

Ogino, Kaoru; Son, Jongmi

Working Paper

India's green hydrogen review and perspective

ADB Working Paper, No. 1491

Provided in Cooperation with:

Asian Development Bank Institute (ADBI), Tokyo

Suggested Citation: Ogino, Kaoru; Son, Jongmi (2025) : India's green hydrogen review and perspective, ADB Working Paper, No. 1491, Asian Development Bank Institute (ADBI), Tokyo, <https://doi.org/10.56506/UXWY2048>

This Version is available at:

<https://hdl.handle.net/10419/322335>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by/3.0/igo/>



ADB Working Paper Series

**INDIA'S GREEN HYDROGEN
REVIEW AND PERSPECTIVE**

Kaoru Ogino and Jongmi Son

No. 1491
February 2025

Asian Development Bank Institute

Kaoru Ogino is a Principal Energy Specialist, and Jongmi Son is an Energy Specialist, both at the Asian Development Bank.

The views expressed in this paper are the views of the author and do not necessarily reflect the views or policies of ADBI, ADB, its Board of Directors, or the governments they represent. ADBI does not guarantee the accuracy of the data included in this paper and accepts no responsibility for any consequences of their use. Terminology used may not necessarily be consistent with ADB official terms.

Discussion papers are subject to formal revision and correction before they are finalized and considered published.

The Working Paper series is a continuation of the formerly named Discussion Paper series; the numbering of the papers continued without interruption or change. ADBI's working papers reflect initial ideas on a topic and are posted online for discussion. Some working papers may develop into other forms of publication.

Suggested citation:

Ogino, K. and J. Son. 2025. India's Green Hydrogen Review and Perspective. ADBI Working Paper 1491. Tokyo: Asian Development Bank Institute. Available: <https://doi.org/10.56506/UXWY2048>

Please contact the authors for information about this paper.

Email: kogino@adb.org, json@adb.org

The authors would like to express their sincere appreciation to Tetsushi Sonobe, Dean of Asian Development Bank Institute (ADBI); Byungsik Jung, Deputy Dean of ADBI; and Dil B. Rahut, Vice-Chair of Research and Senior Research Fellow at ADBI, for their support in the publication of this paper. The authors would also like to express their special gratitude to Shreya Sinha, Manager at KPMG in India; Vaibhav Gupta, Associate Director at KPMG in India; Shreyas Tupe, Consultant at KPMG in India; and Amarjot Singh, Consultant at KPMG in India, for their support in the preparation of this paper, as well as to Grace Cabahug Macalisang for assistance with editing.

Asian Development Bank Institute
Kasumigaseki Building, 8th Floor
3-2-5 Kasumigaseki, Chiyoda-ku
Tokyo 100-6008, Japan

Tel: +81-3-3593-5500
Fax: +81-3-3593-5571
URL: www.adbi.org
E-mail: info@adbi.org

© 2025 Asian Development Bank Institute

Abstract

As a global leader in renewable energy, India is transitioning from fossil fuel-based hydrogen to green hydrogen, driven by technological advancements, cost reductions, and supportive policies. Initiatives like the National Green Hydrogen Mission and Green Hydrogen Policy aim to establish India as a global hub, targeting an annual production of 5 million metric tons by 2030. The strategy emphasizes investments in indigenous technologies, pilot projects, and infrastructure to boost domestic demand and production. However, significant challenges remain in scaling up green hydrogen production. These include high capital expenditures for electrolyzers, gaps in transportation and storage technologies, and material dependencies. While alkaline electrolysis systems are not expected to face long-term material constraints, they still require substantial quantities of steel, nickel, and copper per megawatt. India's dependence on imported nickel could disrupt supply chains even for these systems. To address these challenges, collaboration between the government, public enterprises, and the private sector is essential for building a sustainable green hydrogen ecosystem. By 2030, India's investment in green hydrogen and its ammonia capacity is estimated to reach approximately \$34.0 billion, with \$9.3 billion (27%) from government-owned enterprises and \$24.8 billion (73%) from major private companies, based on their current investment plans. This investment is projected to achieve a green hydrogen and green ammonia capacity of over 10 million metric tons by 2030, doubling the government's target. While economic analysis shows that green hydrogen projects can be viable in accordance with the Asian Development Bank's economic analysis guideline, financial analysis underscores the need for financing mechanisms—such as public funding, guaranteed pricing, and operational support—to make projects more competitive and attract investment. In particular, concessional funding will play a key role in mitigating risk and attracting initial investments. Additionally, a unified policy approach must address the development of infrastructure and foster collaboration across multiple stakeholders. Given the scarcity of key raw materials for electrolyzers, such as iridium and platinum, exploring alternative options like anion exchange membrane electrolyzers could be strategically significant for scaling up production. International partnerships for green hydrogen exports will also be important to support expansion on a large scale.

Keywords: climate change, green hydrogen, green ammonia, India, energy transition

JEL Classification: Q54, Q50, E6, O33, O31

Contents

1.	INTRODUCTION.....	1
2.	POLICY AND REGULATORY ASSESSMENT	3
2.1	Government's Overall Initiatives.....	3
2.2	Various Ministries' Specific Initiatives.....	8
2.3	Public and Private Partnership Initiatives	11
3.	TECHNOLOGICAL ASSESSMENT	11
4.	SECTORAL APPLICATION ASSESSMENT—DEMAND AND SUPPLY	14
5.	INVESTMENT ASSESSMENT	19
5.1	Government's Targets.....	19
5.2	Private Sector Targets.....	21
5.3	Investment Plans.....	22
6.	FINANCIAL AND ECONOMIC ASSESSMENT	23
6.1	Financial Analysis.....	24
6.2	Economic Analysis	26
6.3	Consideration from Financial and Economic Analyses	28
7.	POLICY RECOMMENDATION	29
	REFERENCES	32
	ANNEXURES	
1	R&D and Knowledge-Sharing Initiatives by India's Public and Private Entities	38
2	Assumptions of Financial and Economic Assessments	41

1. INTRODUCTION

As concerns over climate change grow and the challenges posed by greenhouse gas emissions become more evident, the global focus on adopting green, carbon-neutral technologies to drive decarbonization has intensified. India is also actively engaged in both public and private initiatives aimed at decarbonization. One of the major obstacles hindering global climate efforts is the difficulty in transitioning certain industries to low-carbon infrastructures. Hard-to-abate industries like oil refineries, cement, iron, steel, and mobility face significant hurdles in directly adopting electrification or renewable energy solutions. Consequently, there is a crucial need for a versatile fuel that not only meets the primary fuel requirements of these industries but also aligns with the environmentally friendly objectives of policies. Green hydrogen is expected to fulfill this need as a “green” primary fuel for these industries.

The technology behind green hydrogen relies on electrolysis—a chemical process that separates hydrogen and oxygen in water using an electrical current. This electricity is sourced from renewable sources. The supply chain for green hydrogen encompasses production, storage, and transportation. Hydrogen can be stored in solid, liquid, or gaseous forms. Solid storage options include metal hydrides, complex hydrides, chemical hydrides, and high surface area absorbents. Gaseous storage requires containers that can withstand high pressure (ranging from 100 to 700 bar), while liquid storage necessitates cryogenic temperatures or conversion into liquid organic hydrogen carriers. The transportation and local infrastructure vary based on the intended end-use sector.

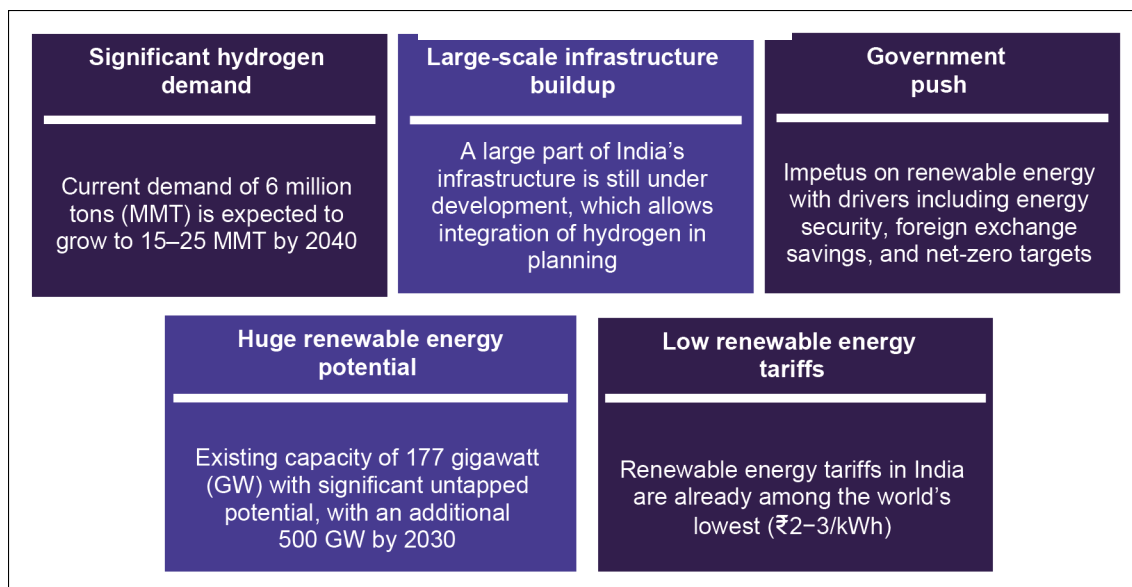
Green hydrogen stands as a promising substitute for fossil fuels in achieving net-zero emission objectives, given its lack of greenhouse gas emissions upon combustion. However, the current adoption of green hydrogen in India remains limited to pilot and research projects due to high technology costs, concerns about potential sunk costs, and a lack of widespread public awareness. With the Indian government’s implementation of the National Green Hydrogen Mission, significant investments are anticipated in this sector, necessitating substantial funding for large-scale projects. In addition to hydrogen, the government has demonstrated a forward-looking focus on both green hydrogen and green ammonia.

Currently, hydrogen production in India relies primarily on fossil fuels (gray hydrogen). However, a shift towards green hydrogen is anticipated, driven by technological advancements in electrolyzers (boosting energy efficiency), reductions in the costs of electrolyzers and renewable energy sources, and the development of the green hydrogen value chain bolstered by supportive policy and regulatory initiatives. This transition is expected to augment the proportion of green hydrogen in India’s overall hydrogen production.

India has several advantages for developing and promoting green hydrogen. Firstly, the nation is anticipated to experience the most substantial surge in energy demand, driven by economic expansion, population growth, urbanization, and industrialization. Secondly, this demand growth presents India with a critical juncture in establishing a sustainable, well-developed economy, especially since a significant proportion of its infrastructure is still in the developmental phase, allowing for the integration of hydrogen in future planning. Thirdly, the government of India has been actively crafting policies and implementing reforms to foster an environment conducive to the development of renewable energy. As the world’s third-largest energy consumer (Energy Institute 2023), India relies heavily on coal and oil, leading to significant carbon emissions and energy imports. With over 40% of its primary energy requirements

imported, valued at over \$90 billion annually (Government of India 2023a), India's energy usage has doubled in the past two decades and is projected to grow by at least 25% by 2030. Key sectors like mobility and industrial production rely significantly on imported fossil fuels. In addition, India ranks as the world's fourth-most attractive renewable energy market (Energy Institute 2023). As of July 2023, its installed renewable energy capacity, including hydro, stood at 177.74 GW (CEA 2023a), representing 42% of the overall installed power capacity, with plans to achieve 500 GW of installed renewable energy capacity by 2030 (IEA 2021a). Notably, solar power capacity has surged by over 27 times, from 2.63 GW in March 2014 to 71.15 GW as of July 2023 (CEA 2023a). India's diverse portfolio of renewable sources, including ample sunlight in regions like Rajasthan, Gujarat, and the southern states, and favorable wind patterns along the western coastline and certain inland regions, contributes to its low-cost renewable energy production. India's reduced renewable energy costs, ranging from Indian rupees (₹2 to ₹3/kWh, are highly competitive on a global scale. These reduced costs are a result of technological advancements, enhanced production efficiency, and economies of scale, particularly in solar and wind power. Compared to global averages, India stands out as a leader in achieving significantly low-cost renewable energy. With its immense renewable energy potential and competitive pricing, India is poised to emerge as a major player in the green hydrogen landscape. Figure 1 illustrates the various factors facilitating the adoption of green hydrogen in India.

Figure 1: Enablers to Facilitate Green Hydrogen Adoption in India



₹ = Indian rupee.

Source: Author.

This paper delves into the green hydrogen ecosystem in India, encompassing a comprehensive review of policies and regulations, technological interventions, and the diversified applications of green hydrogen across multiple end-use sectors. It anticipates investments from both public and private sector entities, evaluating the financial and economic viability of green hydrogen development from both sides. Lastly, the paper concludes with policy recommendations for the field.

2. POLICY AND REGULATORY ASSESSMENT

The Indian government, along with various government agencies, has embarked on a path to promote the adoption of hydrogen. This section highlights initiatives taken by the Government of India and associated ministries aimed at promoting hydrogen development in the country.

2.1 Government's Overall Initiatives

The Government of India is actively promoting hydrogen as a promising energy carrier and has launched various programs and initiatives over the years. Given the importance of hydrogen as an alternative fuel for decarbonization, the Ministry of New and Renewable Energy (MNRE) set up the National Hydrogen Energy Board (NHEB) in 2003. The main objective of the NHEB was to prepare a National Hydrogen Energy Road Map 2006 (NHERM) for India by identifying pathways for the gradual adoption of hydrogen, accelerating commercialization efforts, and facilitating the creation of hydrogen infrastructure. The key government initiatives in hydrogen development over the past 20 years are presented in Table 1.

