Role of green hydrogen in Indian steel sector

April 2025

India Green Steel Coalition
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Acknowledgement

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Credit

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List of common abbreviations

Abbreviation	Definition
BF	Blast furnace
BOF	Basic oxygen furnace
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon Capture, Utilization and Storage
DRI	Direct reduced iron
EAF	Electric arc furnace
EU ETS	European Union Emissions Trading System
GH_2	Green hydrogen
MMT	Million metric ton
MMTPA	Million metric tons per annum
NG	Natural gas
RE	Renewable energy
US$	US dollars

01 Executive summary

India is making substantial strides in its clean energy transition by investing in green hydrogen infrastructure, shifting from carbon-intensive hydrogen production methods to renewable-powered green hydrogen through electrolysis. The National Hydrogen Mission, launched in 2021, aims to establish India as a global leader in green hydrogen, targeting five million metric tons annually by 2030. The initiative is supported by the US$2.1 billion Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, which promotes electrolyzer manufacturing, hydrogen production, and the development of integrated hydrogen hubs, known as "hydrogen valleys", to facilitate production, storage, and utilization.

The steel industry, responsible for 7% of global CO_2 emissions, is central to this transformation. Green hydrogen presents a sustainable alternative to traditional carbon-intensive methods. Alkaline electrolysis, the most commercially viable technology today, is priced at US$7/kg hydrogen. Other emerging technologies like biomass gasification with carbon capture and solid oxide electrolysis show potential but face challenges, such as feedstock availability and technological maturity. India's renewable energy and biomass resources make it well-positioned to integrate hydrogen technologies into steelmaking, supporting the country's commitment to sustainability and industrial innovation.

Integrating green hydrogen into steel production presents a significant opportunity for decarbonization. Hydrogen can be applied across various stages of production, including agglomeration, blast furnace operations, DRI processes, and downstream activities, such as reheating and galvanizing. While partial hydrogen blends have already been successfully demonstrated, full hydrogen adoption is still under exploration. Despite challenges like feedstock availability and infrastructure requirements, technological advancements and supportive policy frameworks are facilitating a move toward a greener future for steel production.

Our analysis in the whitepaper shows, under India's 2070 net zero scenario, the green H2-DRI and electric arc furnace (EAF) route is expected to contribute 13% of the projected 403 MMTPA crude steel output by FY50, growing to 41% of 597 MMTPA by FY70. Green hydrogen demand in the steel sector is expected to grow at a 13% CAGR, reaching 15.15 MMTPA by FY70. In the accelerated net-zero 2050 scenario, H2-DRI steelmaking route shall contribute to 39% of the crude steel production with green hydrogen demand of 9.82 MMTPA by FY50.

Our analysis shows, to achieve a 245 MMTPA H2-DRI capacity by 2070, investments of US$297-US$304 billion are needed. While initial costs for H2-DRI plants are higher than those for BF-BOF setups, falling green hydrogen prices—projected to drop from US$7/kg in 2024 to US$1.8/kg by 2040—and rising global carbon prices are expected to improve the cost competitiveness of H2-DRI by 2035. The production costs of steelmaking via the green hydrogen DRI-EAF route, by which a 90% reduction in emissions can be achieved, are anticipated to decrease from US$600/ton in 2024 to US$421/ ton by 2040, making this a viable and sustainable alternative to traditional steelmaking.

Despite these advantages, widespread adoption of green hydrogen faces significant barriers. High initial infrastructure and technology costs require government incentives, such as production-linked schemes, tax breaks, and public-private partnership (PPP) models. The government's role is central to enabling this transition. A comprehensive National Green Hydrogen Policy should include regulatory measures to reduce renewable power costs and establish adoption targets. Financial incentives, such as tax breaks and carbon pricing mechanisms, are essential to attracting investments to meet the US$264-297 billion funding requirements by 2050–2070. Infrastructure development, particularly through hydrogen hubs and pipeline networks in industrial clusters, will centralize production and distribution, enhancing efficiency and reducing costs. These measures can reduce electricity and capital costs, making hydrogen adoption more affordable. Centralized hydrogen hubs, pipeline networks, and advanced storage solutions are essential to overcoming infrastructure gaps, reducing transport costs by up to 90%, and ensuring a reliable supply.

Additionally, fragmented supply chains and a lack of standardization further complicate adoption. Establishing industry-wide standards, optimizing logistics, and fostering global collaborations will streamline the hydrogen supply chain, facilitating access to advanced technologies and enabling widespread adoption. Significant investments in research and development (R&D) and workforce training are also critical to improving hydrogen technology efficiency and creating a skilled workforce to support the transition.

Steelmakers must adopt proven technologies like green hydrogen DRI-EAF and explore hydrogen production emerging solutions such as solid oxide electrolysis and biomass gasification with CCUS. Public-private partnerships can help co-develop infrastructure, optimize supply chains, and reduce hydrogen delivery costs, accelerating the transition. Collaboration between domestic and international electrolyzer manufacturers in R&D can improve electrolyzer's technology efficiency by 30% to 40%.

In conclusion, India's commitment to green hydrogen presents a transformative opportunity to decarbonize its steel sector, a major emitter of global CO_2 emissions. Addressing economic, technological, and logistical challenges through strategic interventions will enable India to lead the global transition to sustainable steel production. This effort supports broader goals of industrial innovation, energy security, and climate action, ensuring long-term competitiveness and environmental sustainability.

02 Hydrogen production technologies and infrastructure

India is advancing its green hydrogen production infrastructure to support its ambitious clean energy goals. Presently, most of the country's hydrogen is produced from natural gas through steam methane reforming, a carbon-intensive process. However, India aims to transition towards green hydrogen through electrolysis powered by renewable sources like solar and wind, leveraging its abundant renewable energy resources and favorable climate.

The Indian government launched the National Hydrogen Mission in 2021, aiming to make India a global leader in green hydrogen production with a target of five million metric tons per year by 2030. A significant policy under this mission is the Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, which provides incentives for electrolyzer manufacturing and green hydrogen production. The SIGHT scheme has a total outlay of about US$2.1 billion, divided into three main components[1]:

- Incentive Scheme for Electrolyzer Manufacturing: This component has an allocation of around US$0.54 billion
- Incentive Scheme for Green Hydrogen Production: This component is allocated around US$1.59 billion
- Incentive Scheme for the establishment of "Hydrogen Valleys": US$50 million up to 2025-26 – integrated hydrogen ecosystems that connect production, storage, and end-use applications in specific regions to support industry adoption and regional decarbonization

The steel sector is poised to become a major consumer of green hydrogen due to its significant carbon footprint, accounting for approximately 7% of global CO_2 emissions[2]. The key drivers for the adoption of green hydrogen in the steel sector are:

- **Environmental regulations:** Compliance with increasingly stringent environmental regulations and policies aimed at reducing industrial emissions (e.g., EU ETS, CBAM, India's PAT scheme, CCTS)
- **Technological advancements:** Progress in hydrogen-based direct reduction of iron (H2-DRI) technology, which enables cleaner steel production

1. Ministry of New and Renewable Energy, National Green Hydrogen Mission
2. International Energy Agency, October 2020, Iron and Steel Technology Roadmap

- **Policy support:** Strong governmental and policy support for green hydrogen initiatives, including financial incentives and infrastructure development (e.g., SIGHT Scheme, National Hydrogen Mission)
- **Cost-effective green hydrogen:** Growing availability and decreasing costs of green hydrogen, making it a viable alternative to traditional fossil fuels

Thus, it is crucial to explore green hydrogen production technologies and their respective infrastructure requirements. Identifying the best technologies for the steel sector involves evaluating the efficiency of electrolyzers, the scalability of hydrogen production, and the integration of renewable energy sources to ensure a sustainable and cost-effective transition to green steel production.

Table 1: Comparison of green hydrogen production technologies

Technology	Description	Efficiency	Infrastructure requirements	Key advantages	Challenges	TRL
Alkaline electrolysis	Uses an alkaline solution as the electrolyte. Long-established technology	60-70%	Moderate electricity supply, water source, alkaline electrolyte handling	Mature technology, relatively low cost	Lower efficiency, slower response to load changes	9 commercially ready)
Proton Exchange Membrane (PEM) electrolysis	Uses a solid polymer electrolyte. More flexible and responsive than alkaline	60-65%	High-purity water, stable electricity supply, platinum and iridium catalysts	Higher efficiency, faster response, compact system design	High cost due to noble metal catalysts	8-9 (Near commercial)
Solid Oxide Electrolysis (SOE)	Operated at high temperatures, uses a solid ceramic electrolyte, can integrate with waste heat sources	80-90%	High temperature heat sources, stable power supply, ceramic handling	High efficiency, potential for waste heat recovery	High operational temperature, expensive materials	6-7 (pilot to demonstration)
Anion Exchange Membrane (AEM) electrolysis	Uses an anion-exchange membrane, combines features of alkaline and PEM electrolysis	50-60%	Moderate electricity supply, scalable design, less noble metal dependency	Lower cost potential, promising for decentralized systems	Still in development, limited commercial availability	5-6 (pilot to demonstration)

Technology	Description	Efficiency	Infrastructure Requirements	Key Advantages	Challenges	TRL
Photoelectro-chemical (PEC) water splitting	Uses sunlight directly to split water into hydrogen and oxygen	50-60%	Requires high solar intensity, specialized solar cells and materials	Direct use of solar energy, no electricity conversion needed	Low efficiency, limited scalability	3-4 (Research to Laboratory)
Thermo-chemical Water Splitting (TWS)	Uses a high-temperature heat(eg: from solar concentrators) for chemical cycles to produce hydrogen	20-40%	Requires very high temperatures (800-1000C), Solar concentrators	Utilizes renewable heat sources, potential for low-cost hydrogen	Complex, energy-intensive, limited efficiency	3-4 (Research to Laboratory)
Biomass gasification with carbon capture	Converts biomass into hydrogen-rich gas, with carbon capture to make it green	40-55%	Biomass feedstock supply, gasifier, carbon capture, and storage equipment	Uses renewable biomass, potential for lower costs	Complex supply chain, dependence on biomass availability	5-6 (Pilot to demonstration)

For hydrogen usage in steel production in India, alkaline electrolysis and biomass gasification with Carbon Capture, Utilization, and Storage (CCUS) emerge as the most viable options, supported by the following factors:

