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Challenges and Opportunities in Green Hydrogen Adoption for Decarbonizing Hard-to-Abate Industries

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Abstract—Green hydrogen, produced by water electrolysis powered by renewable electricity, is a leading option for reducing emissions in industries that are difficult to electrify directly, such as iron and steel, ammonia and fertilisers, refining, chemicals, long-distance shipping, and aviation. This paper presents a structured, review-based study of the challenges and opportunities of its adoption. It reviews recent literature and policy developments, and describes a framework covering renewable power, electrolysis, storage and transport, industrial conversion, certification, and deployment. Cost, life-cycle emissions, technical readiness, and infrastructure are discussed as the main evaluation dimensions. Challenges such as high production cost, large electricity demand, uncertain offtake, limited infrastructure, water availability, and slow investment are examined together with opportunities in policy support, industrial clusters, and green product markets. The study concludes that green hydrogen should be targeted first at uses with few practical low-emission alternatives, and that supply, demand, and infrastructure must be developed together.

Keywords—Green Hydrogen, Hard-to-Abate Industries, Decarbonization, Electrolysis, Green Steel, Green Ammonia, Energy Transition.

I. INTRODUCTION

Heavy industry and long-distance transport are often described as hard-to-abate because they need very high temperatures, use fossil fuels as chemical feedstocks or reducing agents, release process emissions, or require energy-dense fuels. Their plants are also capital-intensive and long-lived, and many of their products are traded in competitive markets. Improving efficiency and using renewable electricity directly can reduce part of these emissions, but not all of them.

Hydrogen is already an important industrial input. Global demand exceeded 100 million tonnes (Mt) in 2025, almost all of it in refining and industry, while low-emissions hydrogen reached only almost 1 Mt [1]. This category is broader than green hydrogen. Replacing fossil-based supply and serving new uses therefore requires a very large scale-up.

The objective of this paper is to study the main challenges and opportunities of green hydrogen adoption in hard-to-abate industries and to describe a general framework for planning and evaluating such projects. The study emphasizes that announced capacity does not automatically become operating capacity; cost, demand, infrastructure, and real emission reductions must be assessed for each application.

Objectives and Scope

The main objectives are: (1) to understand the need for green hydrogen in industrial decarbonization; (2) to study its major industrial uses; (3) to describe a general framework for adoption; (4) to identify suitable evaluation measures for cost, emissions, and readiness; and (5) to discuss opportunities, challenges, and future improvements. The scope includes iron and steel, ammonia, refining, methanol, cement, shipping, and aviation, with attention to the global situation and to India. This is a secondary study based on published sources; it does not report new experiments or plant measurements. Its findings should not be assumed to apply to every region or site.

II. LITERATURE REVIEW

The International Energy Agency (IEA) reports that low-emissions hydrogen output grew about 20% in 2025 and installed electrolyser capacity exceeded 4 GW. However, the announced pipeline of low-emissions production for 2030 shrank to 27 Mt, of which just above 6 Mt is committed or has strong potential. Only about one-fifth of new offtake volumes were firm [1].

Ueckerdt et al. studied hydrogen-based e-fuels and found them costly, with uncertain future availability. They recommended giving priority to uses where direct electrification is not feasible [2]. Odenweller and Ueckerdt tracked 190 projects and found that only about 7% of the capacity announced for 2023 was completed on schedule. They also identified a large subsidy requirement for realizing announced projects [3].

Vogl et al. assessed hydrogen direct reduction for steelmaking and estimated an electricity demand of 3.48 MWh per tonne of liquid steel, mainly for electrolysis. Competitiveness depended strongly on electricity price,

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scrap share, and carbon price [4]. The International Renewable Energy Agency (IRENA) identified larger plants, mass manufacturing of stacks, and learning from deployment as routes to lower electrolyser costs [5]. Together, these studies indicate that no single measure is sufficient.

III. PROPOSED SYSTEM

1. System Overview

The proposed framework connects renewable electricity and water to industrial demand. Electrolysers split water into hydrogen and oxygen. The hydrogen is used on site or stored and transported, and is then converted into products or fuels. Policy, infrastructure, water supply, and finance support each stage. Projects are evaluated using cost, emissions, reliability, and readiness measures before expansion.

