GREENZO ENERGY INDIA LIMITED
ISO 9001-14001

GREEN HYDROGEN

DECARBONISING STEEL INDUSTRY

DATE :
September 2025

PRESENTED BY :
GREENZO ENERGY INDIA LIMITED

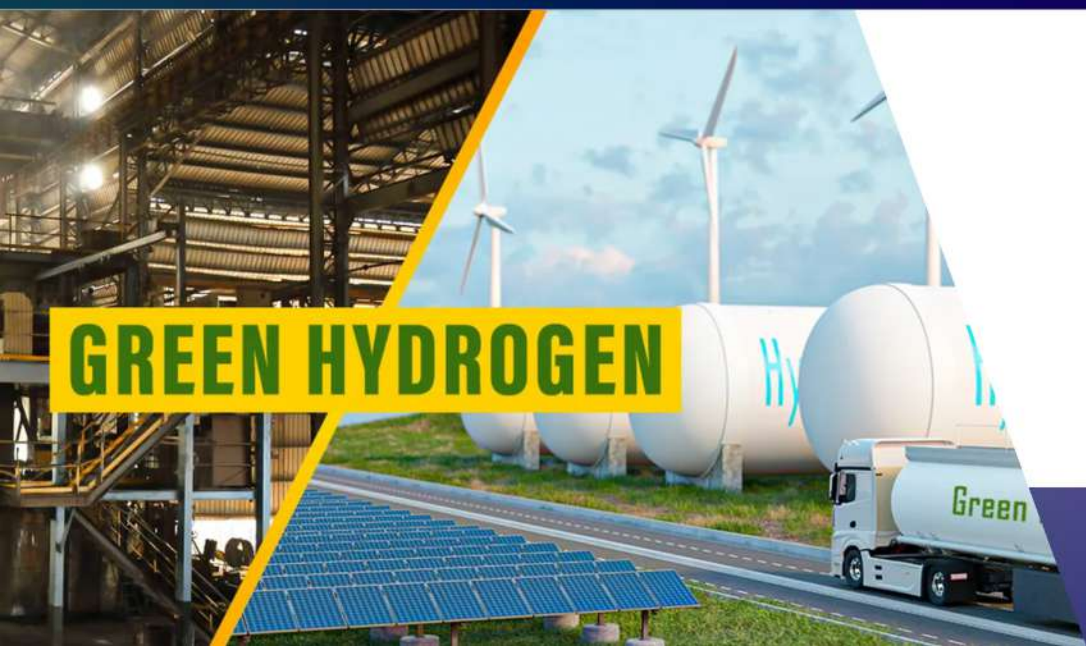
+91 989 710 0900
info@greenzoenergy.com
www.greenzoenergyindia.com

Message of MD

At Greenzo Energy, we firmly believe that green hydrogen is not just a fuel of the future—it is the foundation of a sustainable industrial revolution. The steel industry, being one of the most carbon-intensive sectors, presents both a challenge and an opportunity. Through innovation, collaboration, and scalable green hydrogen solutions, we can redefine the way steel is produced, reducing emissions while enabling economic growth.

This report reflects our commitment to driving this transition, offering insights into technological pathways, investment opportunities, and the role emerging economies can play in shaping the global green hydrogen ecosystem. Together, we can transform challenges into opportunities and position green steel as a cornerstone of a cleaner, resilient future.