- **Cost-effectiveness:** Alkaline electrolysis has a relatively low capital cost, both in terms of electrolyzer (US$600-700/kW) and balance of plant (US$300-400/kW). This makes it economically attractive for large-scale hydrogen production, crucial for cost-sensitive steel manufacturing
- **Mature technology:** Alkaline electrolysis is a commercially ready, reliable, and established technology (TRL 9), ensuring ease of deployment in India's industrial landscape
- **Biomass availability:** Biomass gasification is particularly suitable for India, where agricultural and forestry residues like rice husk and wood chips are abundant. Utilizing this biomass as a feedstock enables hydrogen production while supporting rural economies
- **Carbon capture potential:** Biomass gasification paired with CCUS allows for carbon-neutral hydrogen production, which is advantageous for emissions-intensive industries like steel
- **Less dependence on imported materials:** Both technologies minimize reliance on noble metals, reducing dependency on costly and scarce materials like platinum and iridium, which are required for PEM electrolysis

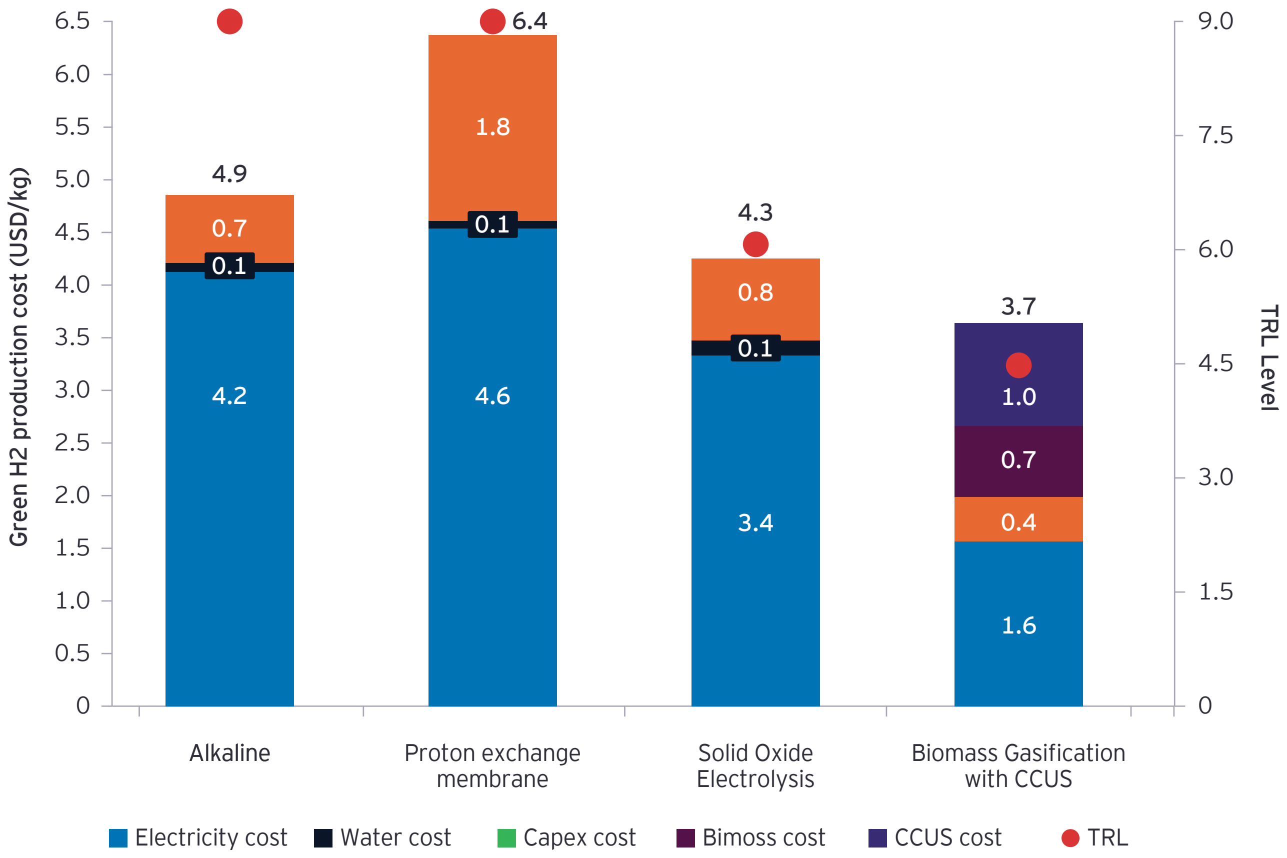
The cost figures mentioned in the report reflect a blended global average, taking into account prices from multiple regions. While the Chinese electrolyzer manufacturers currently offer competitive pricing, there are certain factors, like future government regulations, that could influence the total cost of ownership in the Indian context.

Table 2: Shortlisted green hydrogen production technologies for steel sector

Technology	Electricity requirement (kWh/kg H2)	Water requirement (L/kg H2)	Water quality (PPM)	Electrolyser Cost (US$ / kW)	BoP Cost (US$ /kW)	Other Requirements
Alkaline electrolysis	50-55	9-10	< 10 PPM	600-700	300-400	None; no noble metal dependency; no CCUS required
Proton Exchange Membrane (PEM) electrolysis	55-60	10-12	< 1 PPM	1000-1200	400-500	Requires platinum and iridium; no CCUS required
Solid Oxide Electrolysis (SOE)	40-45	8-10	< 10 PPM	1200-1500	600-700	High-temperature heat source (700-900C); no noble metal dependency; no CCUS required
Biomass gasification with carbon capture	10-20	2-4	50-100 PPM	600-800	200-250	Biomass: dry, low-sulphur quality; 10-12 kg biomass per kg H2; heat source (800-900C from biomass combustion); CCUS required

Together, these factors make alkaline electrolysis and biomass gasification with CCUS highly compatible with India's goals for scalable, affordable, and sustainable hydrogen use in steel production.

Figure 1: Hydrogen production cost and TRLs



Source: EYP analysis

However, after evaluating the infrastructure requirements and levelized cost of green hydrogen production for each technology, we conclude that alkaline electrolysis, with a Technology Readiness Level (TRL) of 9, is commercially mature and ready for deployment. This technology is the most viable option for meeting the hydrogen demands of integrated steel plants. The levelized cost of green hydrogen production is US$4.9 per kg through alkaline technology, and the delivered cost of green hydrogen is approximately US$7 per kg of GH_2.

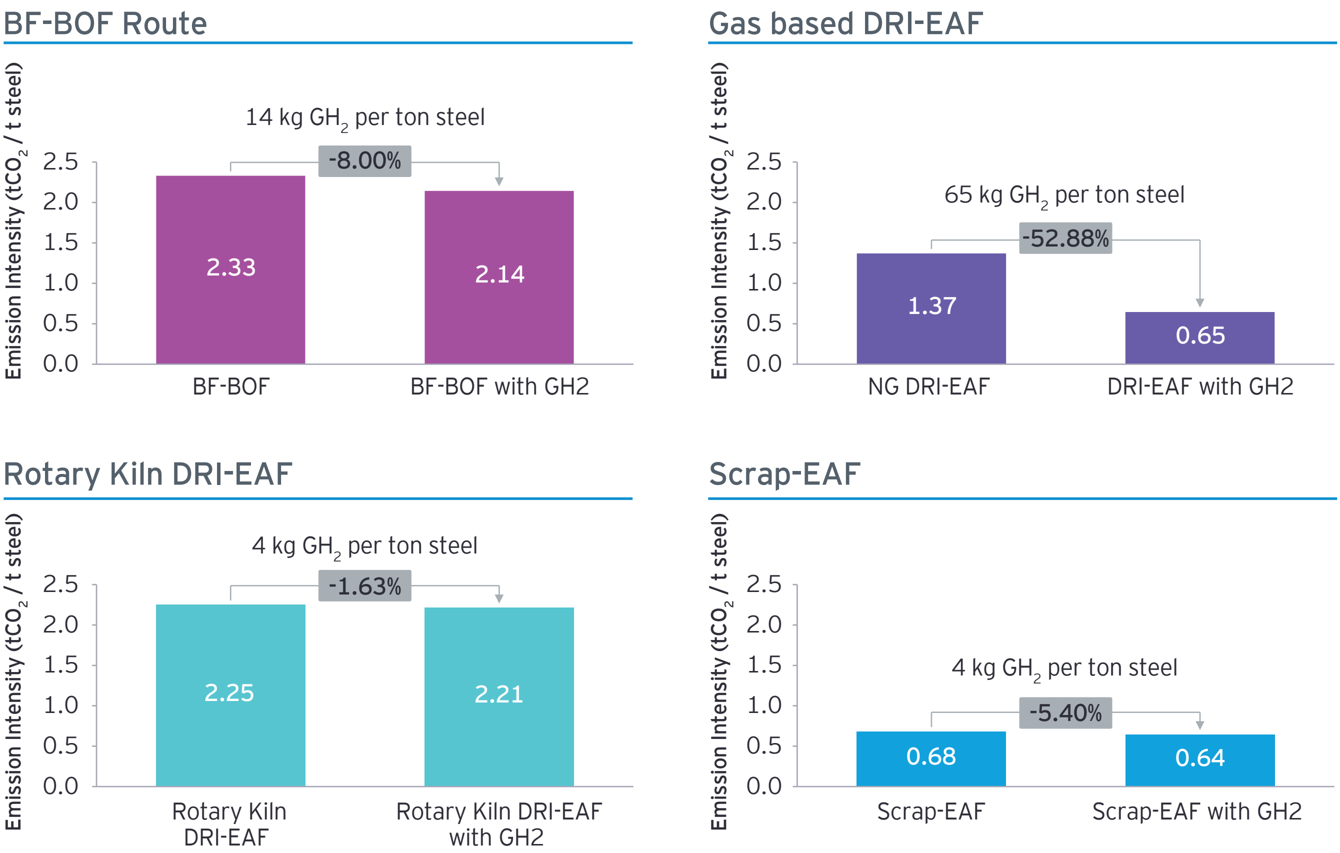
While biomass gasification with Carbon Capture, Utilization, and Storage (CCUS) offers the lowest hydrogen production cost at US$3.7 per kg, its reliance on seasonal biomass availability and a lower TRL of 4 limit its feasibility for large-scale, consistent operations. Despite higher technological risks, steel companies can invest in emerging technologies like Solid Oxide Electrolysis (SOE) and biomass gasification to achieve long-term cost efficiencies as these technologies mature.

Alkaline and, to some extent, PEM electrolysis depending on the falling costs should be prioritized for their proven scalability, operational reliability, and compatibility with renewable energy infrastructure, which are critical for the steel sector's green hydrogen transition.