2. System Architecture

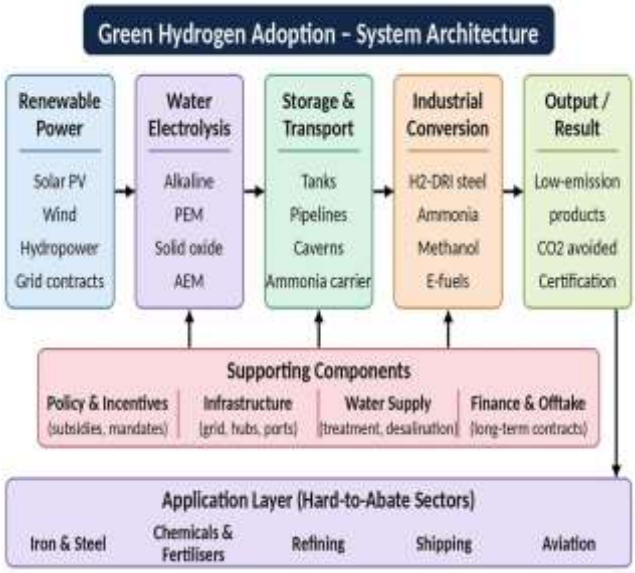

Fig. 1. General architecture of the proposed green hydrogen adoption framework.

3. Working Procedure

First, industrial sites are screened for current and expected hydrogen demand. Second, alternatives such as efficiency, direct electrification, material recycling, and carbon capture are compared.

Third, renewable resources, grid access, water, and land are assessed. Fourth, the electrolyser and storage are sized to match the variable power supply with the needs of the plant. Fifth, long-term offtake, finance, and certification are arranged. Finally, cost, emissions, and reliability are monitored after commissioning, and capacity is expanded in stages.

IV. GREEN HYDROGEN IN HARD-TO-ABATE SECTORS

1. Iron and Steel

In hydrogen-based direct reduction (H2-DRI), hydrogen removes oxygen from iron ore and forms water vapour instead of carbon dioxide. The solid iron is usually melted in an electric arc furnace. In theory, about 54 kg of hydrogen is needed to reduce enough hematite for one tonne of iron; practical plant requirements depend on design and operation. Suitable ore quality and clean electricity are also important.

2. Ammonia and Fertilisers

Ammonia synthesis requires about 0.18 tonne of hydrogen per tonne of ammonia by stoichiometry. Green hydrogen can replace hydrogen made from natural gas or coal without changing the final molecule, which makes ammonia a strong early market. Urea also needs carbon dioxide, so a non-fossil or captured carbon source must be considered.

3. Refining and Methanol

Refineries use hydrogen for desulphurization and hydrocracking, so existing demand can be partly replaced. This lowers refinery process emissions but not those from burning the fuels sold. Green methanol can be made from green hydrogen and carbon dioxide; its climate benefit depends strongly on the carbon source.

4. Cement

A major part of cement emissions comes from the calcination of limestone. Changing the kiln fuel to hydrogen does not remove these process emissions. Clinker substitution, efficiency, alternative fuels, and carbon capture are therefore important, and hydrogen is likely to play only a supporting role.

5. Shipping and Aviation

Hydrogen-derived ammonia, methanol, and synthetic kerosene can serve long-distance transport. Conversion losses and cost are significant [2]. Ammonia also needs strict toxicity controls, while carbon-based e-fuels need a sustainable source of carbon.

VI. DATA SOURCES AND METHODOLOGY

This study uses qualitative review of international agency reports, peer-reviewed research, official government information, and selected news reporting. Sources were chosen for relevance to industrial hydrogen use, cost, deployment, and policy. The review is selective rather than systematic. Figures from different years, boundaries, and

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definitions should not be compared directly. Announced, committed, and operating capacities are treated as separate categories.

VII. PERFORMANCE EVALUATION

A hydrogen project should be assessed from multiple perspectives. Electrolyser efficiency alone is not sufficient, because an efficient plant may still be costly, poorly utilized, or supplied by emission-intensive power.

1. Economic Metrics
The levelized cost of hydrogen (LCOH) divides discounted lifetime costs by discounted lifetime hydrogen output. It depends on electricity price, capital cost, operating hours, efficiency, stack replacement, and cost of capital. Delivered cost, product cost, and cost per tonne of CO2 avoided should also be reported.

2. Emission Metrics
Life-cycle emissions are expressed as kg CO2-equivalent per kg of hydrogen and per tonne of product. Additional renewable supply and the matching of electricity use with generation in time and location help prevent higher fossil generation elsewhere.

3. Technical Metrics
Useful measures include electricity use per kg of hydrogen, capacity utilization, availability, stack degradation, and purity. Water splitting requires about 9 kg of pure water per kg of hydrogen by stoichiometry; raw water and cooling needs can be higher.