Table 1: Key Government Initiatives for Hydrogen in India

No.	Key Initiative/Project	Timeline
1	National Hydrogen Energy Board's setup	2003
2	National Hydrogen Energy Road Map	2006
3	Reports submitted by five subcommittees of the steering committee on hydrogen energy and fuel cells constituted by the MNRE	2016
4	Report submitted by a team of experts for projectization of a few themes on hydrogen energy and fuel cells to steering committee constituted by the MNRE	2016
5	DST Hydrogen and Fuel Cell Program	2018
6	MORTH announcement of standards for hydrogen fuel cell vehicles and hydrogen-enriched compressed natural gas (HCNG) vehicles	2020
7	Draft National Hydrogen Energy Mission	2021
8	DST Advanced Hydrogen and Fuel Cell Program (AHFC)	2021
9	Green Hydrogen Policy	2022
10	National Hydrogen Energy Mission	2023

DST = Department of Science and Technology, MNRE = Ministry of New and Renewable Energy, MORTH = Ministry of Road Transport and Highways

Sources: Government of India (2023b), Government of India (2022a), Government of India (2020c).

These policy initiatives were reviewed and assessed in terms of their targets, progress, and the way forward in promoting green hydrogen at the national level.

National Hydrogen Energy Roadmap. The NHERM was launched under the MNRE in 2006 with the aim of bridging technological gaps across various aspects of hydrogen energy production, storage, transportation, delivery, applications, safety, codes and standards, and capacity building for the period until 2020. It suggested suitable pathways and identified necessary policies, legislation, financing, and support infrastructure. There were two major initiatives under the NHERM, namely the Green Initiative for Future Transport (GIFT) and the Green Initiative for Power Generation (GIP). GIFT aimed to develop hydrogen-powered internal combustion (IC) engines and fuel cell vehicles of various sizes, from small (such as compact cars and three-wheelers) to big, through different phases of development and demonstration.

It was envisaged that one million hydrogen-fuelled vehicles would be on Indian roads by 2020. However, fewer than 150 vehicles were showcased during the demonstration phase, and none appeared on the roads. GIP envisioned the development and demonstration of a hydrogen-powered IC engine/turbine and fuel cell-based decentralized power generating system with a capacity of about 1,000 megawatts (MW) by 2020. Nevertheless, as of 2023, no commercial plant has been established; all projects are either in the research and development (R&D), planning, or pilot stage. The NHERM comprehensively covered all aspects of the hydrogen energy system, encompassing safety, codes and standards, public awareness, and capacity building. However, these developments remain in nascent stages.

In 2016, the MNRE established a high-level steering committee focused on hydrogen and fuel cell development to reexamine the 2006 NHERM. This committee formed subcommittees, which submitted comprehensive reports outlining recommendations to advance the NHERM. In building upon these reports, an expert committee identified and defined specific projects within several themes related to hydrogen energy and fuel cells for further development and demonstration. These projects were shortlisted and recommended for implementation between 2016 and 2021. However, their progress and substantial impacts have been notably limited. The current status of key projects is summarized in Table 2.

Table 2: Status of Projects Recommended by Expert Committee

Project	Current Status as of September 2023
Demonstration of buses fueled by hydrogen-enriched compressed natural gas (HCNG) within specific city bus fleets	This technology combines hydrogen with compressed natural gas to potentially reduce emissions and enhance the efficiency of bus transportation. The Indian Oil Corporation Limited (IOCL) has already started a pilot for the same in the Delhi national capital region with 50 HCNG buses (IOCL 2020).
Demonstration of hydrogen-fueled internal combustion engine buses	These demonstrations aim to exhibit the feasibility and functionality of using hydrogen as a clean and sustainable fuel source for public transportation. The IOCL awarded the contract to Tata Motors for 15 hydrogen fuel cell buses in June 2021, and the buses will be supplied within the next two years (Tata Motors 2022).
Design and development of 20 kW low-temperature proton exchange membrane fuel cell with high indigenous content	The emphasis on "high indigenous content" signifies a focus on incorporating a substantial amount of locally sourced or domestically produced components and materials into the fuel cell's construction and manufacturing process. It seems that during the fiscal year (FY) 2019/20, the project was sanctioned by the MNRE and assigned to the International Advanced Research Center for Powder Metallurgy and New Materials and the Center for Fuel Cell Technology (ARCI-CFCT), in the Department of Science and Technology (DST) of the Ministry of Science and Technology. However, there has been a lack of subsequent updates or information available from the ARCI-CFCT regarding the project's progress or status.
Design and development of indigenous type III carbon composite cylinders for compressed hydrogen storage	These cylinders aim to utilize advanced carbon composite materials and construction techniques, ensuring efficient and safe containment of hydrogen for various applications. The project was awarded to the Council of Scientific and Industrial Research, Central Mechanical Engineering Research Institute (CSIR-CMERI), Durgapur, and the Indian Institute of Technology, Kanpur by the DST during FY 2019/20. No further updates are available from the CSIR-CMERI.
Testing and certification facilities for vehicles fueled by HCNG and hydrogen at the existing center(s) of automobile testing	This project aims to expand and upgrade the current automobile testing centers to accommodate the specific needs of assessing and certifying vehicles running on HCNG and hydrogen fuels. The Automotive Research Association of India (ARAI) set up a green mobility center in Chakan, Pune, in 2020 with an investment of ₹1,000 million. For hydrogen-fueled vehicles, the setting up of a hydrogen test cell at this center has been proposed with a 350 kW transient dynamometer for development testing and certification of hydrogen engines (ARAI 2020).

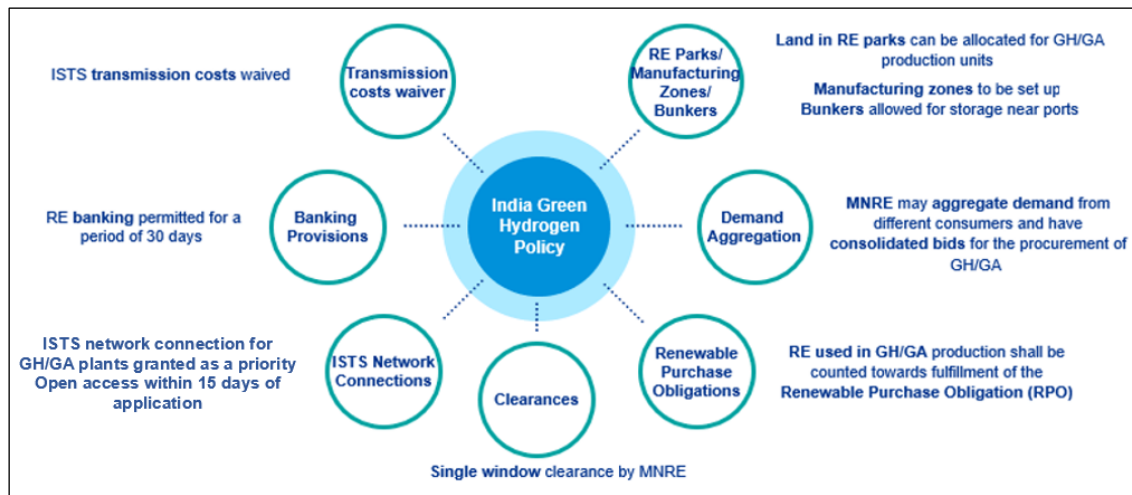
HCNG = hydrogen-enriched compressed natural gas, IOCL = the Indian Oil Corporation Limited.

Sources: IOCL (2020), Tata Motors (2022), ARAI (2020).

Green Hydrogen Policy. In 2022, the Green Hydrogen Policy established targets to increase domestic production of green hydrogen and its derivatives, like green ammonia, to 5 million metric tons per year by 2030 (Government of India 2022a). The

policy aims primarily to bolster renewable energy generation, thereby providing impetus for green hydrogen production within the country. Key highlights of the policy are described in Figure 2:

Figure 2: Key Highlights of Green Hydrogen Policy 2022



GA = green ammonia, GH = green hydrogen, ISTS = interstate transmission network, MNRE = Ministry of New and Renewable Energy, RE = renewable energy.

Sources: Government of India (2022a). Diagrammed by author.

National Green Hydrogen Mission. On 4 January 2023, the Government of India approved the National Green Hydrogen Mission with an outlay of ₹197.44 billion from FY 2023/24 to FY 2029/30 (Government of India 2023b). This mission is designed to provide a comprehensive plan for building a green hydrogen ecosystem and catalyzing a systemic response to the opportunities and challenges within this emerging sector.

The objectives of the mission are twofold: (i) to position India as a global hub for the production, utilization, and export of green hydrogen and its derivatives; (ii) to significantly decrease the carbon footprint of the economy, reduce reliance on fossil fuel imports, and enable India to lead in both technology and market aspects of green hydrogen.

The mission's goal is to establish the capacity to produce a minimum of 5 million metric tons of green hydrogen annually by 2030, with the potential to scale up to 10 million metric tons annually, primarily driven by the expansion of export markets. Its focus will be on facilitating the transition from fossil fuels and fossil fuel-derived resources to renewable alternatives and resources based on green hydrogen. This transition involves multiple initiatives: (i) substituting hydrogen derived from fossil fuels with green hydrogen in ammonia production and petroleum refining processes; (ii) blending green hydrogen into city gas distribution systems; (iii) utilizing green hydrogen in steel production; (iv) employing synthetic fuels derived from green hydrogen (such as green ammonia, green methanol, etc.) to replace fossil fuels across various sectors, including transportation, shipping, and aviation.

The mission's implementation strategy is structured to align with the early stage of development and the dynamic nature of the industry. It plans to roll out in phases, with an initial focus on introducing green hydrogen into sectors that already utilize hydrogen. Additionally, the mission aims to cultivate an ecosystem that facilitates research and development, establishes regulations, and initiates pilot projects. This

phased approach is intended to build a solid foundation for the integration and growth of green hydrogen across various sectors, recognizing the need for a structured evolution in this emerging domain.

During the initial phase from 2022/23 to 2025/26, the mission will concentrate on catalyzing demand and production of green hydrogen. This involves fostering a self-reliant ecosystem by incentivizing the localization of the entire value chain. Concurrently, substantial support will be extended to research and development endeavors. Establishing a robust regulatory framework and standards is pivotal in this phase. Sectors such as refineries, fertilizers, and city gas will serve as launchpads for green hydrogen, creating sustained demand and attracting fresh investments. The overarching aim is to drive down costs and render green hydrogen competitive against fossil fuel-based alternatives, particularly in the refinery and fertilizer sectors. Furthermore, this phase lays a solid foundation for future energy transitions in other hard-to-abate sectors that are traditionally challenging to decarbonize.

During the subsequent phase from 2026/27 to 2029/30, green hydrogen is expected to spread widely across multiple sectors, signifying a profound decarbonization of the economy. While building upon the successes and lessons from the initial phase, the subsequent phase aims for a deeper integration of green hydrogen. It explores new territories, such as steel, mobility, shipping, railways, and aviation through pilot projects and an escalated focus on research and development. Coordination among various government bodies, ministries, departments, and institutions, both at the central and state levels, becomes imperative to ensure the seamless realization of mission objectives.

The comprehensive strategy of the National Green Hydrogen Mission encompasses technological advancements, regulatory frameworks, market stimulation, and cost-effectiveness. This concerted effort aims to propel the widespread adoption and integration of green hydrogen across diverse sectors, thereby forging a sustainable and low-carbon future for India's economy. The government has allocated a substantial budget of ₹197.44 billion for this endeavor. This funding is meticulously divided to address various critical aspects of the mission:

Strategic interventions for green hydrogen transition (SIGHT). A significant proportion of ₹174.90 billion is allocated to the SIGHT program, emphasizing sustainable indigenous green hydrogen technology development and implementation. The strategy encompasses a comprehensive incentive program to facilitate the growth of the green hydrogen industry value chain in the country. This multifaceted strategy entails diverse financial incentives and nonfinancial measures aimed at incentivizing the production of low-cost green hydrogen and promoting the domestic manufacturing of associated equipment and technologies. As the mission progresses and markets evolve, these incentive schemes and programs will adapt, tailored to the dynamics of technological advancements and market demands. Initially, the mission introduces two distinct financial incentive mechanisms. One is specifically targeted at bolstering domestic manufacturing capabilities for electrolyzers, which are crucial devices used in green hydrogen production. The other incentive mechanism is designed to directly encourage and support the production of green hydrogen within the country.

Pilot projects. ₹14.66 billion is earmarked specifically for pilot projects. These projects serve as test beds to evaluate and demonstrate the feasibility and scalability of green hydrogen initiatives across different sectors. The primary aim of these pilot projects is to explore the potential for replacing fossil fuels and their derivatives with green hydrogen in various sectors. Industries such as steel production, long-range heavy-duty mobility, energy storage, and shipping are among those targeted for these

initiatives. By implementing these pilot projects, the mission intends to uncover operational challenges and identify gaps in terms of technology readiness, regulatory frameworks, implementation strategies, infrastructure requirements, and supply chains. This proactive approach allows for a thorough evaluation of the practical aspects and challenges associated with transitioning to green hydrogen. Insights gained from these pilots will be invaluable in refining strategies, addressing obstacles, and streamlining processes as the mission progresses toward wider adoption and integration of green hydrogen technologies across sectors.

Research and development. An allocation of ₹4.0 billion is dedicated to research and development (R&D) efforts. This investment aims to propel technological advancements and innovation in the field of green hydrogen production and utilization. This substantial investment is intended to serve as a catalyst for technological advancements in both the production and utilization of green hydrogen. The overarching goal is to support innovation endeavors focused on enhancing the affordability of green hydrogen production, storage, transportation, and utilization. Additionally, the emphasis will be on improving the efficiency, safety, and reliability of systems and processes integral to green hydrogen technologies. R&D projects under this allocation will follow a goal-oriented, time-bound approach, ensuring that research initiatives are focused, have clear objectives, and are scaled up appropriately to yield measurable and quantifiable outcomes. The aim is to stimulate transformative innovations that will not only make green hydrogen more cost-effective and accessible but will also enhance the overall effectiveness and reliability of green hydrogen technologies and systems.

