies of scale and reductions in the cost of renewable electricity make the economic hurdles large but falling. Hydrogen-based steel can achieve cost parity with traditional approaches in areas with abundant renewable resources by 2030-2035. Strong policy frameworks are needed to facilitate this shift, involving end-to-end packages that cover both supply and demand sides. The shift needs to be considered as part of an overall industrial system change, which calls for intersectoral collaboration to maximize benefits.

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