03 Green hydrogen usage in steel industry

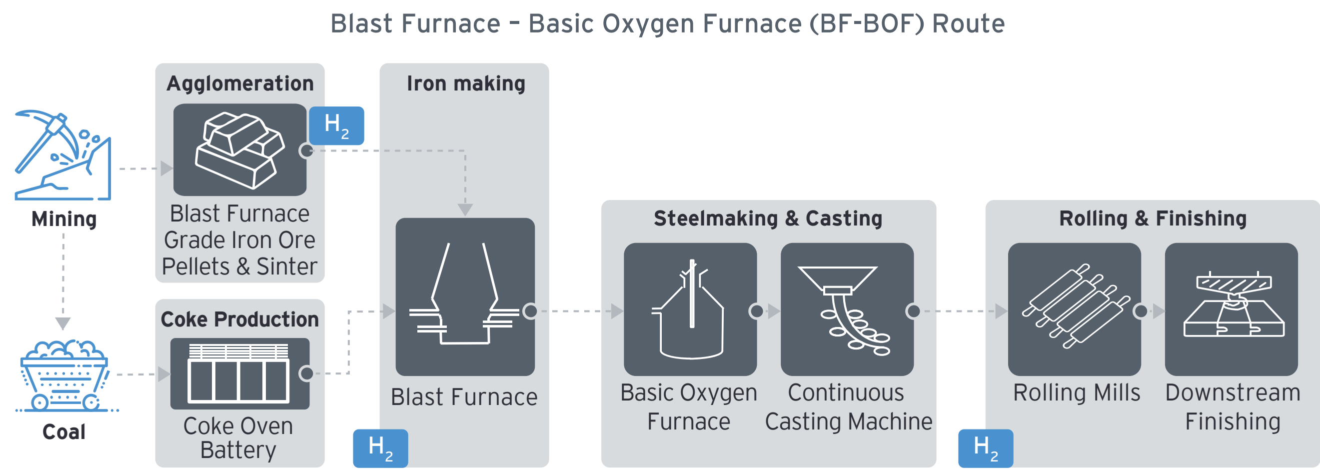
The integrated steel plant's production value chain involves several processes like mining, agglomeration, ironmaking, steelmaking, rolling, and downstream finishing processes. Hydrogen as a fuel, offers several applications within each facility, primarily to decarbonize the operations by eliminating the reliance on fossil fuel. From hydrogen for fuel reduction in agglomeration to direct injection in blast furnaces and DRI processes, hydrogen can significantly curtail fossil fuel consumption. Downstream, hydrogen blending in fuel for reheating, galvanizing, and color coating processes can reduce emissions from hot and cold rolling operations. Hydrogen, with its potential to significantly reduce emissions across the steelmaking value chain, is poised to play a pivotal role in the industry's transition to a low-carbon future.

Figure 2: Emission intensity reduction from green hydrogen usage across steelmaking processes



Source: EYP analysis

Figure 3: Application of green hydrogen in BF-BOF value chain



Source: EYP analysis

Utilizing 14 kgs of green hydrogen per ton of steel in the BF-BOF process could lead to an approximate 8% reduction in total CO_2 emissions from an initial emission intensity of 2.33 tons of CO_2 per ton of steel. The proposed application of green hydrogen includes its use in the sinter and pellet plants for agglomeration, the blast furnace, the reheating furnace during hot rolling, and the color coating and galvanizing units within the cold rolling mill plant. By integrating green hydrogen in these areas, the emission intensity for the BF-BOF process could decrease to 2.14 tons of CO_2 per ton of steel. Although the concept of blending green hydrogen into the fuel mix is still under investigation, the injection of green hydrogen into the blast furnace has been successfully demonstrated. The use of hydrogen in reheating furnaces is also well-established, achieving a TRL of 9. In our analysis, we have assumed a 20% green hydrogen blend with the possibility of increasing to a full 100% in reheating furnaces. The table below outlines the use of hydrogen in the BF-BOF value chain and its potential to mitigate CO_2 emissions.

Table 3: CO_2 abatement potential through green hydrogen in BF-BOF

Plant or unit	CO_2 emissions (tCO_2e / t steel)	Green hydrogen usage	GH_2 consumption (kg / t steel)	CO_2 abatement (tCO_2e / t steel)	TRL
Sinter	0.2	20% GH_2 can be blended with coke oven gas	0.04	0.0140	3-4
Pellet	0.1	20% GH_2 can be blended with COG and BF Gas	0.53	0.0126	3-4
Blast furnace	1.38	GH_2 can be injected to reduce coke consumption	10	0.1242	5
Hot strip mill	0.15	20% GH_2 can be blended with BF gas in reheating furnace	2.58	0.0184	9
Cold rolling mill and finishing	0.1	Galvanizing: 20% H_2 can be blended with propane	0.64	0.0090	3-4
		Color coating: 20% H_2 can be blended with Prop.	0.58	0.0082	

Key notes for the analysis

01 **Sinter plant gas consumption:** 69 Nm3/t sinter coke oven gas

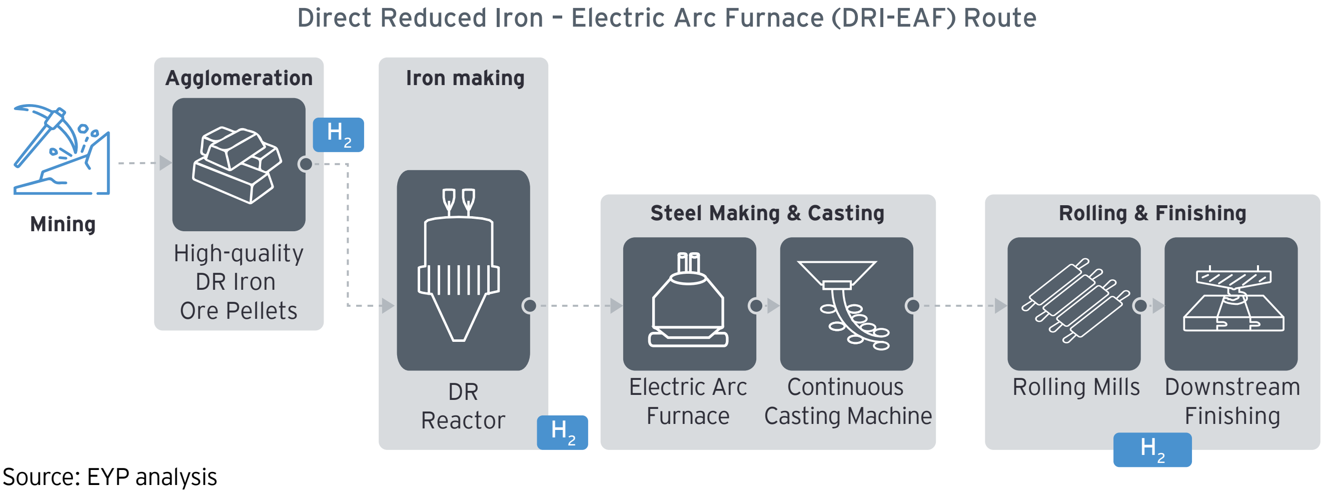
02 **Pellet plant gas consumption:** 23 Nm3/t pellet COG; 73 Nm3/t pellet blast furnace gas

03 **Reheating furnace gas consumption:** 540 Nm3/t steel BFG

04 **Galvanizing:** 10 kg/t steel propane

05 **Color coating:** 9kg/t steel propane

Figure 4: Application of green hydrogen in gas based DRI-EAF value chain



Source: EYP analysis

Incorporating 65 kgs of green hydrogen per ton of steel into the DRI-EAF process, which is gas-based, could potentially slash CO_2 emissions by about 53% from an initial emission intensity of 1.37 tons of CO_2 per ton of steel. The proposed deployment of green hydrogen spans several areas, including the sinter and pellet plants for agglomeration, the DRI shaft, the reheating furnace used in hot rolling, and the color coating and galvanizing units in the cold rolling mill plant. By adopting green hydrogen in these processes, it is possible to reduce the emission intensity to 0.65 tons of CO_2 per ton of steel for the gas-based DRI-EAF process. Although a hydrogen-based DRI-EAF process could nearly eliminate CO_2 emissions, this analysis only accounts for the use of hydrogen in the DRI shaft and does not consider the effects of using renewable energy (RE) in the electric arc furnace or the impact of RE on pellet plant and downstream processes. The table below details the application of hydrogen and its potential for reducing CO_2 emissions.

Table 4: CO_2 abatement potential through green hydrogen in gas based DRI-EAF

Plant or unit	CO_2 emissions (tCO_2e / t steel)	Green hydrogen usage	GH_2 consumption (kg / t steel)	CO_2 abatement (tCO_2e / t steel)	TRL
Pellet	0.11	20% GH_2 can be blended with natural gas	0.98	0.0077	3-4
DRI shaft	0.7	100% GH_2 can be used as reducing agent	60	0.6800	9
Hot strip mill	0.15	20% GH_2 can be blended with natural gas in reheating furnace	2.73	0.0195	9
Cold rolling mill and finishing	0.1	Galvanizing: 20% GH_2 can be blended with propane	0.64	0.0090	3-4
		Color coating: 20% GH_2 can be blended with Prop.	0.58	0.0082	

Key notes for the analysis

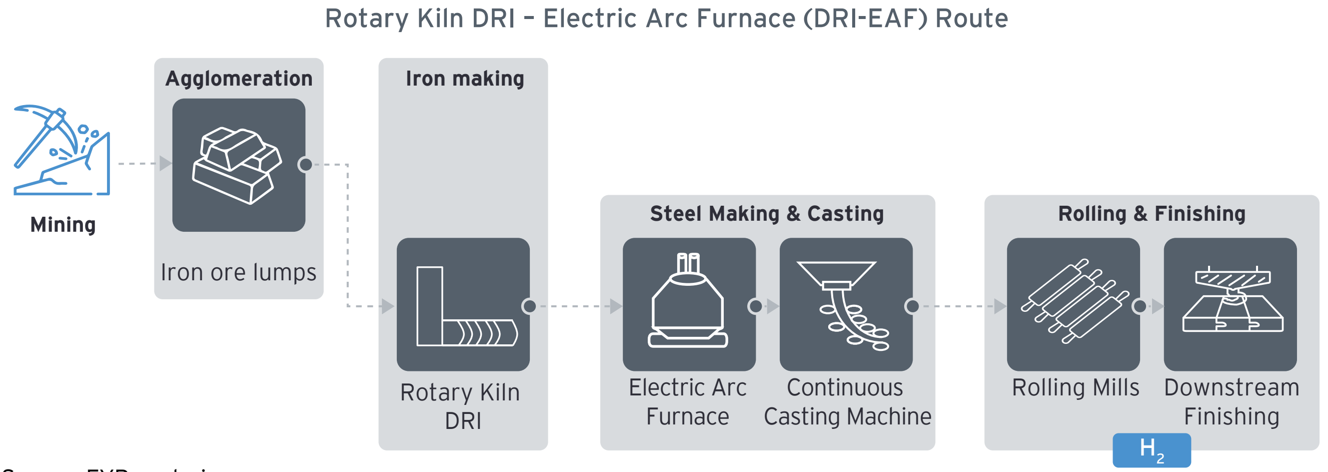
01 **Pellet plant gas consumption:** 18 Nm3/t pellet natural gas