Sandeep Agarwal
Founder & Managing Director



GREENZO ENERGY INDIA LIMITED
ISO 9001-14001

Table Of Content

01 Executive Summary

02 Introduction

03 The Green Hydrogen Economy: Opportunities and Challenges

04 Overview of Low-Carbon Iron & Steelmaking Technologies

05 Roadmap for Hydrogen in the Steel Industry

06 Energy Requirements

07 CO_2 Reduction Potential

08 Technology Readiness and Research Needs

09 Role of Green Ammonia

10 Market Size and Growth (2023–2030)

11 Economic Analysis

Green Hydrogen for De-carbonizing Steel Industry in Emerging Economics

1. Executive Summary

The steel industry is one of the largest contributors to global greenhouse gas emissions, primarily due to its reliance on the conventional Blast Furnace–Basic Oxygen Furnace (BF– BOF) route.Producing one ton of liquidsteel through this method generates approximately 1.8 tons of carbon dioxide equivalent, making the sector responsible for around 7–9% of global emissions. As governments, corporations, and societies push toward net-zero targets, the industry is under immense pressure to decarbonize. Hydrogen presents itself as a transformativesolution, offering the potential to replace carbon-intensive processes with clean, renewable energy-driven alternatives.

This paper explores the roadmap for implementing hydrogen in steel production, highlighting technological pathways, energy requirements, carbon reduction potential, economic implications, and market opportunities. It also examines the complementary role of green ammonia as a hydrogen carrier and outlines strategic recommendations for scaling up this transition. If adopted at scale, hydrogen-based steelmaking could reduce emissions by up to 97% compared to conventional processes, positioning green steel as a cornerstone of sustainable industrialization.

2. Introduction

Green hydrogen is increasingly recognized as a transformative solution for reconciling economic growth with environmental sustainability. Its potential to decarbonize hard-to-abate sectors, particularly the steel industry, makes it centralto global industrial transitions. Beyond emissions reduction, green hydrogen also offers opportunities for fostering industrial development, advancing technological innovation, and creating new employment avenues.

Despite this potential, the pathways through which emerging economies can effectively harness green hydrogen remain underexplored. This paper addresses this gap by analysing green hydrogen strategies with particular relevance to the steel industry. Private sector initiatives often diverge from national strategies, underscoring the difficulty of aligning policy ambitions with market realities. This paper argues that there is no one-size-fits-all blueprint for green hydrogen deployment.

3. The Green Hydrogen Economy: Opportunities and Challenges

The concept of a green hydrogen economy envisions an energy system in which hydrogen produced from renewable sources plays a central role. Green hydrogen's versatility makes it particularly valuable for hard-to-abate sectors that are difficult to electrify, such as steel, chemicals, and heavy transport. It can serve as a chemical feedstock, heating source, and input for synthetic fuel production, as well as be converted back into electricity via fuel cells. Importantly, hydrogen also offers unique capabilities for large-scale energy storage and cross-regional energy transport, supporting flexibility and resilience in the global energy system.

From an economic perspective, the development of green hydrogen markets can generate multiple backward linkages. These include the expansion of renewable energy capacity, attraction of foreign and domestic investment, and enhancement of technical and institutional capabilities. At the core of hydrogen production is investment in electrolyzers, which convert renewable electricity into hydrogen. However, this process is capital-intensive, meaning foreign investments and imported technologies are often dominant in developing countries. Similarly, converting hydrogen into derivatives such as ammonia or methanol—critical for transport and trade—requires further capital-intensive industrial processes.

Despite these barriers, employment opportunities remain significant, especially in the construction and operation of renewable energy facilities. Countries with the right mix of industrial capabilities and strong policy support can also capture long-term industrial benefits. In addition to industrial gains, green hydrogen can deliver broader socio-economic benefits.