Other components such as skill development. Additionally, ₹3.9 billion is set aside to support various other crucial components of the mission as vital support for critical facets beyond direct production and technology innovation. This substantial investment is designated to bolster various essential aspects integral to the mission's success. It encompasses diverse components, including: (a) regulatory frameworks: developing and refining regulations tailored to green hydrogen production, storage, transportation, and utilization; (b) standards: establishing industry benchmarks and standards to ensure quality, safety, and interoperability within the green hydrogen ecosystem; (c) capacity building: initiating programs and initiatives aimed at fostering expertise and skill development across different stakeholders involved in green hydrogen technologies; and (d) infrastructure development: investing in the creation and enhancement of infrastructure essential for the efficient deployment and utilization of green hydrogen.

The mission also aims to foster strategic international partnerships, facilitating the export of green hydrogen and its derivative products. This endeavor will leverage supporting infrastructure, including dedicated hubs and port facilities, to enable efficient export operations. Projections indicate a burgeoning global demand exceeding 100 million metric tons for green hydrogen and its derivatives, such as green ammonia, by 2030. India's ambitious goal is to capture 10 million metric tons (10%) of this expanding market. As part of this aspiration, India is actively engaged in discussions and negotiations with countries like Japan, Singapore, and members of the European Union with a view to cultivating and developing potential export markets. These collaborative efforts and international partnerships are envisioned to create pathways for India to significantly contribute to, and benefit from, the emerging global market for green hydrogen and its derivative products. The establishment of robust infrastructure, coupled with strategic alliances, positions India to play a pivotal role in meeting the rising global demand for sustainable energy solutions.

Domestically, the Government of India intends to stimulate the development of national markets for green hydrogen and its derivative products by introducing specific mandates. These mandates will entail designating a minimum proportion of consumption for designated consumers, outlining the use of green hydrogen or its derivatives like green ammonia or green methanol as energy sources or feedstock. An empowered group will offer recommendations regarding these mandates, and subsequent compliance monitoring will ensure adherence to these specifications. This approach aims to incentivize and drive the adoption of green hydrogen-based solutions within domestic industries and sectors, fostering the transition towards sustainable and eco-friendly energy sources.

2.2 Various Ministries' Specific Initiatives

It is remarkable to note the concerted efforts across various ministries in spearheading specific initiatives aligned with the promotion of green hydrogen and its integration into diverse sectors. The key ministries include:

- (a) **Ministry of New and Renewable Energy (MNRE).** The MNRE has been pivotal in launching initiatives and programs aimed at advancing research, development, and deployment of renewable energy sources, including green hydrogen.
- (b) **Ministry of Petroleum and Natural Gas (MOPNG).** This ministry has undertaken initiatives focused on exploring the potential and integration of hydrogen, particularly green hydrogen, within the existing petroleum and natural gas framework.
- (c) **Ministry of Road Transport and Highways (MORTH).** Initiatives within MORTH likely center on investigating and implementing green hydrogen-powered vehicles or integrating green hydrogen technology within the transportation infrastructure.
- (d) **Ministry of Science and Technology (MOST).** MOST's initiatives are likely oriented toward fostering innovation and technological advancements in green hydrogen production, utilization, and associated applications.

Ministry of New and Renewable Energy. The MNRE is pivotal in driving India's green hydrogen-based economy, particularly through its proactive facilitation of research development and demonstration programs focused on hydrogen energy and fuel. The MNRE has supported various R&D projects in industrial, academic, and research institutions to address challenges in the production, storage, and transportation of hydrogen. In the realm of transportation, the MNRE has demonstrated hydrogen-fueled internal combustion engines, two-wheelers, three-wheelers, and minibuses. Two hydrogen refueling stations have been established at the Indian Oil R&D Center, Faridabad, and the National Institute of Solar Energy, Gurugram (Government of India 2023b), which can be a significant step toward building the necessary infrastructure for hydrogen-based transportation.

To drive offtake of green hydrogen, the MNRE employs a demand aggregator model by aggregating demand from key sectors. This strategic approach aims to create substantial demand volume, promoting the commercial supply of green hydrogen based on the SIGHT program. The MNRE asked the Solar Energy Corporation of India (SECI) to host the bidding process. SECI has promoted bids to select green hydrogen producers for setting up 450 kilo tonnes per annum of green hydrogen production facilities across India (SECI 2023). SECI also awarded contracts for the development of a 1.5 GW electrolyzer production capacity (Renewable Watch 2024). Through

competition in these large-scale tenders, the MNRE aims to significantly reduce the cost of green hydrogen.

In August 2023, the MNRE issued the Green Hydrogen Standard for India, which is a landmark move defining emission thresholds necessary for hydrogen to be classified as “green,” emphasizing its renewable sourcing. These standards specify stringent emission limits for electrolysis- and biomass-based hydrogen production methods, ensuring a low carbon footprint. The ministry plans to introduce a comprehensive methodology for measuring, reporting, monitoring, on-site verification, and certification of green hydrogen and its derivatives. The MNRE’s Bureau of Energy Efficiency became the nodal authority for accreditation. This process should represent a significant stride towards ensuring transparency and accountability in green hydrogen production. In June 2024, the MNRE also revised the SIGHT program to increase the available capacity of green ammonia through bidding processes from 550,000 to 750,000 tons per year (Government of India 2024).

Ministry of Petroleum and Natural Gas. The MOPNG is spearheading initiatives to augment the role of hydrogen in India’s energy landscape. One such significant endeavor involves a current pilot project focusing on the adoption of gray hydrogen in the Hydrogen CNG (HCNG) initiative. This pioneering project aims to blend gray hydrogen with CNG (resulting in an 18% hydrogen blended HCNG) for utilization as fuel in bus transportation. Delhi serves as the testing ground, with 50 buses operated by the Delhi Transport Corporation (DTC) running on HCNG for trial purposes (Government of India 2020a). The execution of this pilot project involves collaboration between the Indian Oil Corporation Limited (IOCL), Indraprastha Gas Limited (IGL), the Delhi Integrated Multi-Modal Transit System (DIMTS), the DTC, and the Delhi Transport Department.

The MOPNG has established the Hydrogen Corpus Fund (HCF) with an allocation of ₹1.0 billion to fund hydrogen-related R&D projects, led in particular by the oil industry (OIDB 2016). The contributions from various public sector undertakings (PSUs) and the Oil Industry Development Board (OIDB) are channeled into the fund, with projects currently being funded focusing on solar-based hydrogen production, HCNG, and hydrogen production via natural gas decomposition.

Another ambitious initiative unveiled by the ministry involves exploring diverse pathways for hydrogen production. This R&D project, amounting to around ₹2,960 million, draws contributions from HCF, IOCL, and other participating entities, such as original equipment manufacturers (Government of India 2023c). The project aims to undertake comprehensive R&D activities and pilots spanning the value chain of hydrogen-based mobility. The IOCL’s R&D segment plans to procure 15 green hydrogen fuel cell buses for a 20,000 km field trial in the Delhi National Capital Region and establish four demo units for hydrogen production, amounting to 40 tons per day. Among these units, three will utilize renewable energy sources like biomass gasification, reforming compressed biogas (CBG), and solar photovoltaics (PV)-based electrolysis.

Moreover, the MOPNG has outlined plans for five pilots based on green hydrogen, where the produced green hydrogen will be utilized both as a transportation fuel and as an industrial input to refineries. These initiatives underscore the MOPNG’s commitment to exploring and integrating various hydrogen pathways, fostering innovative solutions for diverse sectors, and propelling India towards a sustainable and hydrogen-centric energy future.

Ministry of Road Transport and Highways. MORTH has taken substantial strides towards decarbonizing the transportation sector, notably by authorizing HCNG (18% hydrogen) in CNG engines (Government of India 2020b). This represents a significant leap in embracing alternative automotive fuels. To complement this move, the Bureau of Indian Standards (BIS) has formulated specifications (i.e., International Standard (IS) 17314:2019) delineating the use of HCNG as a fuel for automotive purposes. Furthermore, MORTH has issued a pivotal notification establishing standards for the evaluation of safety of hydrogen fuel cell-based vehicles. This move ensures that prospective manufacturers and suppliers of such vehicles have standardized protocols available for testing.

These steps taken by MORTH and the development of stringent standards by BIS underscore the government's commitment to ensuring safety, regulation, and standardization in integrating hydrogen-based fuels and vehicles into the transportation sector. This proactive approach fosters a conducive environment for the adoption of innovative and sustainable technologies within the automotive industry, marking a significant leap towards a cleaner and greener future for transportation in India.

Ministry of Science and Technology. The Ministry's Department of Science and Technology (DST) has undertaken significant initiatives through its Green Hydrogen Research Initiative (HRI), primarily through two key programs: the Hydrogen and Fuel Cell (HFC) Program and the Renewable and Clean Hydrogen Program. The HFC Program, initiated in 2018, focuses on developing transformative technologies to reduce the cost of green hydrogen production, distribution, and storage. Additionally, it explores various feedstock options for economical production of hydrogen, enhances power grid flexibility, and seeks to lower emissions through innovative applications of low-cost green hydrogen, through 30 national research projects under the HFC Program (Government of India 2020c, 2022c). The Renewable and Clean Hydrogen Program aims to accelerate the development of a green hydrogen economy by identifying and surmounting barriers to producing, distributing, storing, and using green hydrogen on large and industrial scales. It envisages collaborative research and demonstrations involving both public and private sectors, yet specific details on the current initiatives and progress under this program are not publicly available.

The DST has established two research centers: the DST-IIT Bombay Energy Storage Platform of green hydrogen (ESPHy) and the DST-NFTDC Center for Materials and Energy Storage Platforms on green hydrogen (MECSP), indicating a strategic focus on fostering research and development in green hydrogen technologies. In June 2021, the DST launched the Advanced Green Hydrogen and Fuel Cell Program (AHFC), with a focus on R&D in green hydrogen and fuel cell technologies across various sectors. This program aims to support the indigenous development of materials, catalysts, membranes, and components for fuel cells and electrolyzers. The AHFC-2021 Program has supported approximately 11 projects, emphasizing the development and implementation of various applications leveraging green hydrogen and fuel cells in the country (Government of India 2021a).

These concerted efforts by the DST reflect a dedicated commitment to advancing green hydrogen technologies, fostering innovation, and overcoming barriers in scaling up green hydrogen utilization across sectors, contributing significantly to India's sustainable energy goals.

2.3 Public and Private Partnership Initiatives

The transition to green hydrogen adoption for decarbonization relies significantly on collaborations between the government, public sector enterprises, and private sector entities. Both the central government and Indian corporates are actively setting targets for decarbonization, undertaking initiatives to advance sustainability.

Numerous R&D and knowledge-sharing initiatives have been introduced by entities such as the IOCL, the Energy and Resources Institute, and Oil and Natural Gas Corporation Limited (ONGC). These efforts involve diverse stakeholders, including think tanks, public sector enterprises, corporations, and educational institutions. HSBC India, for instance, has partnered with the Indian Institute of Technology (IIT) Bombay and the Shakti Sustainable Energy Foundation (SSEF) to drive innovation in green hydrogen. L&T, the IOCL, and Renew also established a joint venture named GH4India to venture into the green hydrogen business. Annexure 1 provides a comprehensive list of upcoming and operational plants by public and private sector entities, showcasing their initiatives in themes like policy and knowledge sharing, production, storage, and fuel cell development R&D.

Several companies, including the IOCL, Adani Gas Limited, and NTPC Renewable Energy Limited, have proposed and executed projects with a focus on developing green hydrogen storage and transportation infrastructure. However, the research and development in green hydrogen transportation remains limited. While hydrogen storage and transportation via hydrides are actively explored, further R&D efforts are needed in these domains.

Early-stage energy technologies like hydrogen encounter initial challenges, including conversion complexities, safety concerns, limited investments due to evolving landscapes, extensive R&D requirements, etc. Consequently, market development often remains confined to pilot projects and research stages.