02 **Reheating furnace gas consumption:** 50 Nm3/t steel natural gas

03 **Galvanizing:** 10 kg/t steel propane

04 **Color coating:** 9kg/t steel propane

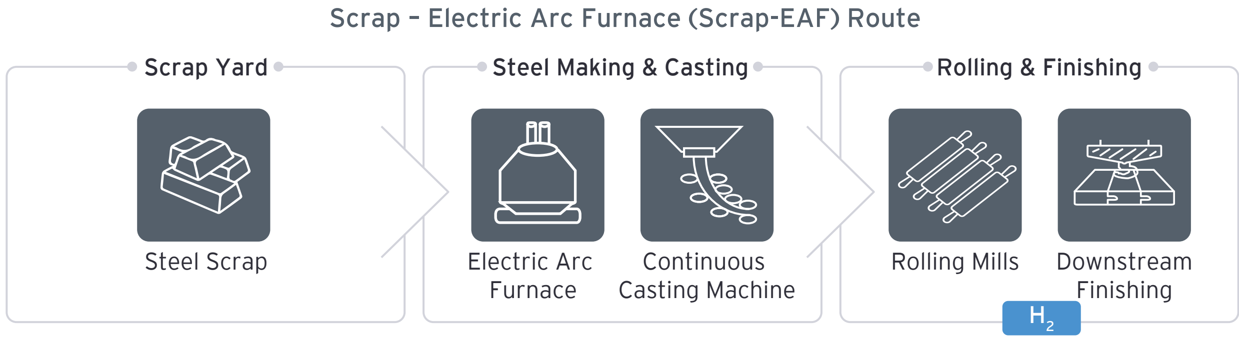
Figure 5: Application of green hydrogen in rotary kiln DRI-EAF value chain



Source: EYP analysis

In the coal-based DRI-EAF process utilizing a rotary kiln, the introduction of four kgs of green hydrogen per ton of steel has the potential to cut CO_2 emissions by approximately 1.6% from a baseline emission intensity of 2.25 tons of CO_2 per ton of steel. The use of green hydrogen is currently envisioned for the reheating furnace in hot rolling and the color coating and galvanizing operations in the cold rolling mill plant. With the integration of green hydrogen in these specific areas, it is possible to reduce the emission intensity to 2.21 tons of CO_2 per ton of steel for the rotary kiln coal-based DRI-EAF process.

Figure 6: Application of green hydrogen in scrap based EAF



Source: EYP analysis

In the process of steelmaking using a scrap-based electric arc furnace (EAF), the application of four kgs of green hydrogen per ton of steel could lead to a reduction of about 5.4% in total CO_2 emissions from an initial emission intensity of 0.68 tons of CO_2 per ton of steel. The utilization of green hydrogen is proposed for the reheating furnace in hot rolling operations, as well as the color coating and galvanizing sections of the cold rolling mill plant. By implementing green hydrogen in these stages, the emission intensity could potentially be decreased to 0.64 tons of CO_2 per ton of steel for the scrap-based EAF steelmaking process.

Table 5: CO_2 abatement potential through green hydrogen in rotary kiln DRI-EAF and scrap-EAF

Plant or unit	CO_2 emissions (tCO_2e / t steel)	Green hydrogen usage	GH_2 consumption (kg / t steel)	CO_2 abatement (tCO_2e / t steel)	TRL
Hot strip mill	0.15	20% GH2 can be blended with natural gas in reheating furnace	2.73	0.0195	9
Cold rolling mill and finishing	0.1	Galvanizing: 20% GH2 can be blended with propane	0.64	0.0090	3-4
		Color coating: 20% GH2 can be blended with Propane	0.58	0.0082	

Key notes for the analysis

01 **Reheating furnace gas consumption:** 50 Nm3/t steel natural gas

02 **Galvanizing:** 10 kg/t steel propane

03 **Color coating:** 9kg/t steel propane

In conclusion, the integration of green hydrogen into various stages of the steelmaking process presents an opportunity to reduce CO_2 emissions and transition towards a more sustainable steel industry. **Green hydrogen based DRI-EAF steelmaking shows the highest potential for curbing CO_2 emissions.** By leveraging hydrogen's clean energy potential, steelmakers can significantly lower their carbon footprint while maintaining production efficiency.

The analysis presented in this section highlights the potential of hydrogen to mitigate emissions across different steelmaking routes. While significant technological advancements and infrastructure developments are required to fully realize the potential of hydrogen-based steelmaking, the growing momentum and increasing global focus on decarbonization provide a strong impetus for the industry to embrace this transformative technology. By investing in research and development, fostering collaborations, and implementing supportive policies, the steel industry can pave the way for a greener and more sustainable future.

04

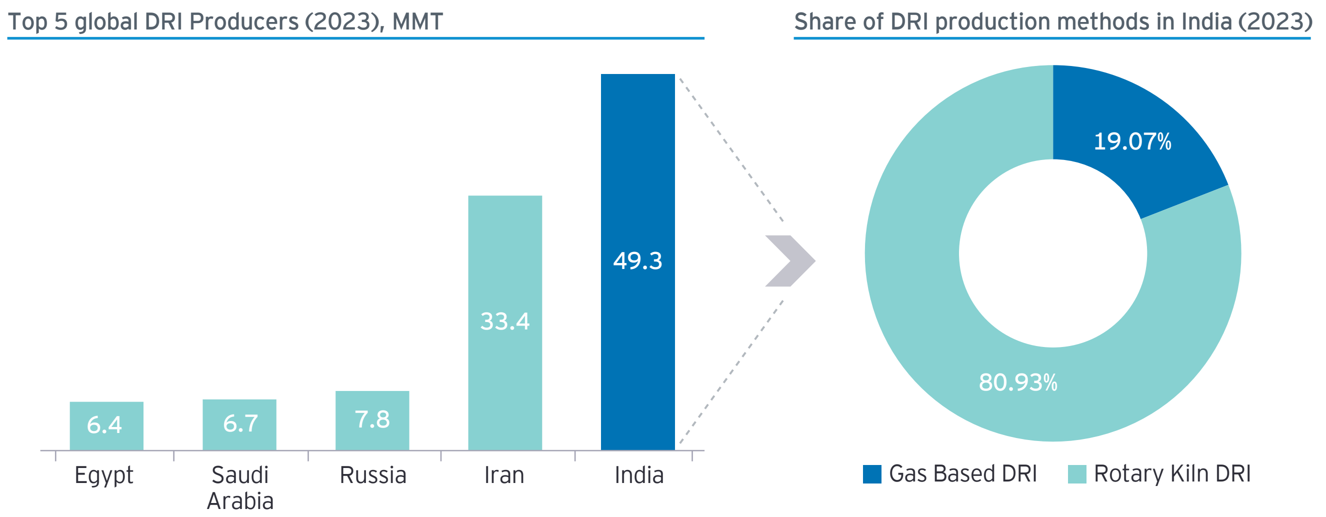
Steelmaking routes in net zero scenario

The insights gleaned from the preceding analysis indicate that the most effective deployment of green hydrogen is in vertical shaft DRI processes and reheating furnaces, owing to their significant CO_2 emission reduction potential and high TRLs. Within the framework of integrated steel production, ironmaking emerges as the primary contributor to CO_2 emissions throughout the value chain. While the integration of hydrogen into blast furnaces poses certain technical hurdles, its application in rotary kilns remains underexplored.

In the context of DRI as a precursor for steelmaking, India maintains its position as the world's leading DRI producer. In 2023, India achieved a record production of 49.3 MMT of DRI. However, a substantial portion, amounting to 39.9 MMT or approximately 81%, was produced using emission-intensive rotary kilns. This pattern is not only persistent but also escalating, as evidenced by the increasing proportion of DRI production via rotary kilns[3].

3. MIDREX, 2023 World Direct Reduction Statistics

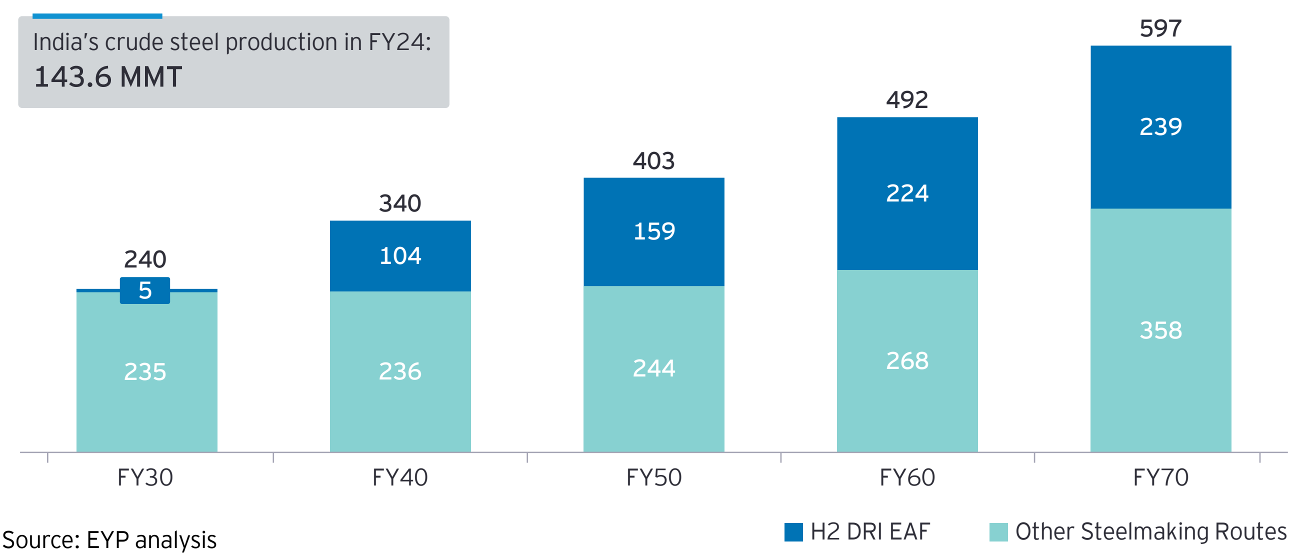
Figure 7: Top DRI producers in the world and share of DRI production routes in India (2023)



Source: World Direct Reduction Statistics - MIDREX

To realize a net-zero emission target for the Indian steel industry, a transition to steel production methodologies with lower emissions is imperative. In an accelerated net zero 2050 scenario, our analysis suggests that by the FY50, a swift move towards a green hydrogen-based direct reduced iron (DRI) - electric arc furnace (EAF) steelmaking process is expected, representing 39% of the estimated 403 MMTPA of crude steel production. The adoption of hydrogen-based DRI is anticipated to rise significantly, capturing 30%, 45%, and 40% of the steel production market share by the FY40, FY60, FY70, respectively. This surge is underpinned by a green steel production trajectory and a forecasted decline in the cost of green hydrogen, which is expected to fall below US$1.8/kg H2 by 2040.