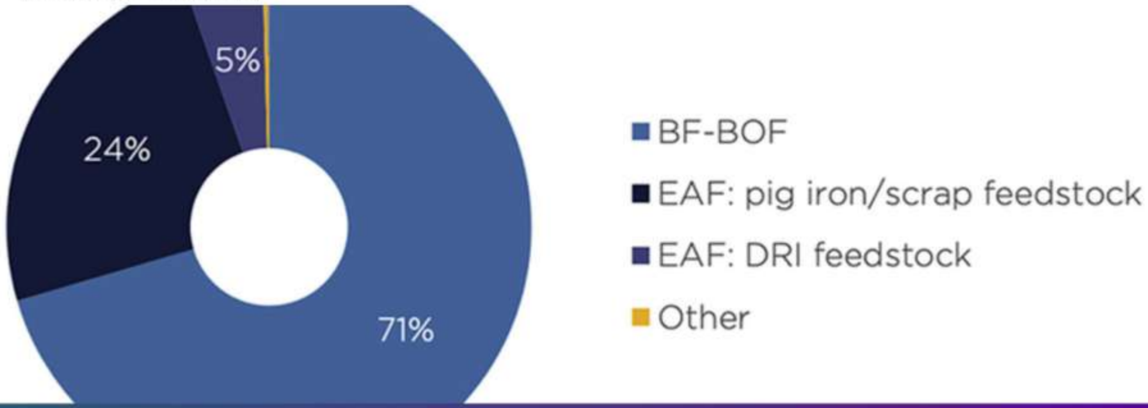
Scaling green hydrogen remains a formidable challenge. Current production costs are significantly higher than hydrogen derived from natural gas. The main cost driver sare the price of renewable electricity and electrolyzer systems, which—although declining—remain high. Further barriers exist across the value chain, including storage, transport, and end-use applications, which are constrained by limited infrastructure, technological immaturity, safety standards, and weak regulatory frameworks.

4. Overview of Low-Carbon Iron & Steelmaking Technologies

Current steelmaking technologies can be broadly categorized into carbon-intensive and low-carbon routes. The conventional BF–BOF pathway continues to dominate but faces growing scrutiny due to its environmental impact. In contrast, the Direct Reduced Iron (DRI) combined with Electric Arc Furnace (EAF) pathway offers a viable alternative.

Traditionally, DRI processes rely on natural gas as the reducing agent, which still emits CO_2, but at a lower level compared to coal-based processes. Natural gas–based DRI can achieve about a 34% reduction in emissions relative to the BF–BOF route. The real breakthrough lies in replacing natural gas with hydrogen in the DRI process. When hydrogen is used as the sole reducing agent, it reacts with iron ore to produce direct reduced iron while emitting only water vapor as a byproduct.

This hydrogen-based DRI can then be processedin an EAF powered by renewable electricity, resulting in “green steel.”Global initiatives such as HYBRITin Sweden and H2 Green Steel are already piloting such technologies, demonstrating the feasibility of scaling hydrogen- based steel production. While full-scale deployment remains in early stages, the pathway is clear: hydrogen offers a nearly carbon-neutral solution.



5. Roadmap for Hydrogen in the Steel Industry

The transition to hydrogen in steelmaking involves a sequence of interlinked technological steps that together enable near-zero emissions. The roadmap begins with renewable energy generation, primarily from solar and wind, which is required to produce green hydrogen via water electrolysis. Electrolysers powered by renewable electricity split water into hydrogen and oxygen, delivering a clean reducing agent for iron ore processing.

Once hydrogen is produced, it is employed in the Direct Reduced Iron (DRI) process. Here, hydrogen replaces natural gas or coal as the reducing agent, directly reacting with iron ore to produce sponge iron while emitting only water vapor.

This DRI is subsequently fed into an Electric Arc Furnace (EAF), which is powered by renewable electricity. The EAF allows for efficient melting of the reduced iron, combined with recycled scrap, to produce high-quality crude steel. This complete cycle—renewable energy, hydrogen production, DRI, and EAF—culminates in green steel production.

By following this roadmap, the industry not only achieves drastic reductions in CO_2 emissions but also establishes a scalable model for sustainable steelmaking. Early pilot projects demonstrate the technical viability of each step, though significant scale-up in hydrogen supply and renewable energycapacity remains essentialfor widespread adoption.

6. Energy Requirements

Switching to hydrogen in steelmaking significantly alters the industry's energy profile. While conventional BF–BOF steel production is heavily dependent on coal, hydrogen-based steelmaking shifts the reliance toward electricity. The estimated requirement for hydrogen-based production ranges from 3.3 to 3.5 megawatt-hours (MWh) per ton of crude steel when accounting for hydrogen generation. This figure increases to nearly 4.1 MWh per ton when chemical energy demands and pelletizing are included.