3. TECHNOLOGICAL ASSESSMENT

Green hydrogen production predominantly relies on water electrolysis powered by renewable energy sources. This process involves using an electric current to split water into hydrogen and oxygen. Three primary electrolyzer technologies are utilized globally. They are as follows:

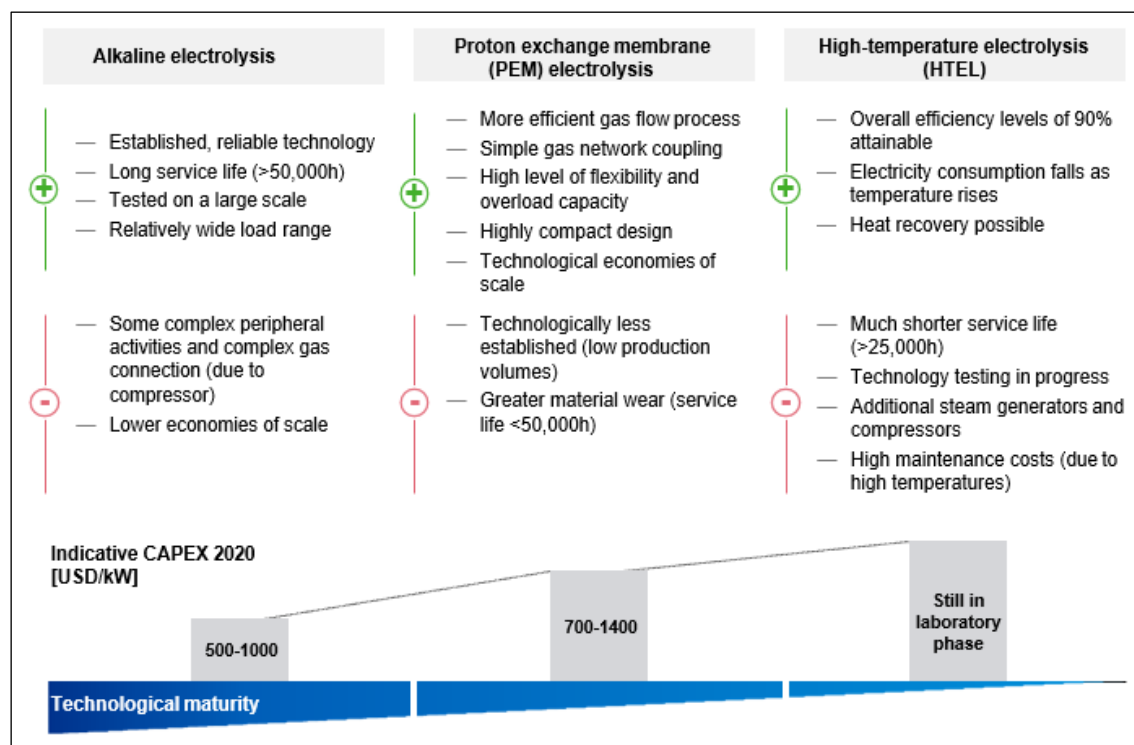
- **Proton exchange membrane (PEM) electrolysis.** This method excels in variable load conditions and is suitable for smaller-scale applications. However, it comes with higher initial costs and sensitivity to impurities, thus limiting its operational lifespan.
- **Alkaline electrolysis.** This method offers a longer operational lifespan and is less costly than PEM. However, it is less efficient in variable load conditions, tends to be bulkier, and exhibits slower startup/shutdown times.
- **Solid oxide electrolyzer cell (SOEC) or high-temperature electrolysis (HTEL).** Operating at higher temperatures, this method potentially delivers greater efficiency and can handle a wider range of feedstock options. Yet it faces challenges due to higher costs, technological complexity, and high-temperature requirements.

Emerging technologies for green hydrogen production include biomass gasification, methane pyrolysis, photolysis, and microbial biomass conversion. Methane pyrolysis, for instance, holds promise as it requires substantially less electricity than water electrolysis (ETC 2021). However, challenges persist. Electrolyzer costs remain a significant hurdle for large-scale adoption. Some emerging technologies are still maturing and may lack widespread commercial viability. Ensuring efficiency and scalability across different production methods is another ongoing concern.

Despite these challenges, ongoing advancements aim to overcome barriers such as cost, efficiency, and scalability, fostering the widespread adoption of green hydrogen as a clean and sustainable energy source. Each method offers unique advantages and drawbacks, guiding the ongoing pursuit of more efficient and cost-effective green hydrogen production methodologies. According to the International Renewable Energy Agency (IRENA), the capital expenditure (CAPEX) costs of electrolyzers vary across different technologies. The cost ranges from approximately \$500 to \$1,000 per kW for alkaline electrolyzers, while PEM electrolyzers cost between \$700 and \$1,400 per kW as of 2020 (IRENA 2020). These costs are indicative of the expenses incurred in setting up electrolysis systems for green hydrogen production.

The higher CAPEX costs of electrolyzers present a substantial challenge to the widespread adoption of green hydrogen. This financial barrier limits large-scale implementation, affecting the cost-competitiveness of green hydrogen compared to conventional methods. The advantages and disadvantages of different production technologies are summarized and compared in Figure 3.

Figure 3: Review of Different Electrolysis Technologies



Source: IRENA (2020). Diagrammed by author.

The cost discrepancy between alkaline and PEM electrolyzers underscores the financial hurdle that electrolyzer expenses pose for the broader implementation of green hydrogen. Efforts to reduce these CAPEX costs are crucial to enhancing the cost-effectiveness and competitiveness of green hydrogen production technologies, enabling their widespread adoption and integration into mainstream energy systems.

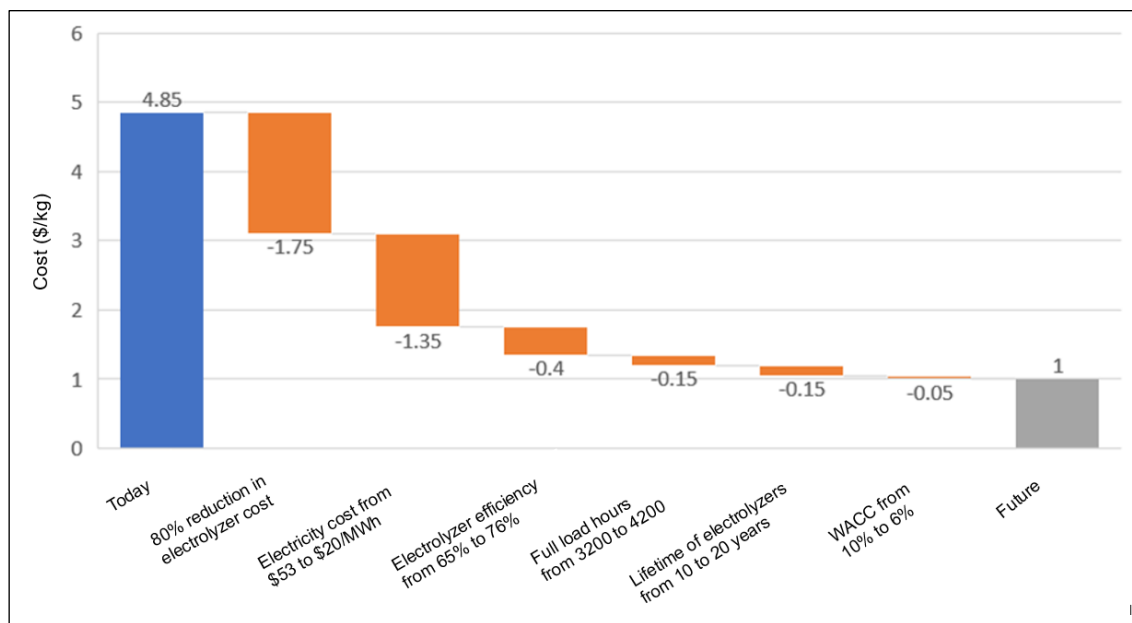
The current cost of producing green hydrogen through existing processes surpasses the costs associated with gray or blue hydrogen pathways. The CAPEX for alkaline electrolyzers ranges from \$650 to \$1,000 per kW, and this figure is anticipated to decrease substantially to between \$130 and \$307 per kW by 2050 for capacities of 1 TW to 5 TW (IRENA 2020).

The installed capacity of electrolyzers for green hydrogen production stands at approximately 0.08 gigawatts (GW), a figure projected to surge to 25 GW by 2030. Technological advancements in electrolyzer technologies are anticipated to drive down the cost of producing green hydrogen, complemented by decreasing prices of power generated through renewable energy sources.

The cost of electricity constitutes roughly 90% of the total operating expenditure for producing green hydrogen in the water electrolysis process. Hence, a low cost of electricity from renewable energy sources will be a key factor in determining the overall levelized cost of green hydrogen production.

IRENA estimates suggest a substantial reduction in the levelized cost of green hydrogen by 2050, projected to decrease to approximately \$0.95–1.2 per kilogram from the \$4.8–4.9 per kilogram recorded in 2020 (Noussan et al. 2021). This forecast reflects an 80% decline in green hydrogen costs due to advancements in technology and cost efficiencies (IRENA 2021), as illustrated in Figure 4:

Figure 4: Potential Cost (\$/kg) Reduction for Green Hydrogen by 2050



WACC = weighted average cost of capital.

Source: IRENA (2021).

These projections highlight the significant potential for cost reduction in green hydrogen production over the coming decades, mainly attributed to technological improvements and the declining costs associated with renewable energy sources.

The production of alkaline electrolysis systems isn't anticipated to face significant long-term material constraints (ETC 2021). However, the current requirements for alkaline electrolysis systems involve approximately 33,333 kilograms of unalloyed steel, 3,167 kilograms of nickel, and 333 kilograms of copper per MW (Hall et al. 2020). For India, procuring nickel might pose challenges due to its high dependence on imports to meet the country's nickel demand (CARE Rating 2019). This dependence on imported nickel could potentially impede the smooth procurement of resources necessary even for alkaline electrolysis systems.

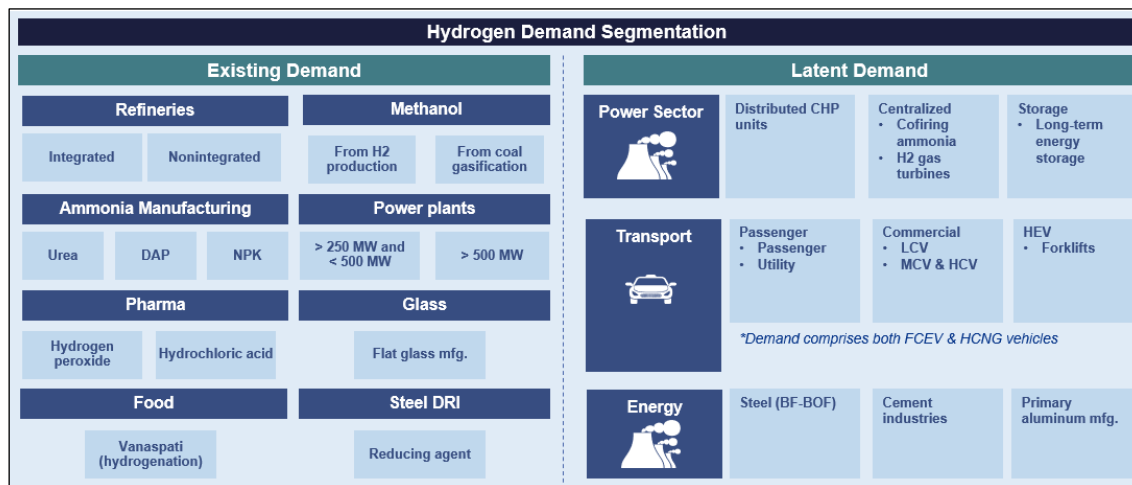
A scarcity of raw materials, like iridium and platinum, could also hinder the goal of achieving the targeted annual manufacturing capacity of PEM electrolyzers on a global scale. IRENA estimates indicate that current iridium and platinum production levels can only support an annual manufacturing capacity ranging from 3 GW to 7.5 GW of PEM electrolyzers, falling significantly short of the projected annual manufacturing capacity of approximately 100 GW by 2030 (IRENA 2020). Consequently, an exploration of alternative electrolyzer options like anion exchange membrane (AEM) electrolyzers is underway. AEM electrolyzers are advantageous as they don't rely on scarce materials like iridium and platinum, as they primarily require steel and nickel.

Moreover, the production of green hydrogen through electrolysis requires substantial water consumption, estimated at around 9 liters per kilogram of green hydrogen output. With global freshwater scarcity concerns and increasing awareness of climate change impacts, securing access to deionized water is expected to become a critical factor for large-scale green hydrogen production plants. Addressing resource availability and environmental impact concerns is crucial to ensuring the sustainability and feasibility of large-scale green hydrogen production pathways.

4. SECTORAL APPLICATION ASSESSMENT—DEMAND AND SUPPLY

Hydrogen is the most abundant element in the universe and accounts for nearly three quarters of all matter, followed by helium and oxygen. Additionally, hydrogen has the highest energy density per unit mass of any fuel, and when burned, it produces little more than water vapor. Today, the oil refining and chemical industries consume over 95% of the hydrogen produced globally. However, green hydrogen is gaining traction across the world in various applications. Historically, the largest consumers of hydrogen globally have been the oil refining and chemical industries, consuming over 95% of the produced hydrogen.

However, the momentum is shifting rapidly, with green hydrogen gaining significant traction across various applications worldwide. As a clean and versatile energy carrier, green hydrogen is increasingly recognized for its potential to decarbonize various sectors, including transportation, power generation, and industry, among others. This shift towards green hydrogen underscores its potential to revolutionize energy systems and significantly contribute to global efforts towards sustainability and reduced carbon emissions.

Figure 5: Existing and Potential Sectors for Green Hydrogen Demand

BF-BOF = blast furnace-basic oxygen furnace, CHP = combined heat and power, DAP = Di-ammonium phosphate, DRI = direct reduced iron, H2 = hydrogen, HEV = hybrid electric vehicle, LCV = light Commercial vehicle, MCV = mobile combat vehicle, MW = megawatt, NPK = nitrogen, phosphorus, potassium oxide.

Source: Diagrammed by author.

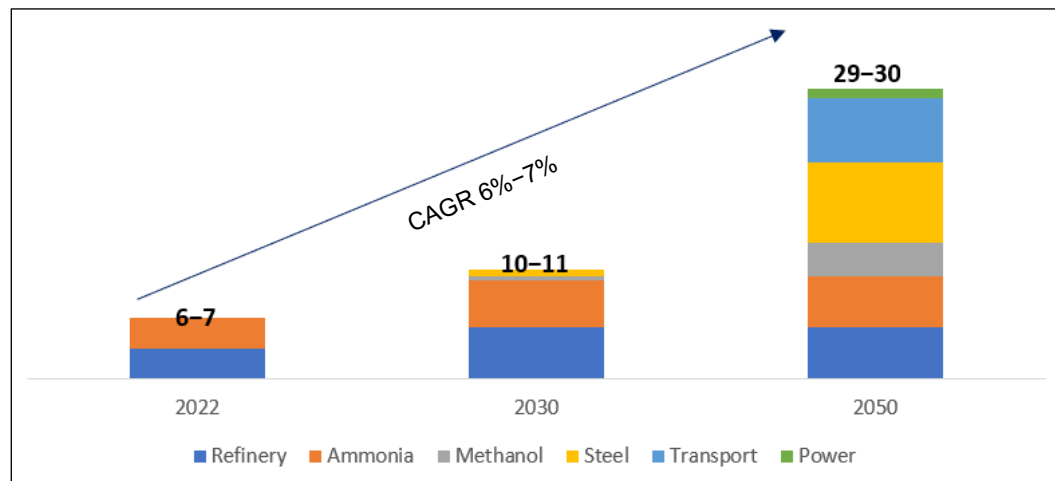
Green hydrogen, categorized as both a fuel and a feedstock, is witnessing rising demand across sectors. Historically, refineries and fertilizer industries have been major consumers of hydrogen, primarily gray hydrogen, yet the potential for increased demand is emerging, notably in transportation (via HCNG and fuel cell electric vehicles [FCEVs]), steel manufacturing (for cleaner production methods), methanol production (as a critical component), and power generation (utilizing hydrogen as an energy carrier and storage medium). These sectors exhibit a growing inclination towards green hydrogen, indicative of its versatile applications and its role in fostering sustainable, low-emission practices across diverse industries. The applications for green hydrogen by major sectors are presented in Table 3.