Figure 8: Share of steel production routes in 2050 net zero scenario



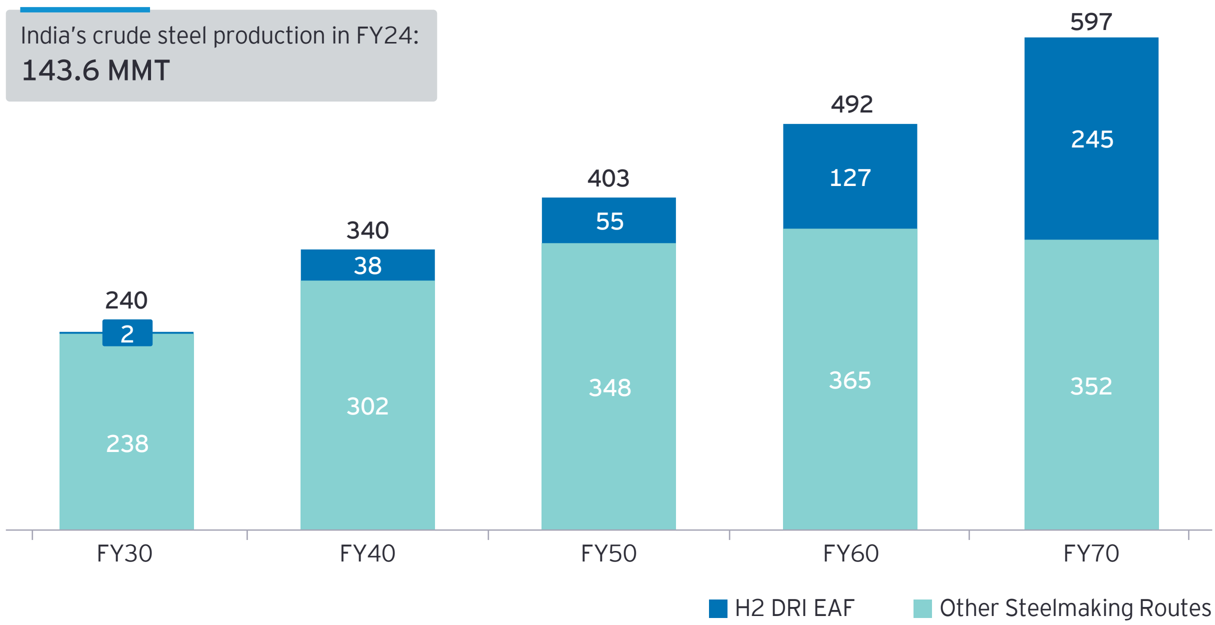
Source: EYP analysis

"Other steelmaking routes", which will be utilized until net zero objectives are met, include blast furnace-basic oxygen furnace, coal-based direct reduced iron-electric arc furnace, natural gas direct reduced iron-electric arc furnace, and scrap-electric arc furnace. A progressive shift toward, and eventual full implementation by the net zero target year, of sustainable and low-emission steel technologies is anticipated. These technologies encompass scrap-based electric arc furnaces powered by renewable energy, carbon capture from BF-BOF, and molten oxygen electrolysis, among others.

As part of the nation's ambition to achieve a net-zero carbon footprint by the year 2070, hydrogen-based DRI steelmaking is projected to constitute 41% of the total crude steel production, estimated at 597 million metric tons per annum (MMTPA). A gradual yet consistent rise in the adoption of H2 DRI is anticipated, with its contribution to steel production expected to be 11%, 13%, 26% by the FY40, FY50, FY60, respectively.

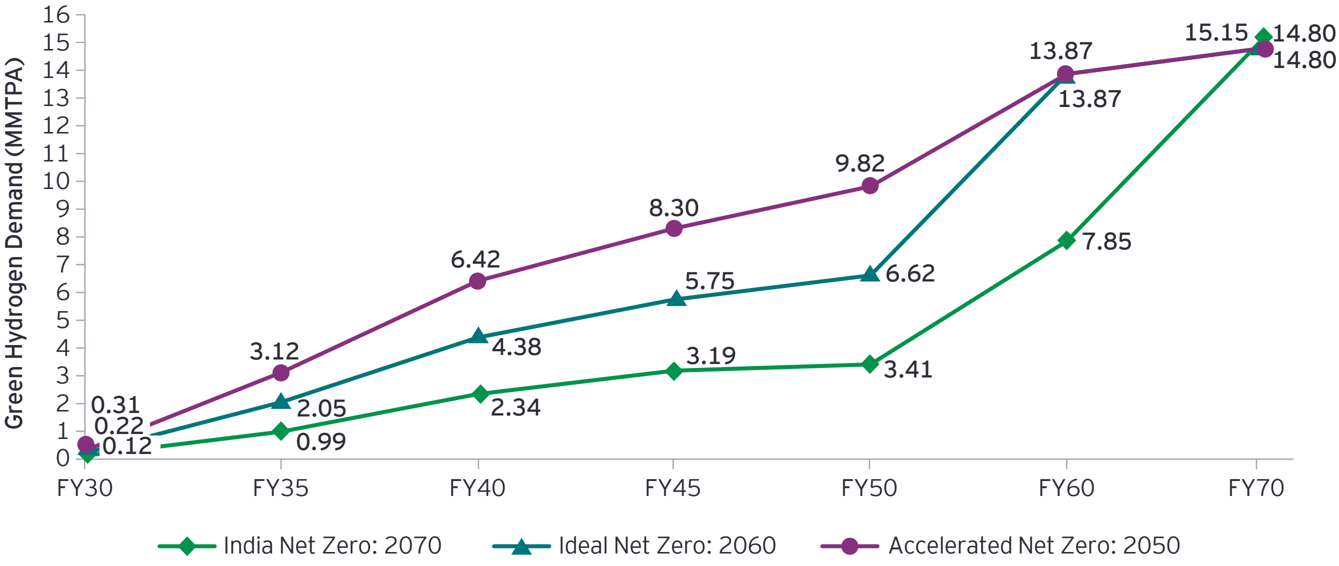
As the capacities for hydrogen-based direct reduced iron (H2 DRI) electric arc furnace (EAF) expands, a substantial increase in the demand for green hydrogen is anticipated. In the context of India's net zero 2070 scenario, the demand for green hydrogen in H2-DRI steelmaking is expected to grow at a CAGR of 13%, surging to 15.15 MMTPA by the fiscal year 2070, up from 0.12 MMTPA in FY30. In an accelerated net zero 2050 scenario, this demand is projected to rise at a CAGR of 10%, reaching approximately 14.8 MMTPA by FY70, starting from 0.31 MMTPA in FY30. Under the "Ideal Net Zero 2060" scenario, the demand for green hydrogen in H2-DRI steelmaking is also expected to grow at a 13% CAGR, achieving a similar level of ~14.8 MMTPA by FY70, up from 0.22 MMTPA in FY30. This scenario anticipates that H2-DRI will contribute to steel production volumes of 71, 134, 209, and 239 MMTPA, corresponding to market shares of 21%, 33%, 42%, and 40% for the fiscal years 2040, 2050, 2060, and 2070, respectively.

Figure 9: Share of steel production routes in 2070 net zero scenario



Source: EYP analysis

Figure 10: Demand of green hydrogen from DRI-EAF route (MMTPA)



Source: EYP analysis

While the transition is green, this shift towards a more sustainable steel production method using hydrogen-based DRI comes with its own set of technical challenges that need to be addressed[4]:

01 **Modifications in electric arc furnaces:** Existing EAFs will require retrofitting to accommodate the continuous feed of DRI. This change is more straightforward in new, greenfield setups where EAFs can be designed to handle H2-DRI from the outset.

02 **Requirement for high-grade iron ore:** The quality of DRI is crucial for efficient steelmaking in EAFs. The use of high-grade iron ore, with an average iron (Fe) content above 67%, is necessary to produce quality DRI. Currently, such high-grade ore represents only 4% of global iron ore shipments. Lower grade ores with higher impurity levels can lead to increased slag production, which is problematic for EAFs that are sensitive to DRI quality. High slag volumes can result in significant iron loss due to the oxidation of impurities. Iron ore beneficiation can be pivotal in solving this challenge.

03 **Challenges with bath mixing:** H2-DRI's melting behavior is less favorable compared to conventional DRI, presenting challenges during the melting process. Traditional stirring methods in EAFs rely on oxygen injection, which is less effective with H2-DRI due to its low carbon content. This can hinder the melting process and reduce the maximum feed rate that can be achieved.

04 **Slag foaming issues:** Effective slag foaming is essential for maintaining heat transfer from the electric arc to the molten steel bath, minimizing refractory wear, controlling noise levels, and preventing slag spills. However, in the case of H2-DRI, the absence of carbon in the EAF means that energy savings from CO foam cannot be realized, which can affect the overall efficiency of the steelmaking process when using H2-DRI. The issue can be addressed through the usage of biochar in EAF steelmaking.

In conclusion, the journey towards a greener and more sustainable Indian steel industry is marked by a clear roadmap that includes the integration of green hydrogen in steelmaking processes, particularly in the vertical shaft DRI. The anticipated rise in the adoption of hydrogen-based DRI underscores the industry's commitment to reducing its carbon footprint. However, this path is not without its challenges, as technical obstacles related to green hydrogen DRI steelmaking must be overcome. Addressing these issues is critical to ensuring the successful implementation of low-emission steel production methods. With the right strategies and continued innovation, India's steel industry is poised to make significant strides towards achieving its net-zero targets, setting a precedent for sustainable industrial practices on a global scale.