4. Readiness Metrics
Readiness includes technology maturity, grid connection, storage, permits, skilled workers, safety, certification, and the share of output covered by firm offtake contracts.

Opportunities
Existing demand in refining and ammonia offers an early market with known users. Industrial clusters and ports can share pipelines, storage, and renewable power. Flexible electrolysis with storage may help integrate variable renewable energy. Low-emission steel, fertilisers, and fuels can create new export markets, jobs, and equipment manufacturing, while local production can reduce exposure to imported fossil fuels. The IEA notes that the 2026 conflict in the Middle East exposed risks in fossil-based hydrogen and fertiliser supply chains [1].

India's National Green Hydrogen Mission, with an initial outlay of ₹19,744 crore, targets annual production of 5 Mt of green hydrogen by 2030. As of May 2025, 19 companies had been allocated 862,000 tonnes per year of production capacity, and steel pilot projects were part of the programme [6]. In a Solar Energy Corporation of India auction covering 724,000 tonnes per year of green ammonia for fertiliser units, the lowest reported price was about ₹49.75 per kg; 10-year purchase agreements were signed in March 2026 [7]. Allocations and contracts are not the same as operating capacity.

Trade rules may also influence demand. The definitive phase of the European Union Carbon Border Adjustment Mechanism (CBAM) began on 1 January 2026 and covers selected imports including iron and steel, cement, fertilisers, aluminium, electricity, and hydrogen [8]. It can increase the importance of measuring and lowering the emissions of exported goods.

Challenges and Limitations
Cost is a central barrier. The IEA expects low-emissions hydrogen to remain more expensive than fossil-based hydrogen in most regions in the near term, with China a possible exception for renewable hydrogen by 2030 [1]. High capital cost, electricity price, financing cost, and low utilization can all raise the cost. Large electricity demand also requires new renewable generation and transmission.

Investment faces a coordination problem: producers need long-term buyers, buyers wait for lower prices, and infrastructure developers need both. Hydrogen is difficult to store and transport because of its low volumetric energy density. It is highly flammable and needs careful leak detection, material selection, and safety design. Water stress, land use, permitting, supply chains, and differing certification rules add further risk. Public support should therefore be linked to verified emission reductions and actual delivery.

Future Scope
Future work may compare green hydrogen with direct electrification and carbon capture using consistent system boundaries and site-level data. Research can focus on durable and efficient electrolysers, lower use of scarce materials, hydrogen storage, H2-DRI with different ore grades, and flexible chemical synthesis. Artificial intelligence and data science may support renewable forecasting, electrolyser scheduling, predictive maintenance, and emission tracking. These tools should be validated on real plant data before they are used in operational decisions.

VIII. CONCLUSION

Green hydrogen is a valuable option for decarbonizing parts of hard-to-abate industry, especially existing ammonia and refining demand, steelmaking through direct reduction, and

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some fuels for long-distance transport. It is not the best solution for every use. This paper described a framework linking renewable power, electrolysis, delivery, industrial conversion, and supporting conditions. Reliable adoption requires affordable clean electricity, firm demand, shared infrastructure, credible certification, safety, and stable policy. Priority should go to applications with few practical alternatives, and progress should be measured by operating capacity and verified emission reductions rather than announcements alone.

REFERENCES

1. International Energy Agency, "Global Hydrogen Review 2026," IEA, Paris, 2026.
2. F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, and G. Luderer, "Potential and risks of hydrogen-based e-fuels in climate change mitigation," Nature Climate Change, vol. 11, no. 5, pp. 384–393, 2021.
3. A. Odenweller and F. Ueckerdt, "The green hydrogen ambition and implementation gap," Nature Energy, vol. 10, pp. 110–123, 2025.
4. V. Vogl, M. Åhman, and L. J. Nilsson, "Assessment of hydrogen direct reduction for fossil-free steelmaking," J. Cleaner Production, vol. 203, pp. 736–745, 2018.
5. International Renewable Energy Agency, "Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal," IRENA, Abu Dhabi, 2020.
6. Press Information Bureau, Government of India, "Unlocking India's Green Hydrogen Production Potential," Release ID 2189126. [Online]. Available: pib.gov.in
7. Business Standard, "India discovers lowest price for green ammonia at ₹49.75 per kg," Mar. 2026. [Online]. Available: business-standard.com
8. European Commission, "Carbon Border Adjustment Mechanism." [Online]. Available: taxation-customs.ec.europa.eu AUTHOR PROFILE Asmita Siddharth Salve

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