Such a transition would therefore demand substantial expansion in renewable electricity generation and grid infrastructure. The steel industry, already one of the most energy-intensive sectors, would need to coordinate closely with the energy sector to ensure stable and affordable supply. Integrating hydrogen into steelmaking also underscores the importance of developing robust energy storage solutions to balance intermittent renewable generation with industrial demand. Without addressing these energy challenges, large-scale hydrogen adoption in steel may remain constrained.

7. CO_2 Reduction Potential

The potential for carbon dioxide mitigation through hydrogen in steelmaking is substantial. Using natural gas as the reducing agent in the DRI process offers about a 34% reduction in emissions compared to the conventional BF–BOF pathway. While this represents a meaningful step, the ultimate target is nearly complete decarbonization.

By replacing naturalgas with 100% renewable hydrogenin the DRI process and powering the EAF with renewable electricity, the industry can achieve up to a 97% reduction in CO_2 emissions. This makes hydrogen-based steel production one of the most promising decarbonization pathways for heavy industry. Furthermore, if carbon capture and utilization technologies are coupled with residual emissions, net-zero or even net-negative steel production could be possible in the long term. The hydrogen roadmap thus holds the key to aligning steelmaking with global climate goals and reducing one of the most significant industrial carbon footprints.

8. Technology Readiness and Research Needs

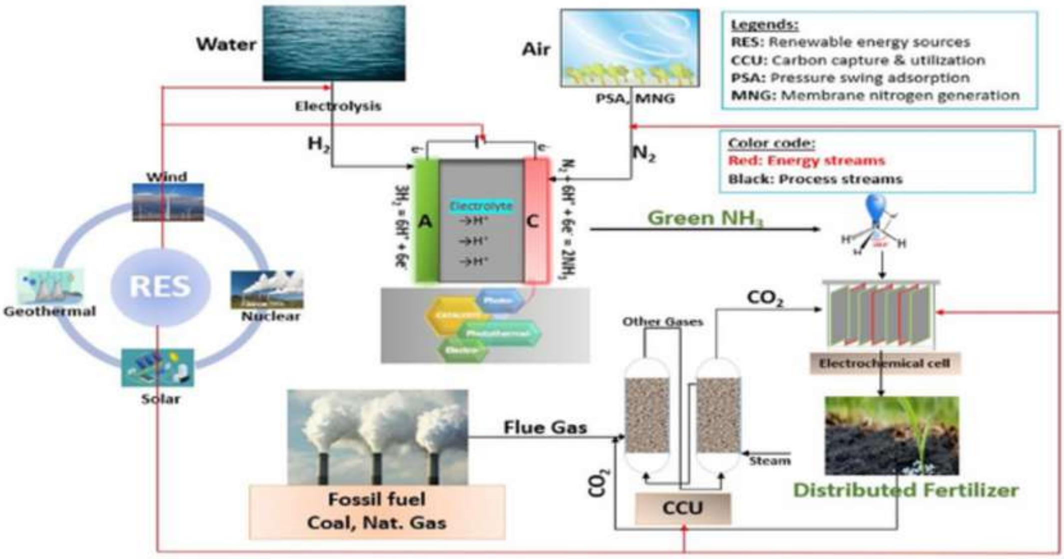
Hydrogen-based steelmaking is not just a vision—it is already being tested through pilot projects worldwide. The technology readiness level (TRL) for hydrogen in the DRI process currently ranges between 6 and 8, depending on the share of hydrogen employed. When hydrogen is partially blended with natural gas, the TRL is higher and closer to commercial readiness. However, when hydrogen is used as the sole reducing agent, the TRL is lower, reflecting the need for further validation, scaling, and cost optimization.