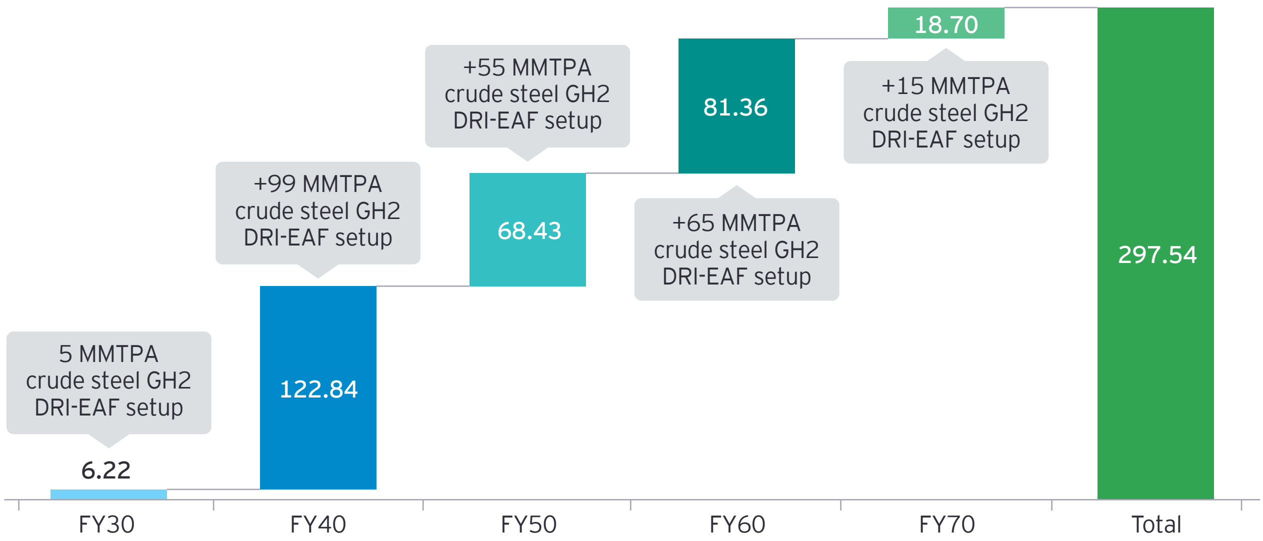
4. Ali Hasanbeigi, Cecilia Springer, and Hannah Irish, March 2024, Green H2 - DRI Steelmaking: 15 Challenges and Solutions

05 Economics of green hydrogen based DRI production

In light of the prominent role that hydrogen-based DRI steelmaking plays in both the accelerated 2050 and the national net zero 2070 scenarios, it is crucial to examine the financial commitments needed over time to reach the desired levels of crude steel production. Figure No. 11 delineates the capital expenditures necessary for establishing a green hydrogen-based DRI-EAF steelmaking facility under the accelerated net zero 2050 framework. The initial setup, with a capacity of five MMTPA GH_2 DRI-EAF, will require an investment of US$6.22 billion (value in nominal terms) by the fiscal year 2030. By FY40, it is projected that an additional 99 MMTPA of crude steel production capacity will be developed, necessitating an investment of US$122.84 billion. Further expansions are planned to add capacities of 55 MMTPA and 65 MMTPA, with corresponding investments of US$68.43 billion and US$81.36 billion. The concluding expansion phase, which will increase crude steel production by another 15 MMTPA, is estimated to require an additional US$18.70 billion. Therefore, a total investment of approximately US$297 billion is anticipated to be required for achieving a 245 MMTPA H2 DRI steelmaking capacity by FY70 in India.

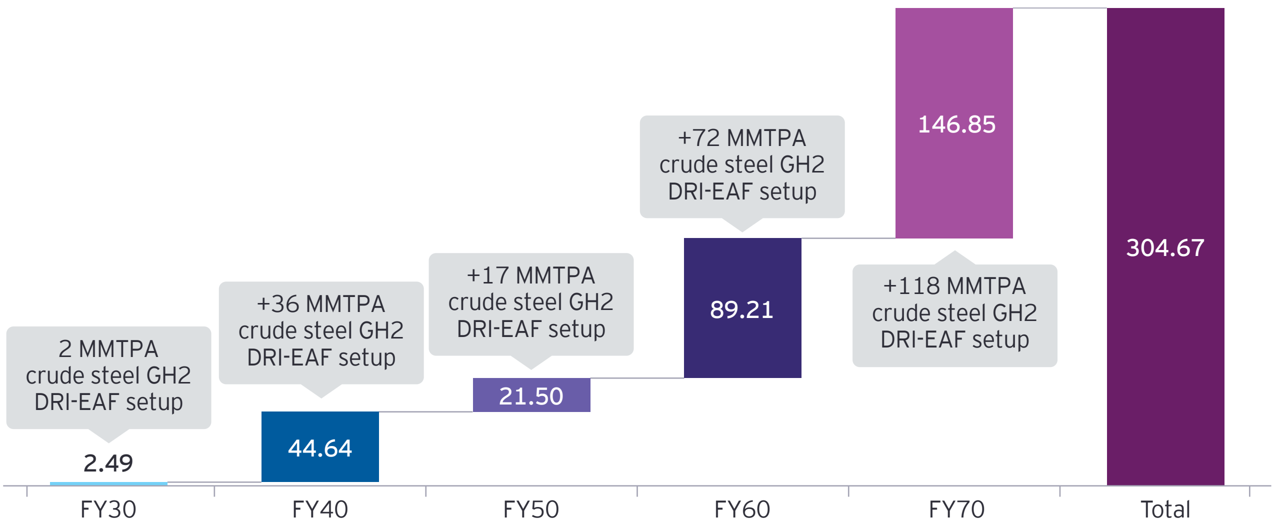
Figure No. 12 presents the projected capital investment needed to develop a green hydrogen-based DRI-EAF steelmaking infrastructure aligned with India's net zero 2070 ambitions. The establishment of the initial 2 MMTPA GH_2 DRI-EAF facility is expected to require an investment of US$2.49 billion by the fiscal year 2030. By FY40, the plan is to augment the capacity by an additional 36 MMTPA of crude steel production, at a cost of US$44.64 billion. Future expansion phases are set to increase capacity by 17 MMTPA and 72 MMTPA, with investments of US$21.5 billion and US$89.21 billion, respectively. The ultimate expansion stage, which aims to add 118 MMTPA to crude steel production, will call for a further investment of US$146.85 billion. Consequently, a cumulative investment of approximately US$304 billion is anticipated to establish a 239 MMTPA H2 DRI steelmaking capacity by FY70 in India.

Figure 11: CAPEX requirement for H2 DRI steelmaking in 2050 net zero scenario (billion US$, nominal terms)



Source: EYP analysis

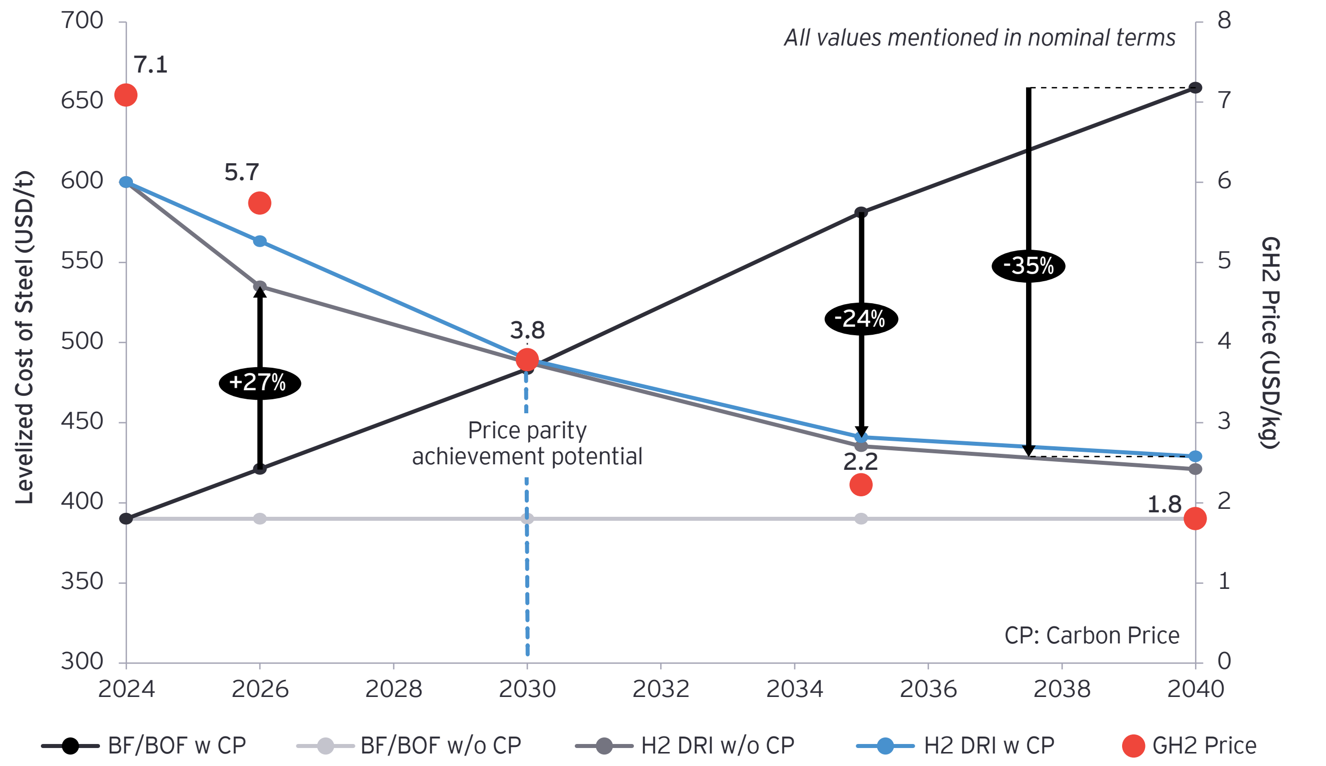
Figure 12: CAPEX requirement for H2 DRI steelmaking in 2070 net zero scenario (billion US$, nominal terms)



Source: EYP analysis

Although the upfront capacity setup cost of H2 DRI (hydrogen direct reduction of iron) plants is higher than that of BF-BOF (blast furnace-basic oxygen furnace) plants, the economics are expected to shift with the onset of carbon pricing, as seen in multiple geographies around the world, such as the EU ETS (Emissions Trading System), CBAM (Carbon Border Adjustment Mechanism) etc.