How to prioritize green hydrogen applications across sectors will be dependent on the future demand, which involves complex factors such as energy efficiency, cost-competitiveness compared to alternatives, market size, technological maturity and scalability, financial feasibility, policies fostering decarbonization, and existing investments and pilot projects. Globally, the hydrogen demand stood at approximately 94 million tons in 2021 (IEA 2022), which is projected to expand nearly sixfold to 614 million tons per year by 2050 to meet climate goals (IRENA 2022). The current demand for hydrogen in India is around 6 million metric tons (Government of India 2023b), and it is expected to surge four to five times by 2040 (Government of India, 2022a). By 2030, green hydrogen is anticipated to fulfill an estimated 15% of this demand (Government of India 2022b). The distribution of this demand across various end-use sectors is shown in Figure 6:

Table 3: Green Hydrogen Applications—Major End-Use Sectors

No.	Sector	Green Hydrogen Usage
1	Fertilizers (ammonia)	<ul style="list-style-type: none"> Green hydrogen is used as a feedstock to produce ammonia and make nitrogenous fertilizers like urea. It is also used to produce DAP (diammonium hydrogen phosphate) fertilizer.
2	Refineries	<ul style="list-style-type: none"> Hydrotreatment and hydrocracking are the main hydrogen-consuming processes in the refinery. Hydrotreatment is used to remove impurities, especially sulfur (desulfurization), and accounts for a large share of refinery hydrogen use globally. Hydrocracking is a process that uses hydrogen to upgrade heavy residual oils into higher-value oil products.
3	Gas blending—spiked green hydrogen (transport)	<ul style="list-style-type: none"> Green hydrogen is blended with CNG to make Hydrogen Compressed Natural Gas (HCNG), which is used to run buses, cars, and other vehicles. For vehicle engines, hydrogen has been blended to an extent of 18%.
4	Gas blending—spiked green hydrogen (industry)	<ul style="list-style-type: none"> Green hydrogen is injected into natural gas pipelines, and the blend is then used to generate power and heat in the industry and for other conventional uses of natural gas.
5	Food processing (hydrogenating agent)	<ul style="list-style-type: none"> Green hydrogen is used to turn unsaturated fats into saturated oils and fats. Food industries use hydrogen to make hydrogenated vegetable oils such as margarine and butter.
6	Float glass manufacturing	<ul style="list-style-type: none"> Green hydrogen is used as a getter gas to prevent oxidation over the tin baths used in the float glass manufacturing process. The green hydrogen keeps the tin baths free of oxidation and ensures that the glass formed in the baths is made without defects.
7	Green hydrogen for cooling	<ul style="list-style-type: none"> Green hydrogen is used for generator cooling in thermal and gas-based power plants. Large-capacity generators, usually more than 67.5 MW, require hydrogen to cool generator windings.
8	Passenger FCEVs	<ul style="list-style-type: none"> Fuel cell electric vehicles (FCEVs) derive energy from hydrogen and emit no harmful gases into the environment.
9	Methanol	<ul style="list-style-type: none"> Green hydrogen is used as a feedstock to make methanol by directly combining hydrogen and carbon dioxide, using palladium as a catalyst.
10	Steel DRI	<ul style="list-style-type: none"> Green hydrogen is used to produce steel from iron using hydrogen-based direct reduction of iron (DRI). Green hydrogen is used as a key reducing agent (as opposed to carbon monoxide derived from fossil fuels).
11	Hybrid renewable energy with H ₂ storage	<ul style="list-style-type: none"> Excess renewable energy from wind/solar is used to produce hydrogen. The stored hydrogen is then used during the lean period when renewable energy is not sufficiently available to produce electricity for stand-alone off-grid applications or for backup power generation to replace diesel.
12	Ammonia cofiring with coal	<ul style="list-style-type: none"> Ammonia is used for efficient storage and transport of hydrogen and is also used directly as a fuel in thermal power generation; as a fuel, it does not emit carbon dioxide when burned. Cofiring ammonia is done in a coal-fueled boiler, with a 1%–20% share of ammonia (in terms of total energy content).
13	Green hydrogen for power generation (combined cycle gas turbines)	<ul style="list-style-type: none"> Green hydrogen is used as a fuel to power modified gas turbine engines. Companies like Siemens Energy are working to attain higher hydrogen percentage capability in turbines; the target is to use 100% hydrogen to power turbines by 2030.
14	Boilers and heating	<ul style="list-style-type: none"> Green hydrogen could be blended into existing natural gas networks for gas-fired central home heating supplies. Green hydrogen-fired heating has maximum utility in multifamily and commercial buildings in cooler regions, particularly in dense cities, such as cities with existing natural gas supply networks.
15	Hydrogen trains	<ul style="list-style-type: none"> Green hydrogen-powered fuel cells are used to produce electricity that runs trains. The first hydrogen-powered trains debuted in Germany.
16	Aviation	<ul style="list-style-type: none"> Green hydrogen can be burned in a jet or internal combustion engine. Green hydrogen has three times the energy density per unit mass of jet fuel. Other possibilities include hydrogen in a fuel cell producing electricity to propel an aircraft.
17	Marines	<ul style="list-style-type: none"> Green hydrogen fuel cells powering marine transportation can be used especially for long-haul shipping.

Source: Based on discussions with industry experts and primary stakeholder consultations.

Figure 1: Hydrogen Demand by End-Use Sectors in India (in Million Metric Tons)

CAGR = computed annual growth rate.

Source: Government of India (2022b).

The global demand for hydrogen has shown consistent growth since the 1980s, nearly tripling from 24.5 million tons in its pure form and 10 million tons in mixed form in 1980 (IEA 2019) to 70 million tons in pure form and an additional 20 million tons in mixed form by 2020 (IEA 2021b). Green hydrogen is poised to play a pivotal role in upcoming global decarbonization efforts, prompting numerous countries to establish hydrogen-based economies through strategies, policies, and pilot projects. India, aspiring to achieve energy independence by 2047 and aiming for net zero by 2070, has implemented significant policies, such as the Green Hydrogen Policy and the National Green Hydrogen Mission. These initiatives lay the foundation for promoting green hydrogen production, yet India needs to augment these efforts with comprehensive strategies encompassing both the supply and demand sides. Integration of green hydrogen into traditionally fossil fuel-intensive industries and sectors necessitates multifaceted approaches on both production and utilization fronts.

Consideration for immediate demand-side initiatives. India's drive to integrate green hydrogen across sectors necessitates robust demand-side initiatives that align environmental benefits with existing carbon credits, potentially establishing hydrogen credits and a trading scheme akin to renewable energy certificates. In the transport sector, incentivizing hydrogen FCEVs through targets and subsidies for vehicle purchases and refueling infrastructure can bolster uptake. Mandating renewable fuel use in transportation and industry can be a robust mechanism for integrating hydrogen within fuel systems, initially facilitated by government establishments. Exploring the colocation of green hydrogen plants with renewable energy or industrial consumers offers cost-effective energy consumption, aided by power wheeling, facilitating rapid adoption of hydrogen fuels. Hydrogen blending within natural gas pipelines presents a seamless utilization option, contingent on addressing safety and technical limitations. In order to promote the adoption of green hydrogen, it is also crucial to incentivize the replacement of gray hydrogen with green hydrogen within the existing refinery process. India must prioritize educational and reskilling initiatives, collaborating with the Ministry of Skill Development and Entrepreneurship under the National Green Hydrogen Mission. Developing tailored courses and programs across the value chain—from equipment manufacturing to project installation, operations, and maintenance—ensures a skilled workforce ready for the burgeoning hydrogen economy. These proposed immediate actions are itemized below:

(i) Hydrogen Credits and Trading Scheme

- Recognizing environmental benefits through hydrogen credits.
- Creation of a hydrogen trading scheme based on mandated green hydrogen usage.
- Leveraging past experiences with renewable energy certificates.

(ii) Transport Sector Initiatives

- Setting targets and offering subsidies for hydrogen FCEVs.
- Providing subsidies for establishing hydrogen refueling infrastructure.

(iii) Mandating Renewable Fuels

- Imposing mandates for renewable fuel use in transportation and industrial sectors.
- Initial facilitation through government establishments.

(iv) Colocation of Green Hydrogen Plants

- Exploring sites colocated with renewable energy or industrial consumers.
- Leveraging cheaper energy consumption via power wheeling for faster adoption.

(v) Replacement of the existing hydrogen use

- Exploring hydrogen blending within natural gas pipelines.
- Exploring the substitution of gray hydrogen with green hydrogen in oil refineries.
- Addressing safety and technical constraints for effective utilization.

(vi) Educational and Reskilling Initiatives

- Collaborating with the Ministry of Skill Development and Entrepreneurship.
- Developing courses for skill building across the hydrogen value chain.
- Covering manufacturing, installation, operations, and maintenance aspects.

Consideration for immediate supply-side initiatives. On the supply side, India can leverage its existing natural gas infrastructure while ensuring that safety standards align with hydrogen regulations. It will also be crucial to upgrade electricity transmission lines for decentralized hydrogen production and consider the load increase to support green hydrogen manufacturing. With India's robust renewable energy capacity, it will be an essential avenue to foster international partnerships for green hydrogen exports. For this purpose, embracing global standards through initiatives like the MNRE's "Green Hydrogen Standards in India" with clarity and classification is strategically important. Mechanisms such as contracts for difference can protect hydrogen suppliers against risks, while balancing safety regulations and practicality in transportation and storage is pivotal. The Indian government's commitment to achieving net-zero emissions by 2070 can drive the proactive promotion of green hydrogen as an alternative to conventional fuels. These proposed immediate actions are itemized below:

(i) Utilization of Existing Infrastructure

- Exploring the integration of green hydrogen within the current natural gas infrastructure.
- Upgrading infrastructure to align with safety measures and hydrogen regulations.

(ii) Decentralized Production Upgrades

- Upgrading electricity transmission lines for decentralized hydrogen production.
- Adapting infrastructure for increased load due to green hydrogen production.

(iii) International Export Potential

- Leveraging India's robust renewable energy capacity for hydrogen exports.
- Establishing partnerships to fund green hydrogen production and exports.

(iv) Adoption of International Standards

- Embracing global hydrogen standards, licenses, and certificates.
- Clarifying the MNRE's initiative with "Green Hydrogen Standards in India" for.

(v) Contract for Difference (CFD) Mechanism

- Mechanisms like CFDs should be considered to protect hydrogen suppliers against risks.
- Potential establishment of price guarantee mechanisms for hydrogen production and supply.

(vi) Balancing Safety and Regulations

- Finding an equilibrium between safety guidelines and ease of hydrogen transportation and storage.
- Implementing regulations and standards for hydrogen while ensuring practicality.

5. INVESTMENT ASSESSMENT**5.1 Government's Targets**

India aims to produce 5 million tons of green hydrogen annually by 2030, with a view to meeting its climate targets and establishing itself as a production and export hub for this fuel. The National Green Hydrogen Mission outlines a framework for stimulating demand, a range of measures to support the production and utilization of green hydrogen, and encouragement for indigenous manufacturing. Additionally, the mission specifies explicit sector-wise targets for the utilization of green hydrogen. Along with the government's target, public sector entities, such as the IOCL, GAIL (the former Gas Authority of India), the National Thermal Power Corporation (NTPC), and others, have announced green hydrogen targets and investments for the upcoming years. These investments encompass refinery upgrades, the augmentation of electrolyzer capacities, pilot projects, and the establishment of green hydrogen plants, among other initiatives. Table 4 outlines the green hydrogen setups planned by these state-owned enterprises in India.