For example, the HYBRIT project in Sweden launched pilot operations in 2020, marking a landmark achievement in hydrogen-based steel production. Other initiatives in Germany, Japan, and the Middle East are progressing rapidly. Still, challenges remain: large-scale hydrogen supply and storage infrastructure is underdeveloped, and metallurgical performance under 100% hydrogen reduction requires further research. In addition, scaling electrolyzer production and integrating renewable power at industrial levels remain urgent needs. Addressing these research gaps will be vital for accelerating the commercial readiness of hydrogen steelmaking.

9. Role of Green Ammonia

While hydrogen stands at the centre of steel industry decarbonization, green ammonia plays a vital complementary role. Ammonia (NH_3) consists of one nitrogen atom and three hydrogen atoms, meaning that to produce 1 kilogram of ammonia, approximately 0.75 kilograms of hydrogen and 0.25 kilograms of nitrogen are required. This makes ammonia an effective hydrogen carrier, enabling easier storage and transportation of hydrogen over long distances.

Traditionally, nearly 80% of global ammonia production is consumed in agriculture as fertilizer. However, as the world transitions to low-carbon energy systems, green ammonia is gaining importance in industrial and energy applications. It can be used as a refrigerant gas, a component in the production of plastics and textiles, and in water purification and explosives manufacturing. More importantly, in the energy sector, ammonia is emerging as a versatile carrier of hydrogen. It can serve as a transport fuel, an energy storage medium, and even as a direct input in power generation when cracked back into hydrogen.



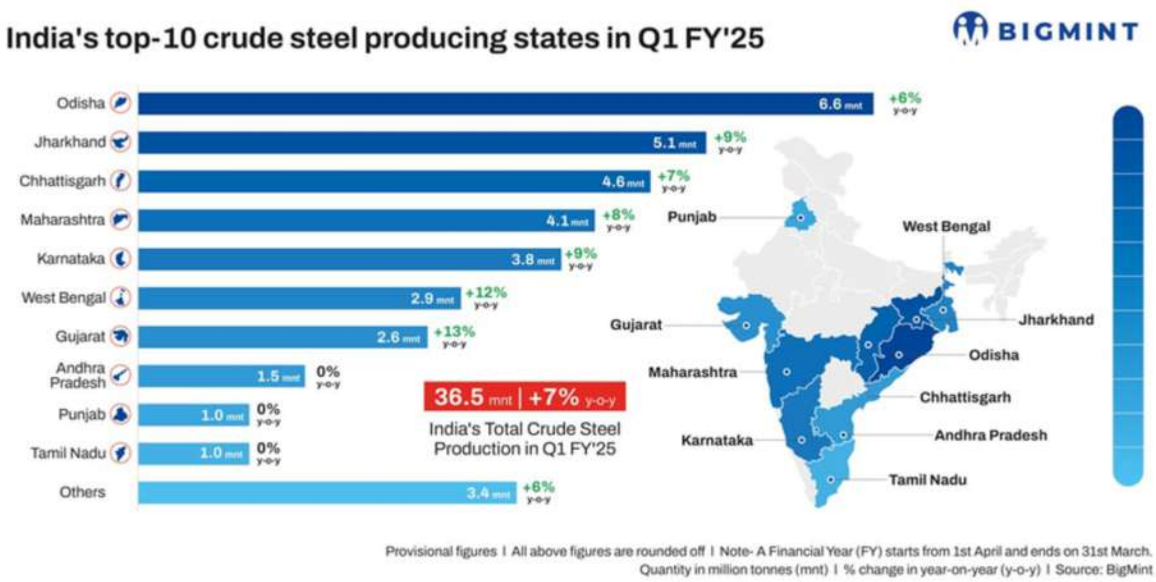
For steelmaking, green ammonia can provide a means of transporting hydrogen from regions with abundant renewable energy to industrial hubs. Countries with significant renewable potential, such as Australia, Saudi Arabia, and India, are already investing heavily in green ammonia projects to supply international markets. Thus, green ammonia strengthens the hydrogen roadmap by ensuring security of supply and enabling global trade in low-carbon fuels.