Figure 13: Levelized cost of H2 DRI steelmaking



Source: EYP analysis

The business case for using the H2 DRI method in steelmaking is becoming more attractive as we move towards a sustainable future. The costs of H2 DRI technology are expected to drop significantly from US$600 per ton in 2024 to US$421 per ton by 2040. This decrease is due to better technology and improved efficiency, making H2 DRI more cost-effective over time. On the other hand, due to carbon pricing, the cost of traditional BF-BOF steelmaking is projected to rise from US$390 per ton in 2024 to US$659 per ton by 2040.

Using green hydrogen in H2 DRI processes not only cuts the carbon footprint significantly compared to BF-BOF methods but also aligns with global goals to reduce emissions. The price of green hydrogen is expected to fall from US$7 per kg in 2024 to US$1.8 per kg by 2040, thanks to improved production technology, lower renewable energy costs, and larger production scales. This significant reduction in green hydrogen costs will be crucial in making H2 DRI a financially viable option for steel production.

The cost parity is likely to be achieved around 2030, depending on when and how carbon pricing is implemented. As carbon pricing becomes more common and stricter, the economic benefits of H2 DRI will become even clearer. By 2035-2040, the cost of H2 DRI steel production is expected to be about 25-35% lower than that of BF-BOF, mainly due to the impact of rising carbon prices and the maturity of H2 DRI technology.

Additionally, adopting H2 DRI technology supports the steel industry's move towards sustainable and low-carbon production methods. The significant reduction in CO_2 emissions achieved through H2 DRI processes is essential for meeting international climate targets and regulatory requirements. As efforts to combat climate change intensify globally, the demand for green hydrogen and H2 DRI technology is expected to grow.

In summary, the H2 DRI route offers a viable and economically attractive path for the steel industry. With the expected decrease in green hydrogen costs and the increasing financial burden of carbon pricing on traditional methods, H2 DRI is set to become the preferred choice for steel production. This transition not only provides cost benefits but also aligns with broader environmental and sustainability goals, making it a strategic investment for the future of the steel industry. Additionally, H2 DRI steel made with green hydrogen has a 90%+ lower emission factor compared to the traditional BF-BOF route, significantly reducing the carbon footprint of steel production.

06 Strategies for overcoming challenges of green hydrogen adoption in steel industry

The Indian steel industry, a cornerstone of the nation's industrial landscape, faces the imperative to reduce its significant carbon footprint. Green hydrogen, produced through electrolysis powered by renewable energy sources, emerges as a promising solution. However, its widespread adoption necessitates addressing several critical challenges:

High initial investment costs

- **Key issues:** One of the primary challenges in adopting green hydrogen in the steel sector is the high upfront investment required for infrastructure and technology setup. This includes the cost of electrolyzers, hydrogen production facilities, and other necessary technologies, which make the transition financially prohibitive for many stakeholders.
- **Proposed strategies:** To address this, the government can play a crucial role by introducing targeted incentives such as Production Linked Incentive (PLI) schemes and tax breaks. These measures can significantly reduce electricity costs to the range of 2.5-4 INR/kWh, making green hydrogen production more economical. Furthermore, the adoption of public-private partnership (PPP) models, particularly those based on Build-Own-Operate-Transfer (BOOT) frameworks, can help distribute the financial burden and reduce the capital expenditure on electrolyzer infrastructure by approximately US$0.6-0.8 million/MW.
- **Potential benefits:** The potential benefits of these interventions include a significant reduction in the financial burden associated with GH2 infrastructure, fostering private investments, and achieving long-term economic gains through lower hydrogen prices and emissions in the steel sector.

Lack of mature infrastructure

- **Key issues:** The absence of a well-established infrastructure for green hydrogen production, storage, and transportation is another critical barrier. Currently, there are limited hydrogen production hubs, no dedicated pipeline networks, and insufficient storage and fueling stations to support large-scale adoption in the steel industry. The power requirement for GH_2 production and EAF steelmaking is also an issue, resulting an additional load to the power grid.
- **Proposed strategies:** A solution to this challenge involves developing centralized hydrogen hubs, supported by viability gap funding, public-private partnerships, and access to green finance. These hubs can act as focal points for hydrogen production and distribution, improving efficiency and reducing costs. Additionally, building a dedicated pipeline network for hydrogen transport can lower delivery costs by 70–90% (primary research basis natural gas pipeline transportation costs and hydrogen offtake costs discovered at 50km,100km and 250km away from the production area. The primary research was conducted in September–November 2024), offering a reliable and cost-effective method of distribution. To address the storage and fueling challenges, advanced storage solutions such as underground hydrogen caverns and liquid storage systems should be developed. These solutions can be complemented by the establishment of an extensive network of fueling stations, ensuring that hydrogen is readily available for industrial applications. Implementation of captive green hydrogen production in the steel mills could be explored in parallel. The demand of electricity for GH_2 production and EAF steelmaking can be met through a group captive RE model.
- **Potential benefits:** Implementing these strategies will reduce hydrogen costs through economies of scale, improve supply reliability, and expand the use of hydrogen as a clean energy source in the steel sector.

Climate risks of large-scale hydrogen value chains

- **Key issues:** Production, storage, and transportation of hydrogen often involve significant greenhouse gas emissions, especially when reliant on fossil fuel-based energy sources. High energy demands further exacerbate this challenge. Unregulated hydrogen leaks pose another climate risk.
- **Proposed strategies:** Establishing clear emission standards and offering incentives for adopting such technologies will accelerate this transition. Comprehensive environmental assessments should guide the planning and development of hydrogen infrastructure to minimize land and ecosystem disruptions.
- **Potential benefits:** Adopting these strategies will significantly reduce the carbon footprint of hydrogen production and align the sector with global climate goals. Improved water-use efficiency will enhance the viability of hydrogen production in water-scarce regions, ensuring long-term sustainability. Mitigating hydrogen leakage will prevent unintended impacts on atmospheric chemistry, improving the environmental profile of hydrogen energy.

Supply chain logistics and standardization

- **Key issues:** The current supply chain for hydrogen in India is fragmented, with no standardized processes for its transport and distribution. This lack of uniformity hinders the development of a cohesive ecosystem and increases logistical complexities. Additionally, there is limited global collaboration to facilitate the transfer of knowledge and technologies related to hydrogen production and usage.

- **Proposed strategies:** To overcome this, establishing industry-wide standards for hydrogen transport and storage is essential. These standards will ensure consistency and safety across the supply chain, making it easier for stakeholders to adopt hydrogen. Optimizing supply chain logistics, such as improving transportation routes and integrating advanced technologies, can further enhance efficiency. Furthermore, fostering international collaborations can help India access advanced technologies and expertise in hydrogen production and delivery. By establishing offtake agreements for green hydrogen and its derivatives, India can integrate into global supply chains, benefiting from shared innovations and economies of scale.
- **Potential benefits:** The benefits of these measures include lower delivery costs, improved infrastructure availability, and access to advanced hydrogen technologies, ultimately enabling India to develop a globally competitive hydrogen ecosystem.

Technical challenges and skill development

- **Key issues:** Technical inefficiencies in current hydrogen technologies present another challenge, as existing systems are not optimized for large-scale, cost-effective production. Additionally, there is a shortage of skilled workers with expertise in hydrogen technologies, and limited collaboration between research institutions hinders knowledge sharing and innovation.
- **Proposed strategies:** To address these issues, increasing investments in research and development (R&D) is vital. R&D efforts can help improve the efficiency of hydrogen technologies by 15–20%, making them more competitive and reducing costs. Simultaneously, upskilling and training programs for workers in the steel and energy sectors are necessary to build a knowledgeable workforce capable of supporting hydrogen adoption. Collaboration with global research institutions can further accelerate advancements in hydrogen production and usage by enabling access to the latest innovations and fostering knowledge exchange. These efforts will drive technological progress and create a highly skilled workforce, ensuring the long-term success of green hydrogen in the steel sector.
- **Potential benefits:** By implementing these strategies, the Indian steel sector can overcome technological barriers, build capacity, and establish itself as a leader in sustainable steel production.

By addressing these challenges through targeted strategies, the Indian steel sector can unlock the immense potential of green hydrogen, paving the way for sustainable industrial growth while significantly reducing emissions.

07 Recommendations

The transition to green hydrogen is essential for decarbonizing the steel sector, a major contributor to global carbon emissions. To accelerate its adoption, targeted recommendations have been developed for key stakeholders, including the government, the steel industry, and green hydrogen (GH_2) producers. These recommendations focus on creating a supportive policy and regulatory framework, advancing technology and infrastructure development, and fostering collaboration through strategic partnerships. By addressing economic, technological, and logistical challenges, these initiatives aim to promote the widespread adoption of green hydrogen, ensuring a sustainable and competitive future for the steel industry.

Recommendations to the government

The government plays a critical role in enabling the adoption of green hydrogen in the steel sector. Key recommendations include:

01 **Policy and regulatory frameworks:** The government should prioritize the development of a comprehensive National Green Hydrogen Policy to meet the projected demand of approximately 15 MMTPA of green hydrogen required for the H2-DRI-EAF steelmaking route by 2070. This policy should include year-on-year mandates for green hydrogen adoption and implement streamlined regulatory measures to lower renewable energy (RE) prices from the current 6.5 INR/kWh to 2.5–4 INR/kWh. This reduction in RE prices can be achieved through waivers on transmission, wheeling, and cross subsidy surcharges for green hydrogen production. Additionally, establishing regulatory standards, such as a green steel definition, limiting emissions to less than 500 kilograms of CO_2 per ton of steel, can facilitate the transition to green steel production. This stringent benchmark drives innovation, supports global competitiveness, boosts export demand of low carbon steel, and mitigates climate risks by promoting near zero emissions steelmaking technologies.

02 **Development of RE parks:**
The development of renewable power hubs for clusters of steel production facilities, especially energy intensive secondary steelmaking facilities, presents a transformative opportunity to reduce CO_2 emissions, enhance operational efficiency, and drive sustainable economic growth. By providing centralized access to clean energy sources like solar, wind, and hybrid, these hubs reduce reliance on fossil fuels, cut energy costs, and promote innovation in green technologies. The co-location of multiple facilities enables economies of scale along with support for decarbonization goals, enhances competitiveness, and aligns with global sustainability targets, ensuring long-term environmental and economic sustainability.

03 **Financial incentives and support:**
To support the transition to green hydrogen-based steelmaking, the government should introduce production-linked incentives, tax breaks, and concessional loans aimed at meeting the investment requirements of US$264–297 billion by 2050–2070. Furthermore, the creation of a carbon pricing framework, such as a Carbon Credit Trading Scheme (CCTS) mechanism with a price of approximately US$90–100 per ton of CO_2, can attract investments in steel decarbonization and encourage industrial adoption between 2030 and 2040.