Table 4: Green Hydrogen Plants by State-Owned Organizations

No.	Entity	Key Insights
1	IOCL	<ul style="list-style-type: none"> A joint venture company, GH4India Private Ltd, was formed after entering into an agreement with Renew Power and L&T for green hydrogen production. Plans to convert at least 50% of its hydrogen demand (50% of its refining capacity) from gray hydrogen to green hydrogen by 2030. Plans to use green hydrogen across all of its refineries in the coming years. Targets producing 350 KTPA in total.
2	HPCL	<ul style="list-style-type: none"> Placed orders for large industrial electrolyzers. Submitted bid for green hydrogen/green ammonia tenders in Germany and Oman through a consortium between the HPCL and ACME. Set up a 0.37 KTPA electrolyzer-based green hydrogen plant at Visakh Refinery in Andhra Pradesh. Targets producing 29 KTPA in total.
3	BPCL	<ul style="list-style-type: none"> Plans to establish a 1 MW electrolyzer manufacturing facility in the country by 2025 using the Bhabha Atomic Research Center's technology for green hydrogen. Plans to put up a 20 MW electrolyzer at its refinery in Bina, Madhya Pradesh, to produce green hydrogen. Invited bids to set up a 5 MW electrolyzer and associated system for producing green hydrogen and hydrogen blending with natural gas in the city gas distribution network. Targets producing 28 KTPA in total.
4	GAIL	<ul style="list-style-type: none"> Awarded a contract to set up one of the largest PEM electrolyzers at its Vijaipur complex in Guna, Madhya Pradesh. Plans to build a green hydrogen plant with 10 MW capacity in Madhya Pradesh. Targets producing 45 KTPA in total.
5	MRPL	<ul style="list-style-type: none"> Plans to build green hydrogen facilities in Karnataka by 2030. Targets producing 5 KTPA in total.
6	NRL	<ul style="list-style-type: none"> Sets up a green hydrogen plant at Numaligarh, Assam. A tender for the supply of a 20 MW electrolyzer has been floated, and the plant is targeted for completion by the end of 2024. The electrolyzer will be based on AEL, AEM, or PEM technology. Targets producing 9 KTPA in total.
7	ONGC	<ul style="list-style-type: none"> Signed a Memorandum of Understanding with Greenko ZeroC (Greenko), to jointly pursue opportunities in renewables, green hydrogen, green ammonia, and other derivatives of green hydrogen. Targets producing 360 KTPA in total.
8	CPCL	<ul style="list-style-type: none"> Plans to set up 1 KTPA unit in Tamil Nadu by 2027. Targets producing 5 KTPA in total.
9	NTPC	<ul style="list-style-type: none"> Plans to build a green hydrogen plant (5 MW capacity) from its upcoming 4,750 MW renewable energy park at the Rann of Kutch. Taken up the initiative of blending green hydrogen in the Piped Natural Gas network of GGL (Gujarat Gas Limited) at NTPC Kawas. Green hydrogen will be produced by using electricity from the existing 1 MW floating solar project of NTPC Kawas. Set up a hydrogen fueling station and solar plant and provided five fuel cell buses for operation on intracity routes of Leh. Targets producing 650 KTPA in total.
10	SECI	<ul style="list-style-type: none"> Set up production facilities for green hydrogen in India under the SIGHT program. Targets producing 450 KTPA in total.

BPCL = Bharat Petroleum Corporation Limited, CPCL = Chennai Petroleum Corporation Limited, HPCL = Hindustan Petroleum Corporation Limited, IOCL = Indian Oil Corporation Limited, KTPA = kilo tons per annum, MRPL = Mangalore Refinery and Petrochemicals Limited, MW = megawatt, NRL = Numaligarh Refinery Limited, NTPC = National Thermal Power Corporation Limited, ONGC = Oil and Natural Gas Corporation Limited, SECI = Solar Energy Corporation of India Limited.

Sources: Government of India (2023d), Government of India (2021b), NTPC (2022), ET Energyworld (2023a, 2023b), The Economic times (2021), RW (2022), ONGC (2022), Money Control (2023), Jana A (2022).

5.2 Private Sector Targets

Private sector entities such as Adani, ACME, and Avaada have announced their green hydrogen and green ammonia production targets and investments for the upcoming years. These targets vary, with some entities specifying goals at the organizational level while others outline plans for particular locations or plants, involving both new additions and partial adoption. Table 5 presents the proposed green hydrogen and green ammonia plants along with their capacities declared by these private enterprises in India.

Table 5: Green Hydrogen Plants by Private Organizations

No.	Company	Key Insights
1	Adani New Industries Limited	<ul style="list-style-type: none"> The target is to produce 1 MMTPA of green hydrogen capacity and around 30 GW of renewable power generation capacity by 2030. TotalEnergies plans to acquire a 25% minority interest in Adani New Industries Ltd. However, the acquisition has not materialized.
2	ACME Solar	<ul style="list-style-type: none"> Installed the first integrated pilot project for a green hydrogen and green ammonia plant (1.7 KTPA) at Bikaner in Rajasthan. Announced integrated green hydrogen/green ammonia plants in Tamil Nadu (1.32 MMTPA [0.22 MMPTA of green hydrogen and 1.1 MMTPA of green ammonia]), Karnataka (1.2 MMTPA of both green hydrogen and green ammonia), and Odisha (1.1 MMTPA of green hydrogen and green ammonia).
3	Hygenco India	<ul style="list-style-type: none"> Plans to invest \$2.5 billion in green hydrogen projects across India over the next three years.
4	Avaada Group	<ul style="list-style-type: none"> Targets setting up a 0.5 MMPTA green hydrogen/ammonia facility. Plans to invest its initial investment of ₹80,000 million (equivalent to \$964 million).
5	AM Green Ammonia BV (Backed by Greenko Group)	<ul style="list-style-type: none"> Plans to develop a 1 MMPTA green ammonia plant in Kakinada, Andhra Pradesh. Plans to invest its initial investment of ₹125,000 million (equivalent to \$1.5 billion). Plans to invest an additional \$6 billion into pumped storage hydropower facilities to support green ammonia production.
6	ReNew Power	<ul style="list-style-type: none"> Plans to develop a green hydrogen plant (0.22 MMPTA) and a green ammonia plant (1.1 MMPTA) in Kerala. Plans to invest ₹264,000 million (equivalent to \$3.2 billion) in all facilities, including associated facilities such as renewable energy plants.
7	Ocior Energy	<ul style="list-style-type: none"> Signed MoU with Gujarat government for 1 MMTPA green hydrogen/green ammonia production in Kutch district with an investment of \$4.8 billion.
8	ABC Cleantech	<ul style="list-style-type: none"> Signed a Memorandum of Understanding with the government of Karnataka to build a green hydrogen plant underpinned by a 5 GW renewable energy supply in the Indian state. Plans to develop a green hydrogen plant (0.2 MMPTA) and a green ammonia plant (1.0 MMPTA). Plans to invest ₹500 billion (equivalent to \$6 billion) in all facilities, including associated facilities such as renewable energy plants.

kW = kilowatt, KTPA = kilo tons per annum, MMTPA = million metric ton per annum, MW = megawatt.

Sources: Avaada Group (2024), ACME (2023, 2024), Adani (2022, 2024), Baruah R (2024), ET Energyworld (2024), Gupta (2024), Hazarika (2023), Ohmium (2024), Ramesh (2023), Renewables Now (2022), The Economic Times (2024), TotalEnergies (2022).

5.3 Investment Plans

Based on public and private players' plans to expand the green hydrogen and green ammonia capacity, the investment requirements up to 2030 were estimated at approximately \$34,030 million. This comprises: (i) \$9,248 million (27% of the total) from government-owned enterprises (Table 6) and (ii) \$24,782 million (73% of the total) from the major private companies (Table 7). With these investments, the total capacity of green hydrogen and green ammonia is expected to reach more than 10 million metric tons by 2030. The key assumptions for calculating the investment requirements are as follows:

- (a) Electrolyzer cost is considered to be \$700/kW (Christensen 2020).
- (b) For an electrolyzer, the green hydrogen production quantity is considered to be 146 kg/kW/year, a value of which is averaged among relevant capacity data (Borden 2022; Businessline 2021; Eckert 2021).
- (c) For green ammonia plants, 177 kg of green hydrogen is required to produce 1 ton of green ammonia (Rivarolo et al. 2019).
- (d) The investment requirements do not assume the inclusion of costs for associated facilities, such as solar and wind power plants and transport infrastructure.

Table 6: Public Sector Investment Plans

No.	Company	Description (Project Site)	Estimated Production Capacity 2030 (KTPA)	Approx. Funding Requirement (\$ Million)
1	IOCL	Multiple refinery sites	350	1,676
2	HPCL	Visakh, Andhra Pradesh; Barmer, Rajasthan	29	139
3	BPCL	Bina, Madhya Pradesh; Kochi, Kerala; Mumbai, Maharashtra	28	134
4	GAIL	Hydrogen blending in city gas distribution networks	45	216
5	MRPL	Mangalore, Karnataka	5	24
6	NRL	Numaligarh, Assam	9	43
7	ONGC	Mangalore, Karnataka; Gujarat	360	1,724
8	CPCL	Manali, Chennai	5	24
9	NTPC	Multiple locations	650	3,113
10	SECI	Multiple locations	450	2,155
Total			1,931	9,248

IOCL = Indian Oil Corporation Limited, HPCL = Hindustan Petroleum Corporation Limited, BPCL = Bharat Petroleum Corporation Limited, GAIL = Gail India Limited, KTPA = kilo tons per annum, MRPL = Mangalore Refinery and Petrochemicals Ltd, NRL = Numaligarh Refinery Limited, ONGC = Oil and Natural Gas Corporation, CPCL= Chennai Petroleum Corporation Limited, NTPC = National Thermal Power Corporation, SECI = Solar Energy Corporation of India Limited.

Sources: Various sources referred to in Table 4.

Table 7: Private Sector Investment Plans

No.	Company	Description (Project Site)	Estimated Production Capacity 2030 (KTPA)	Approx. Funding (\$ Million)
1	Adani New Industries Limited	Locations to be finalized	1,000 (green hydrogen)	4,789
2	ACME Solar	Tamil Nadu, Karnataka and Odisha	660 ^a (green hydrogen) and 2,960 ^a (green ammonia)	5,670
3	Hygenco India	Across India	Not available	2,500 ^b
4	Avaada Group	Gopalpur, Odisha	500 (green hydrogen)	2,395
5	AM Green Ammonia BV	Kakinada, Andhra Pradesh	1,000 (green ammonia)	848
6	ReNew Power	Kerela	220 (green hydrogen) and 1,100 (green ammonia)	1,986
7	Ocior Energy	Kutch, Gujarat	1,000 (green hydrogen)	4,789
8	ABC Cleantech	Karnataka	200 (green hydrogen) and 1,000 (green ammonia)	1,805
Total			8,640	24,782

KTPA = kilo tons per annum.

^a Assumes that the proportion between green hydrogen and green ammonia in Karnataka and Odisha follows the same ratio as in Tamil Nadu.^b Assumes that since the capacity size is unknown, the company's announced investment size has been captured.

Sources: Various sources as illustrated in Table 5.

6. FINANCIAL AND ECONOMIC ASSESSMENT

As the hydrogen market continues to grow, there are several key factors that determine the financial and economic viability of green hydrogen projects. The cost of green hydrogen production can vary significantly across various geographies due to different plant yields of renewable power plants, logistics, financing costs, and market demand. The financial and economic assessments were conducted for the sample green hydrogen project for refineries in the context of India based on the current estimated market price and solar and wind energy plant yields. The analysis assumed that the green hydrogen produced from the sample project will be used in refineries to replace gray hydrogen.

Table 8: Key Features of Sample Green Hydrogen Project

Particulars	Value
Plant size of green hydrogen	7.58 tons per day
Electrolyzer capacity	25 MW
Electricity generated from solar	40 MWh
Electricity generated from wind	30 MWh
Total project cost in financial price	₹6,543 million

MW = megawatts, MWh = megawatt-hour, ₹ = Indian rupee.

Source: Asian Development Bank estimate.

6.1 Financial Analysis

Methodology. The financial analysis of the green hydrogen project in India was carried out in accordance with Asian Development Bank (ADB) guidelines (ADB 2005). The project's financial viability was assessed by comparing the incremental costs and revenues in scenarios with and without the project. A discounted cash flow analysis was conducted to calculate key indicators: the weighted average cost of capital (WACC), the financial internal rate of return (FIRR), and financial net present value (FNPV). A financial analysis ascertained whether the FIRR can be above the calculated WACC to assess the financial viability. Additionally, the levelized cost of hydrogen (LCOH) was calculated to evaluate the cost of producing and delivering hydrogen over the project's entire lifespan. LCOH is a variable that indicates how much it costs to produce 1 kg of green hydrogen, taking into account the estimated capital costs and operating costs involved in its production.

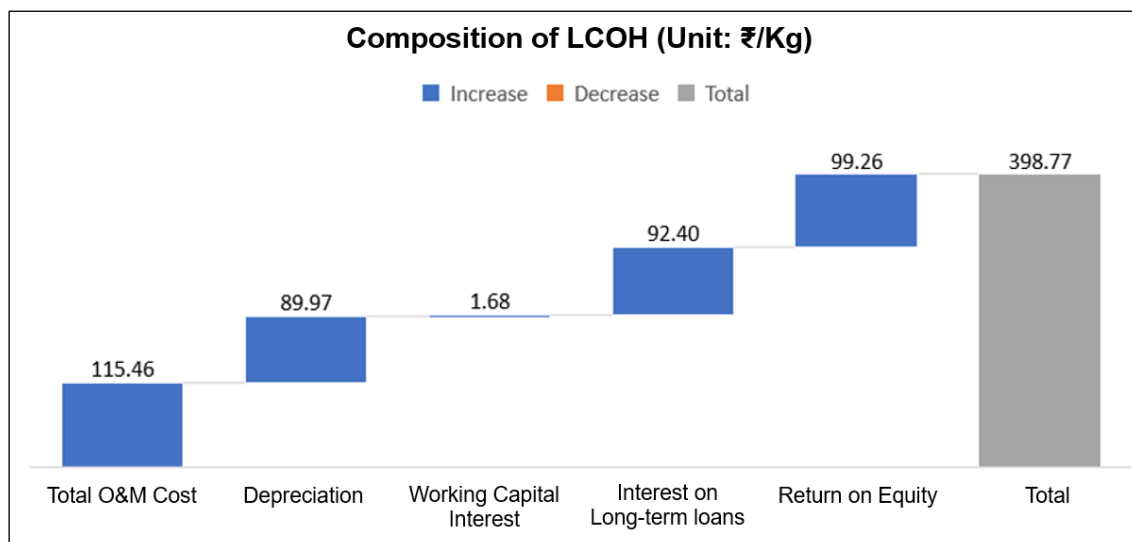
Assumptions. A financial cost-benefit analysis was conducted for the sample green hydrogen project with the following assumptions. Details are included in Annexure 2.