10. Market Size and Growth (2023–2030)

The global market for green hydrogen and ammonia is set to expand rapidly between 2023 and 2030, driven by policy commitments, industrial adoption, and falling renewable energy costs. North America, led by the United States and Canada, is projected to reach a market size of approximately $50.9 billion for green hydrogen and $4.3 billion for green ammonia. The U.S. has announced substantial investments in hydrogen infrastructure, while Canada is positioning itself as a supplier of green ammonia under its Zero Carbon mission.

Europe is also at the forefront, with Germany emerging as the largest green hydrogen producer and France actively investing in decarbonizing industries. By 2030, Europe’s green hydrogen market is expected to reach $76.3 billion, with green ammonia at $6.5 billion. In the Asia-Pacific region, the market potential is even greater, with projected values of $102.1 billion for green hydrogen and $7.5 billion for green ammonia. China is accelerating hydrogen production capacity, Japan is focusing on hydrogen fuel cells, and Australia is leveraging its vast renewable resources to expand exports. India, through its National Hydrogen Mission, aims to integrate hydrogen deeply into its industrial and energy mix by 2050.

Meanwhile, the MiddleEast and Africaare investing heavilyas part of their long-term visions. Saudi Arabia's Mission 2030 includes large-scale hydrogen and ammonia projects, while the United Arab Emirates is developing multiple hydrogen initiatives. Together, these regions account for an additional $25.1 billion hydrogen market and $3.2 billion ammonia market by 2030. These figures highlight the scale of investment flowing into hydrogen and ammonia, confirming that the steel industry will have access to a rapidly expanding ecosystem of clean fuels.



11. Economic Analysis

Transitioning to hydrogen steel making is capital-and energy-intensive, but costs are expected to decline with scale and technological advancement. Current capital expenditure (CapEx) for electrolysers ranges between $500 and $1,200 per kilowatt, while nitrogen separation systems cost approximately $300,000 to $500,000 for a 1,000 Nm³/h plant. Ammonia synthesis units add another $1,000 to $1,500 per ton of production capacity, and ammonia cracking for hydrogen recovery costs around $200 to $400 per ton of capacity.