04 **Infrastructure development via business models:**
The establishment of hydrogen hubs and pipeline networks is essential to centralize production and distribution, especially leveraging existing industrial clusters in eastern India. This approach can help reduce capital expenditure for the steel sector to US$0.6–0.8 million per MW. Additionally, business models such as third-party supply agreements, where steel mills procure green hydrogen under long-term contracts, can ensure stable supply chains. Alternatively, captive green hydrogen plants can be set up for on-site production, customized to meet the specific demand of individual steelmakers, enhancing efficiency and reliability.

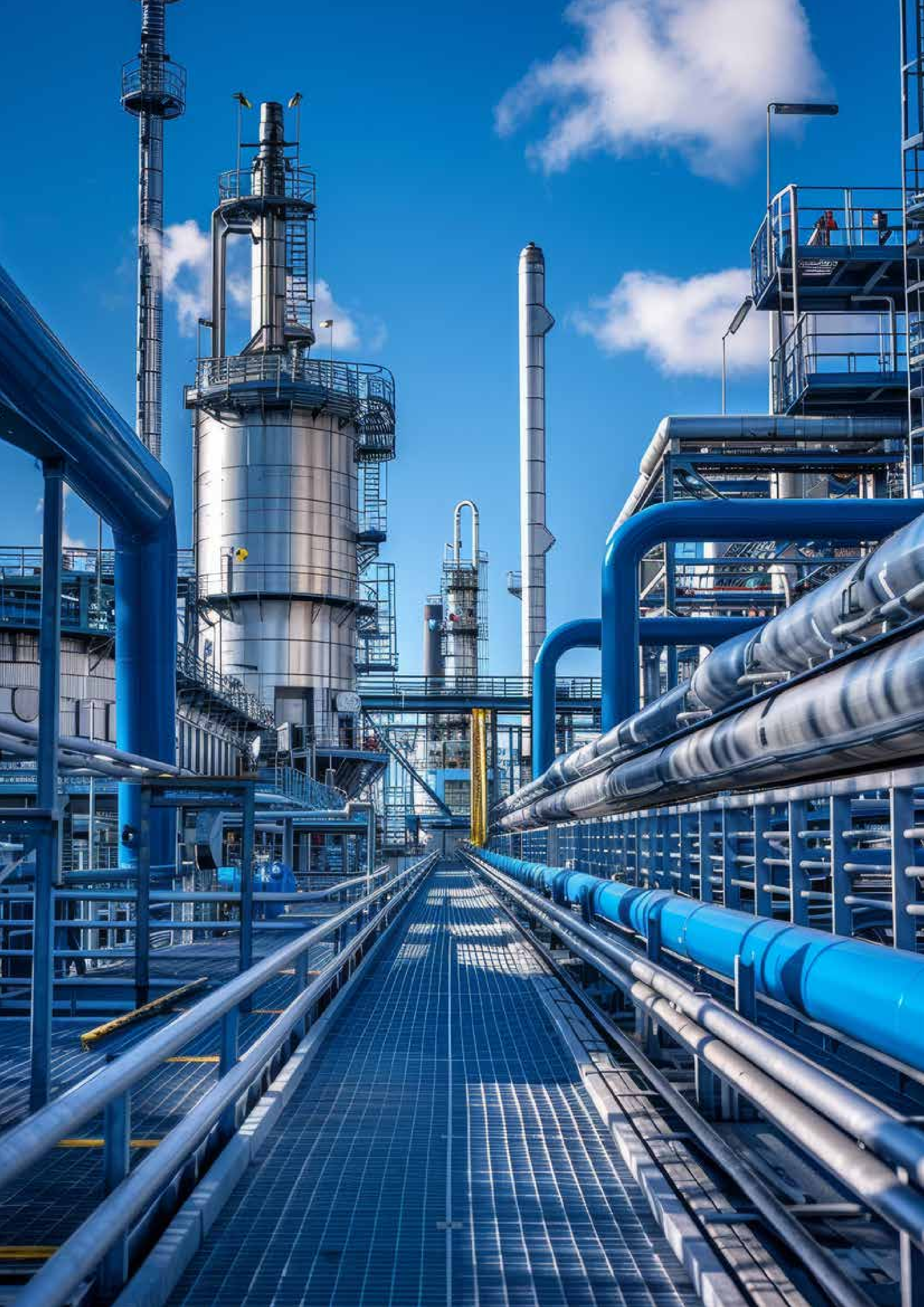
Recommendations to the steel industry

The steel industry must proactively adopt green hydrogen to align with the global shift toward sustainability. Recommendations include:

01 **Adoption of proven technologies:**
The steel industry should focus on the adoption of proven technologies, such as alkaline and PEM electrolysis, which have achieved technology readiness levels (TRLs) of 9 and are capable of meeting current hydrogen production requirements with high efficiency. Transitioning to green hydrogen (GH2)-based DRI-EAF steelmaking is another key priority, as it is projected to become economically advantageous by 2040. The expected reduction in GH_2 prices to US$1.8/kg, coupled with the financial impact of carbon pricing on BF-BOF steelmaking, is anticipated to lower steel production costs by 35%, making the DRI-EAF route a cost-effective and sustainable alternative. Going ahead, adoption of GH_2 DRI-EAF route should be adopted in order to realize net zero goals of the steel industry.

02 **Embracing emerging solutions:**
Emerging technologies, such as solid oxide electrolysis (SOE) and biomass gasification integrated with Carbon Capture, Utilization, and Storage (CCUS), should be piloted and scaled to enhance cost efficiency. These technologies currently incur production costs of US$4.3 and US$3.3 per kilogram of hydrogen, respectively, but long-term advancements can significantly reduce these costs. Furthermore, investing in robust R&D programs in collaboration with domestic and global manufacturers can improve the efficiency of mature GH_2 production pathways by 30%–40%[5], targeting implementation between 2030 and 2035. This approach will ensure the gradual integration of innovative technologies into the steel production process.

5. Hydrogen Science Coalition, November 2023, Can electrolysers of the future solve hydrogen's efficiency problem?



03 **Collaboration and public-private partnerships (PPPs):**
Public-private partnerships should be leveraged to co-develop critical infrastructure for green hydrogen, including hydrogen hubs, storage facilities, and transportation networks. Such collaborations will play a pivotal role in optimizing supply chains and reducing delivery costs by 70%–90% between 2030 and 2040. The shared investment and expertise of public and private stakeholders will accelerate the establishment of an integrated hydrogen economy, ensuring cost efficiency and reliability in the supply of GH2 for the steel sector.

Recommendations to green hydrogen producers

Producers of green hydrogen are central to creating a reliable and scalable supply chain for the steel sector. Key recommendations are:

01 **Exploring business models**
Strategic business models like Captive, BOO, and BOOT can ensure a reliable, cost-effective hydrogen supply. In the Captive model, steelmakers own hydrogen production facilities, providing supply security but requiring high upfront investment and expertise. The BOO model involves third-party producers managing hydrogen supply, reducing costs but creating dependency and tariff risks. The BOOT model allows developers to build and operate facilities, transferring ownership later, balancing cost, and long-term control. Indexed pricing, government incentives, risk-sharing, and scalable agreements are essential for ensuring predictable and competitive tariffs while aligning with financial capabilities and national policies to drive sustainable steel production.

02 **Technology and infrastructure development**
Investing in research and development (R&D) is critical to improving the efficiency of electrolyzers and reducing their costs from the current US$1,200–US$1,500 per kW to a targeted US$500–US$700 per kW. Such advancements are essential for making green hydrogen more affordable and scalable. Concurrently, establishing robust green hydrogen production infrastructure through localized manufacturing of electrolyzers is imperative. This will enable producers to meet the anticipated demand of 13.15 to 15.15 MMTPA of green hydrogen between 2050 and 2070, ensuring self-reliance and cost efficiency in hydrogen supply chains.

03 **Strategic partnerships and market development**
Forming partnerships within India's steel hubs is essential to create integrated hydrogen supply chains specifically tailored to the steel sector. These collaborations can offer substantial benefits, including emission reductions of 5%–53% and cost savings of 28-32%, making the transition to green hydrogen economically attractive. Furthermore, supporting the development of India's carbon pricing market for hard-to-abate sectors is crucial to mitigate the financial and regulatory impacts of global mechanisms like the Carbon Border Adjustment Mechanism (CBAM). These measures will help Indian industries remain competitive while advancing decarbonization goals.

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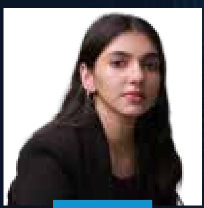

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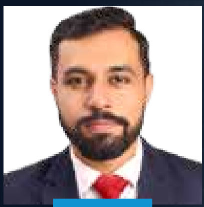

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About India Green Steel Coalition

To promote green steel manufacturing and consumption in India through enabling policies and demand alignment, India Green Steel Coalition (IGSC) has been constituted by WWF-India and Confederation of Indian Industry (CII). IGSC has a vision towards ensuring optimal reduction in steel sector's emissions intensity by 2030.

IGSC will support the efforts of the government towards increasing domestic steel production and for creating an enabling environment for sustained reduction in emissions intensity of the sector. IGSC will work actively with the primary and secondary producers, demand side players to understand the challenges in this transition and advocacy for policy making on steel sector decarbonization.

About WWF-India

WWF-India is a science-based organization which addresses issues such as the conservation of species and its habitats, climate change, water and environmental education, among many others. Over the years, its perspective has broadened to reflect a more holistic understanding of the various conservation issues facing the country and seeks to proactively encourage environmental conservation by working with different stakeholders- Governments, NGOs, schools and colleges, corporates, students and other individuals.

About WWF Finland

WWF Finland is part of the global WWF network that has offices in about 50 countries and operations in over one hundred countries. WWF Finland was established in 1972 and is now the most recognized environmental NGO in Finland. Alongside domestic conservation projects, WWF Finland is working with WWF partners in Asia, Africa and South America. WWF Finland is hosting the WWF global Steel Decarbonisation Workstream.

About CII- GBC

The CII - Sohrabji Godrej Green Business Centre (CII - GBC) is CII's Developmental Institute for Green Practices and Businesses, focused on offering world-class advisory services dedicated to the conservation of natural resources. Its mission is to help India emerge as a global leader in green business by 2030.

The Centre promotes sustainable practices and supports businesses through a comprehensive range of services, including Green Buildings, Energy Management Initiatives, Energy Efficiency Initiatives, GreenPro Certification, GreenCo Rating System, Green Entrepreneurship Council (GEC), Solar Vendor Rating Program (VRP) etc.

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