- (i) All costs and revenues are expressed and converted at \$1=₹83 (approximately).
- (ii) The analysis was conducted from 2024 to 2045, including a two-year construction period, and the hydrogen plant was assumed to have 20 years of operation upon completion.
- (iii) The capacity utilization factor of 67% for an electrolyzer was used throughout the project life.
- (iv) The residual value of assets was estimated at 5% of the total equipment cost, to be realized at the end of the final year of operations, and depreciation was calculated on a straight-line basis based on India's accounting and tax regulations.
- (v) The corporate income tax rate is currently 17.16% and it was assumed it would remain unchanged over the life of the project.

Furthermore, the analysis includes operating expenditures, with approximately 90% attributed to the electricity costs required for water electrolysis in the production of green hydrogen. The electricity used for electrolysis is supplied by a combination of solar energy and wind energy (with a ratio of 40 to 30 between solar and wind power sources). Hydrogen generation is achieved using an alkaline electrolyzer with a capacity of 25 MW. The capital expenditure is divided into two components: \$700 per kilowatt-hour (kWh) for the electrolyzer and \$50 per kWh for cooling and water treatment facilities. Additionally, the capital cost includes ₹4,250 million for constructing the solar and wind renewable energy facilities. The electrolyzer is expected to consume 53 kWh per kilogram (kg) of hydrogen produced. The water requirement for hydrogen production is estimated to be 10–15 liters per kg, considering a demineralized water supply. Depreciation and tax rates were applied according to Indian companies' standards and the Income Tax Act in India. The analysis used a sales price estimate of hydrogen in line with the IRENA estimate (IRENA 2021), which projects a year-on-year reduction due to advancements in technology. The financial analysis assumes a hydrogen production cost of approximately \$4.7 per kg in 2026, with market prices expected to decline to approximately \$3.95 per kg by 2045, based on conservative assumptions about cost reductions in renewable energy and electrolyzers.

Levelized cost of hydrogen. The cost-competitiveness of green hydrogen depends on several factors, including wind and solar potentials, renewable energy generation costs, electrolyzer costs, connection facilities, costs of hydrogen transportation to consumption sites, operation and maintenance costs, and the cost of water used in production. LCOH consists of the investment costs for electrolyzer and renewable energy facilities, as well as operational and financing costs. For the green hydrogen project sample in India, the LCOH is estimated to be approximately ₹399 per kg (equivalent to \$ 4.8 per kg) based on the market price in India. The costs are broken down into total operations and maintenance (O&M) costs (29%), depreciation on assets (23%), interest on long-term loans and working capital interest (23%), and return on equity (25%). The current production cost of green hydrogen in India is slightly higher than that of gray hydrogen produced from fossil fuels. Gray hydrogen costs range from ₹160 to 200 per kg, based on an input cost of natural gas of between \$10 and \$13 per MMBTU (million British thermal units).

Figure 7: Levelized Cost of Green Hydrogen for the Sample Project



LCOH = levelized cost of hydrogen, O&M = operations and maintenance.

Source: Asian Development Bank estimate.

Financing costs. Financing costs represent approximately 24% of the LCOH in India, highlighting the importance of reducing financing costs to enhance the financial viability of the green hydrogen project. Financing costs include interest on long-term loans and working capital interest. The return on equity (ROE) is assumed to be 14%. Without accounting for inflation, the weighted average cost of capital is calculated at 10.58%, based on 9% interest on long-term loans, a 2% risk premium, and a debt-to-equity ratio of 70:30, against 14% of ROE. Similarly, a weighted average cost of capital of 8.84% is estimated if concessional lending is applied, with a 6% interest rate on long-term loans.

Table 9: Weighted Average Cost of Capital

Item	Commercial Terms		Concessional Terms	
	Loan	Equity	Loan	Equity
A. Weighting (%)	70.0	30.0	70.0	30.0
B. Nominal cost (%)	11.0	14.0	8.0	14.0
C. Tax rate (%)	17.0	—	17.16	—
D. Tax-adjusted nominal cost [B*(1-C)]	9.11	14.0	6.63	14.0
E. Weighted component of WACC	6.38	4.20	4.64	4.20
WACC	10.58%		8.84%	

Source: Asian Development Bank estimate.

Financial results. The results are summarized in Table 10. The FIRR is calculated at 9.51%, which is below the WACC of 10.58% with commercial terms and slightly above the WACC of 8.84% with concessional terms. The results show that the green hydrogen project can be financially viable with a low cost of funding.

Table 10: Financial Results

Particulars	Units	Value
Plant Size (green hydrogen)	TPD	7.58
Total Project Cost	₹ million	6,543
Project IRR	%	9.51%
LCOH	₹ per KgH ₂ (\$/KgH ₂)	399 (4.8)

₹ = Indian rupee, IRR = internal rate of return, LCOH = levelized cost of hydrogen, TPD = ton per day.

Source: Asian Development Bank estimate.

Sensitivity analysis. A sensitivity analysis was carried out to examine the robustness of the FIRR to adverse changes in the values of key variables; the results are summarized in Table 11.

Table 11: Sensitivity of Financial Internal Rate of Return to Adverse Changes in Key Input Parameters

Input Parameter	Variation	FIRR	Baseline Value	Switching Value
Base case		9.51%	9.51%	—
1 Sales price of hydrogen (decreased) ¹	(10%)	7.69%	₹391 per Kg	₹352 per Kg
2 Capital cost for electrolyzer and others (increased)	10%	9.43%	₹1,400 million	₹1,540 million
3 Capital cost for renewable energy (increased)	10%	9.27%	₹4,250 million	₹4,675 million
4 Operation cost (increased)	10%	9.03%	₹6,833 million	₹7,516 million

() = negative, FIRR = financial internal rate of return, ₹ = Indian rupee.

Source: Asian Development Bank estimate.

6.2 Economic Analysis

Methodology. The economic analysis of the sample green hydrogen project in India was conducted in accordance with Asian Development Bank (ADB) guidelines (ADB 2017). The economic costs and benefits are based on constant prices for 25 production years, from 2026 until 2050. The economic internal rate of return (EIRR) was calculated by comparing the “without-project” scenarios where this project is compared with the existing gray hydrogen production. All financial prices were converted into

economic prices by applying the corresponding conversion factors in accordance with the ADB guidelines.

Assumptions. The green hydrogen plant's production capacity is fixed and operates at full efficiency throughout the project's lifespan. The construction period for the project investment is assumed to be two years, and the benefits were assumed to be realized over the 25 commercial years of the project in the future. The carbon dioxide (CO₂) value was calculated based on \$54.1 per ton and increased by 2% annually in real terms, and the fuel emission factor (imported coal) was taken from the Intergovernmental Panel on Climate Change (IPCC). The depletion premium for coal and water consumption is 10% and 5%, respectively.

Benefits. The project has economic benefits from (i) the avoided fuel costs, (ii) the associated GHG emission reduction, and (iii) the reduction of water consumption. Economic benefits include avoided fuel costs and environmental benefits from a GHG emission reduction and from a fuel and water consumption reduction compared to gray hydrogen. The green hydrogen plant is considered to displace gray hydrogen, for which electricity is utilized from the thermal power plant, which uses coal as the raw material. The calculation for a reduction in fuel cost takes into consideration the quantum of coal requirement for producing electricity, which is 2,162.79 kWh per ton. The value is calculated based on the efficiency of electricity generation from coal usage. The depletion premium for the coal is considered to be 10% on a year-over-year basis (Steel Orbis 2023). The import parity price of coal was estimated to calculate the avoided fuel cost. To quantify the greenhouse gas emissions (GHG), the carbon emission factor of the Indian electricity grid of 0.715 tCO₂/MWh was used (CEA 2023b). CO₂ emissions during operation were estimated to be 65,916.38 tons per year. The reduction of water consumption was quantified when shifting to green from gray hydrogen produced in thermal-powered plants. This saving in the quantity of water is then multiplied by the existing economic rate of water. A depletion premium of 5% is charged on a yearly basis over this economic rate over the project's tenure.

Table 12: Benefits and Its Economic Net Present Value

Benefits	ENPV (₹ million)
Avoided Fuel Cost	2,771.00
Reduction in GHG Emission	726.48
Reduction in Water Cost	72.51
Total	3,570.00

ENPV = economic net present value, GHG = greenhouse gas emission.

Source: Asian Development Bank estimate.

Results. The evaluation indicates that the project is economically viable with the calculated EIRR value with an economic discount rate of 9%. The EIRR and ENPV of the project are 12.02% and ₹2,077.01 million with GHG emission benefit and 11.12% and ₹6,078.70 million without GHG emission benefit.

Sensitivity analysis. To examine the robustness of the calculated EIRR, sensitivity analyses were conducted for adverse changes in four inputs to the EIRR for the project; they indicated that the project is robust against adverse changes. The results are summarized in Table 14 below. The economic analysis suggests that the project would satisfy the minimum required EIRR of 9.0%, and that the result is robust against adverse changes in key input parameters to the analysis.

Table 13: Results of Economic Internal Rate of Return

Particulars	EIRR	ENPV
Baseline EIRR	12.02%	₹2,077.01
EIRR without GHG emission reduction benefit (a)	11.12%	N/A
EIRR without water consumption reduction benefit (b)	11.71%	₹1,851.80
EIRR without environmental benefit for both (a) and (b)	8.17%	N/A

N/A = not applicable, EIRR = economic internal rate of return, ENPV = economic net present value, GHG = greenhouse gas emission.

Source: Asian Development Bank estimate.

Table 14: Sensitivity of Economic Internal Rate of Return to Adverse Changes in Key Input Parameters

Sr. No.	Sensitivity Analysis	Variation	EIRR	Baseline Value	Switching Value
1	Baseline		12.02%	—	—
2	Changes in Operational Cost	10%	11.50%	1	2.7
3	Change in Capital Cost	10%	11.10%	1	3.4
4	Change in Capacity	10%	10.47%	2.768MnKgs	1.135MnKgs
5	Depletion Premium	5%	11.53%	10%	–3%

6.3 Consideration from Financial and Economic Analyses

Given the capital-intensive nature of the green hydrogen project, significant financing is required, which can impact the financial viability of the project. The financial analysis showcases the importance of financing mechanisms to make green hydrogen projects financially more competitive and attract investments. The economic analysis demonstrates that the green hydrogen project meets the minimum required EIRR of 9.0% for the ADB infrastructure project, deeming it economically viable. However, investment support from the government—such as public financing, guaranteed pricing, and operational support—is essential to enhance the project's financial viability and facilitate implementation. Unlocking the decarbonization potential of green hydrogen requires robust policies and regulatory actions to create a market and improve financing conditions. Early adoption of this technology depends on both creating demand for green hydrogen and closing the cost gap between it and conventional fossil fuels.

To achieve the government's target of producing 5 million metric tons per annum of green hydrogen by 2030, India needs to implement robust policy incentives to encourage private sector investments and establish a supportive regulatory framework for developing a green hydrogen ecosystem. These measures will not only help close the cost gap but also accelerate the country's transition to a cleaner and more sustainable energy future. While the government can provide initial financial assistance and establish the regulatory framework, private sector finance will be indispensable in scaling up the green hydrogen projects. Despite the availability of various financing instruments with a proven track record in renewable energy technology, innovative financing mechanisms are necessary to overcome the uncertainties surrounding green hydrogen demand. Furthermore, it is required to consider providing adequate financial support for associated facilities, including renewable energy power generation plants and transport infrastructure for green hydrogen and green ammonia, such as pipelines and vessels. Successfully transitioning to green hydrogen requires an immense financing volume that draws from a wide array of sources. While governments play a

crucial early-stage role, a combination of public and private finance can provide unique benefits, as demonstrated in the success of renewable energy technologies.

7. POLICY RECOMMENDATION

India has set ambitious targets for deploying green hydrogen, yet several challenges must be addressed to meet the National Green Hydrogen Mission's objective of establishing India as an export hub for green hydrogen and its derivatives. It is anticipated that these challenges will be mitigated through more effective public-private partnerships, with the government spearheading various policies and schemes under the National Green Hydrogen Mission. Assessing the policy targets and initiatives adopted by global economies has identified several key gaps and challenges, which suggest that immediate policy actions should be taken by India. These recommendations aim to create an enabling environment conducive to the growth and adoption of green hydrogen technologies across diverse sectors in India.

(i) Bridging Technological Gaps

- **Investment Support.** Create dedicated funds to drive R&D, focusing on the advancement of electrolysis technologies, storage systems, and critical components essential for the hydrogen value chain. Encourage private investment by offering subsidies or tax incentives for early adopters.
- **International Collaboration.** Form strategic alliances and partnerships with developed nations to access vital green hydrogen production technologies and expertise. Facilitate technology transfer and joint R&D initiatives to expedite India's technological capabilities.

(ii) Policy Refinement and Adoption

- **Sectoral Mandates.** Introduce clear mandates and targets for hard-to-decarbonize sectors like cement, iron, steel, and transportation to gradually shift to green hydrogen. Start with blending strategies before full-scale adoption, ensuring compatibility with existing systems while adhering to emission reduction norms.
- **Policy Adaptation.** Conduct a thorough policy review to address bottlenecks hindering the accelerated adoption of green hydrogen. Resolve ambiguities in offtake models, banking provisions, and energy banking charges. Establish robust financing mechanisms and reduce dependencies on global supply chains.

(iii) Transitioning R&D into Practical Use

- **Deployment Funding.** Redirect substantial government funding towards large-scale deployment and commercialization of hydrogen technologies. Create conducive environments for public-private partnerships to expedite technology transfer from research to practical applications.
- **Global Knowledge Exchange.** Foster collaborations with global counterparts to expedite R&D, focusing on crucial aspects across the hydrogen value chain. Emphasize knowledge transfer and joint research ventures with an international consortium of experts.