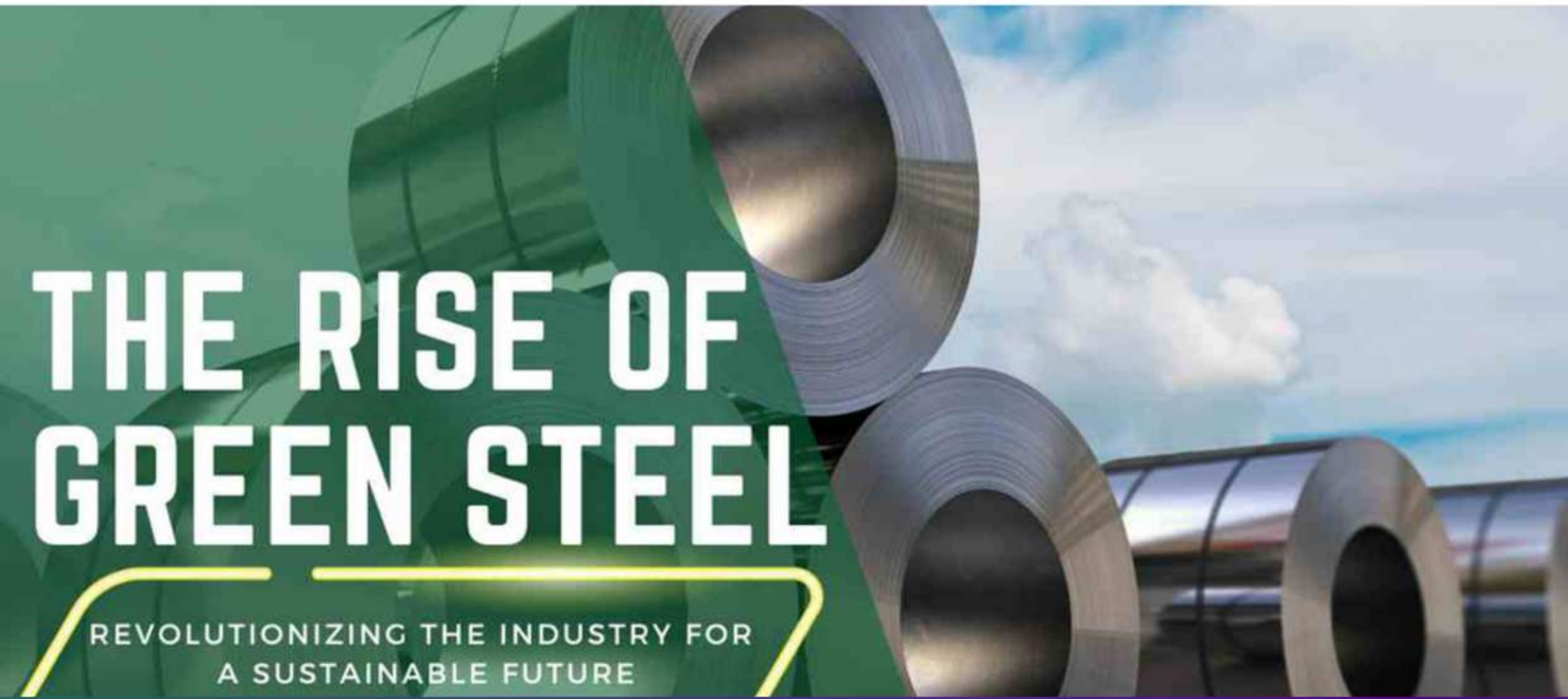
Operational expenditures (OpEx) are similarly diverse. Electrolysis costs average $0.02 to $0.04 per kilowatt-hour, while nitrogen separation costs range from $0.02 to $0.04 per Nm³. Ammonia synthesis requires $150 to $300 per ton, and ammonia cracking adds $200 to $400 per ton of hydrogen capacity. As a result, the current production costs stand at approximately $3 to $7 per kilogram of hydrogen, $300 to $600 per ton of ammonia, and $2 to $4 per kilogram of hydrogen when recovered from ammonia cracking.

These costs remain higher than fossil-fuel-based steelmaking inputs, but economies of scale, falling renewable energy prices, and advancing electrolyser efficiency are expected to drive costs down significantly by 2030. Furthermore, government incentives, carbon pricing, and green procurement programswill help close the cost gap, makinggreen steel more competitive in global markets.

12. Conclusion

The decarbonization of steelmaking is among the most critical industrial transformations of the 21st century. Hydrogen offers a pathway to reduce emissions by up to 97% compared to conventional methods, with the added benefit of aligning the steel industry with global net-zero ambitions. While significant challenges remain—particularly around costs, energy demand, and infrastructure—the roadmap outlined in this white paper demonstrates that the transition is both technologically viable and economically promising.

Green ammonia further strengthens this ecosystem by serving as a scalable hydrogen carrier, enabling global trade and supply chain integration. As investment flows accelerate and governments enact supportive policies, the transition to hydrogen steelmaking is no longer a distant vision but an unfolding reality.With coordinated effortand strategic planning, hydrogen-based steel can become the foundation of a truly sustainable industrial future.



Greenzo Energy India Limited

GREENZO ENERGY INDIA LIMITED
ISO 9001-14001

Contact Us

+91 991 066 9939

info@greenzoenergy.com

www.greenzoenergyindia.com

HO: Unit 1104, 11th floor, Surya Kiran Building, CP, Delhi 110001 India

BO: 4th Floor, 410, Sarthik Square, Bodakdev, Ahmedabad Gujarat, 380054

Manufacturer Unit:
Plot no 678&679, GIDC, Sanand Gujarat 382110, India