(iv) **Economic Viability and Cost Management**

- **Policy Intervention.** Explore the implementation of carbon pricing mechanisms, such as carbon taxes and emissions trading, to bridge the cost gap between green hydrogen and conventional fuels. Develop contractual frameworks to procure green hydrogen technologies at competitive rates, ensuring a level playing field.
- **Strategic R&D Investments.** Direct substantial investments into R&D efforts to enhance the cost-competitiveness of green hydrogen production. Support initiatives for breakthrough technologies that reduce production costs while improving efficiency.

(v) **Standardization and Certification**

- **Regulatory Development.** Establish a centralized regulatory authority focused on setting industry standards for safety, product protocols, and best practices across the hydrogen value chain. Facilitate harmonization of national standards with global benchmarks, fostering interoperability and facilitating trade.
- **Certification Framework.** Create a comprehensive certification system for green hydrogen, including rigorous criteria for its production, distribution, and utilization. Implement a robust certification process and develop a dedicated registry for green hydrogen and related products.

(vi) **Funding and Infrastructure Enhancement**

- **Financial Support.** Incentivize private investments through subsidies, tax breaks, or concessional loans to drive the commercial deployment of green hydrogen. Leverage public-private partnerships to fund infrastructure development and widespread adoption across sectors.
- **Infrastructure Development.** Invest in an extensive network of hydrogen dispensing units, storage facilities, and transportation infrastructure through public-private partnership models. Develop comprehensive strategies to scale up storage and transportation capabilities, ensuring seamless integration of green hydrogen in the energy landscape.

(vii) **Unified R&D Platform**

- **Integrated Knowledge Sharing.** Establish a centralized platform to collate and disseminate information among R&D entities working on hydrogen production, storage, transportation, and utilization. Create a repository of ongoing projects and initiatives, fostering stakeholder collaboration and synergies.

(viii) **Enabling Holistic Ecosystem**

- **Diverse Funding Scope.** Extend the scope of funding programs to encompass various hydrogen carriers, supporting broader technological applications beyond electrolysis. Encourage cross-disciplinary initiatives and innovation in green hydrogen technologies.
- **Stimulating Demand.** Offer regulatory and financial incentives to transition existing fossil-based assets to renewables, reducing emissions and supporting retrofitting. Develop policies that incentivize the uptake of green hydrogen in various industries, aligning with emission reduction goals.

- **Low-Cost Financing.** Establish dedicated credit lines and concessional funding avenues to accelerate the adoption of green hydrogen technologies across sectors. Facilitate easy access to low-cost financing options for hydrogen-related projects.
- **Policy Coordination.** Ensure harmonized policy actions by fostering coordination among stakeholders involved in the green hydrogen value chain. Facilitate cohesive policy development and implementation, promoting a supportive and unified ecosystem for green hydrogen initiatives.

Green hydrogen can play a significant role in India's energy transition by enhancing its industrial competitiveness, thus contributing to achieving India's net-zero goal by 2070. Major countries worldwide are investing in hydrogen-based technologies, and India is actively positioning itself to lead the low-carbon hydrogen transition. Policymakers and industry stakeholders are committed to implementing subsequent phases of development effectively in this journey. In particular, the Government of India and its associated ministries are pivotal in fostering a green hydrogen economy, having initiated several measures to boost green hydrogen production. The landmark Green Hydrogen Policy of 2022, the subsequent National Green Hydrogen Mission of 2023, and dedicated funding mark critical steps toward facilitating widespread adoption. However, challenges persist in both implementing these measures and identifying the need for additional ones. Green hydrogen could play a key role in decarbonizing various sectors, including hard-to-abate ones.

India is favorably positioned to develop a hydrogen economy, given its substantial demand, extensive renewable energy potential, and low renewable energy tariffs. Anticipated decreasing costs of green hydrogen over time suggest a potential surge in demand within India. As green hydrogen costs decrease due to advancements in electrolyzer technology and high-scale manufacturing, it will become more competitive with existing fuel options and technologies. Addressing challenges across the green hydrogen value chain is crucial for facilitating this transition. The production cost of green hydrogen significantly exceeds that of fossil fuel-based alternatives. Clarity in regulations and standards, alongside overcoming financing hurdles, remains imperative.

Enabling a green hydrogen economy in India necessitates coordinated efforts by policymakers, financial institutions, and industry players. A unified policy approach to developing the green hydrogen ecosystem, fostering collaboration among relevant stakeholders, and aligning existing policies will propel India toward a green hydrogen economy. Crucially, financing green hydrogen production projects through concessional funding is pivotal for this transition. Such funding would mitigate risks for industry players venturing into green hydrogen production. Moreover, dedicated funding for domestic pilot projects can bolster investor and lender confidence.

India holds tremendous potential to emerge as a leading nation in the global hydrogen energy ecosystem and become a hub for green hydrogen manufacturing. Achieving this status will require robust policy support, industry collaboration, and fostering market acceptance of green hydrogen.

REFERENCES

- Avaada Group. 2024. Role of Green Hydrogen Used in the Fertilizer Industry. <https://avaada.com/role-of-green-hydrogen-used-in-the-fertilizer-industry/#:~:text=Avaada%20Group%20has%20launched%20a%20significant> (accessed 17 October 2024).
- ACME. 2023. *India Projects – Rajasthan, Tamil Nadu, Karnataka, and Odsha*. <https://www.acme-ghc.com/india-green-hydrogen-project/rajasthan> (accessed 20 December 2023).
- . 2024. *Global Energy Transition – Trillion Dollar Opportunity, Advanced Stem Towards Sustainability*. <https://www.acme.in/about-us#:~:text=With%20innovation%20being%20the%20forte%20of%20ACME%20Group%2C,in%20sa ving%20approx.%204400%20tons%2Fannum%20of%20CO2%20emissions..in> (accessed 30 September 2024).
- Adani. 2022. *Adani and TotalEnergies to Create the World's Largest Green Hydrogen Ecosystem*. <https://www.adani.com/en/Newsroom/Media-Release/Adani-and-TotalEnergies-to-create-the-worlds-largest-green-hydrogen-ecosystem> (accessed 30 September 2024).
- . 2024. *Adani New Industries Limited Green Hydrogen Ecosystem*. <https://www.adanienterprises.com/-/media/Project/Enterprises/Investors/Investor-Downloads/Investors-Presentation/ANIL-Investor-Presentation---June-2024.pdf> (accessed 30 September 2024).
- ADB. 2005. *Financial Management and Analysis of Projects*. Manila.
- . 2019. *Technical Guidance Note on Financial Analysis and Evaluation*. Manila.
- . 2017. *Guidelines for the Economic Analysis of Projects*. Manila. <https://www.adb.org/sites/default/files/institutional-document/32256/economic-analysis-projects.pdf>.
- Automotive Research Association of India (ARAI). 2020. *Inauguration of Centre of Excellence for Green Mobility, ARAI*. Pune. https://cms.araiindia.com/MediaFiles/CoE_Greener_Mobility_1480.pdf (accessed 16 December 2023).
- Baruah, B. 2022a. *ReNew Power plans ₹1 Trillion Investment in Maharashtra, Karnataka* Mint (26 May 2022). <https://www.livemint.com/companies/news/renew-power-plans-rs-1-trillion-investment-in-maharashtra-karnataka-11653459574347.html> (accessed 20 December 2023).
- . 2022b. *NTPC to Blend Green Hydrogen in PNG Network of Gujarat* Gas Mint (5 April 2022). <https://www.livemint.com/industry/energy/ntpc-to-blend-green-hydrogen-in-png-network-of-gujarat-gas-11649170992115.html> (accessed 30 September 2024).
- . 2024. *AM Green Ties Up with RWE, to Start Supplying Green Ammonia by 2027*. Mint (19 September 2022). <https://www.livemint.com/companies/news/am-green-rwe-greenko-group-green-ammonia-green-hydrogen-clean-energy-oecd-avaada-group-mysore-ammonia-11726719788758.html> (accessed 17 October 2024).

- Borden, K. 2022. *Plug Provides 10 MW Unit to Produce Green Hydrogen*. KHI (28 April 2022). [Plug provides 10 MW unit to produce green hydrogen - CompressorTECH² \(compressortech2.com\)](https://compressortech2.com) (accessed 6 January 2024).
- Businessline. 2021. *GAIL to Procure 10 MW Hydrogen Electrolyzer Soon*. Businessline (14 December 2021). <https://www.thehindubusinessline.com/companies/gail-to-procure-10-mw-hydrogen-electrolyzer-soon/article37952856.ece> (accessed 6 January 2024).
- CARE Rating Limited. 2019. *CARE Rating: Nickel Industry*. Mumbai. <https://www.careratings.com/upload/NewsFiles/Studies/Nickel%20Industry.pdf> (accessed 16 December 2023).
- Central Electricity Authority (CEA). Government of India. 2023a. *Installed Capacity Report*. New Delhi. <https://cea.nic.in/installed-capacity-report/?lang=en> (accessed 20 December 2023).
- . Government of India. 2023b. *CO2 Baseline Database for the Indian Power Sector User Guide Version 19.0*. https://cea.nic.in/wp-content/uploads/baseline/2024/04/User_Guide_Version_19.0.pdf.
- Christensen A. 2020. *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*. https://theicct.org/wp-content/uploads/2021/06/final_icct2020_assessment_of_hydrogen_production_costs-v2.pdf (accessed 20 December 2023).
- Eckert, V. 2021. *Shell Opens 10 MW German Hydrogen Electrolyzer to Boost Green Fuel Output*. Reuters (3 July 2021). <https://www.reuters.com/business/energy/shell-opens-10-mw-german-hydrogen-electrolyser-boost-green-fuel-output-2021-07-02/> (accessed 6 January 2024).
- Energy Institute. 2023. *Statistical Review of World Energy 2023*. London. https://www.energyinst.org/__data/assets/pdf_file/0004/1055542/EI_Stat_Review_PDF_single_3.pdf.
- Energy Transitions Commission (ETC). 2021. *Making the Hydrogen Economy Possible – Accelerating Clean Hydrogen in an Electrified Economy*. <https://www.energy-transitions.org/publications/making-clean-hydrogen-possible/>.
- ET Energyworld. 2023a. *Indian Oil to Convert 50 Per Cent of Its Refineries' Hydrogen Use to Green by 2050, Says Dir - R&D SSV Ramakumar*. ET Energyworld (3 Jul 2023). <https://energy.economictimes.indiatimes.com/news/renewable/indian-oil-to-convert-50-per-cent-of-its-refineries-hydrogen-use-to-green-by-2050-says-dir-rd-ssv-ramakumar/101408808> (accessed 30 September 2024).
- . 2023b. *Govt Floats Tender to Set Up 4.5 Lakh Tonne Green Hydrogen Production Facility in India*. <https://energy.economictimes.indiatimes.com/news/renewable/govt-floats-tender-to-set-up-4-5-lakh-tonne-green-hydrogen-production-facility-in-india/101681694> (accessed 30 September 2024).
- . 2024. *Hygenco to Invest \$2.5 bn Over 3 Years to Set Up Green Hydrogen Projects in India*. <https://energy.economictimes.indiatimes.com/news/renewable/hygenco-to-invest-2-5-bn-over-3-years-to-set-up-green-hydrogen-projects-in-india/107295764> (accessed 30 September 2024).

- ETN. 2024. *ACME, Greenko, Reliance, BPCL Among SECI's Green H2 Production Tender Winners*. ETN (3 January 2024). <https://etn.news/buzz/seci-green-hydrogen-tender-bid-winners-india-sight-scheme#:~:text=It%20is%20to%20be%20noted,and%20green%20hydrogen%20in%20the> (accessed 6 January 2024).
- Government of India, Ministry of New and Renewable Energy. 2021b. *India Set to Achieve 450 GW Renewable Energy Installed Capacity by 2030: Ministry of New and Renewable Energy (MNRE)*. New Delhi. https://dst.gov.in/sites/default/files/AHFC%202021%20-%20List%20of%20DST%20Funded%20Projects_0.pdf (accessed 20 December 2023).
- . 2023a. *3-Day International Conference on Green Hydrogen Begins in New Delhi*. <https://pib.gov.in/PressReleaseframePage.aspx?PRID=1937584> (accessed 6 December 2023).
- . 2023b. *National Hydrogen Mission Decarbonising India, Achieving Net-Zero Vision*. New Delhi. <https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/jan/doc2023110150801.pdf> (accessed 16 December 2023).
- . 2024. *Government enhances allocation for Fertilizer Sector under SIGHT Programme of the National Green Hydrogen Mission (NGHM)*. <https://pib.gov.in/PressReleaseframePage.aspx?PRID=2027858> (accessed 25 December 2024).
- Government of India, Ministry of Science and Technology. 2022c. *LOK SABHA UNSTARRED QUESTION No. 1212 TO BE ANSWERED ON 09.02.2022*. New Delhi. <https://sansad.in/getFile/loksabhaquestions/annex/178/AU1212.pdf?source=pqals> (accessed 10 November 2024).
- Government of India, Ministry of Petroleum and Natural Gas. 2020a. *Providing Clean and Reliable Energy Supplies to Meet the Requirements is the Top Most Priority of the Government, Says Shri Dharmendra Pradhan*. New Delhi. <https://pib.gov.in/PressReleaseframePage.aspx?PRID=1666180> (accessed 16 December 2023).
- . 2023c. *Hydrogen Mission: Hydrogen Initiatives of the Ministry of Petroleum & Natural Gas*. New Delhi. <https://mopng.gov.in/en/page/12> (accessed 16 December 2023).
- . 2023d. *Hydrogen Times*. New Delhi. <https://mopng.gov.in/files/article/articlefiles/2023Q2.pdf> (accessed 20 December 2023).
- Government of India, Ministry of Power. 2022a. *Ministry of Power Notifies Green Hydrogen/Green Ammonia Policy*. New Delhi. <https://pib.gov.in/PressReleasePage.aspx?PRID=1799067> (accessed 16 December 2023).
- Government of India, Ministry of Road Transport and Highways. 2020b. *Notification Allowing Use of H-CNG Issued*. New Delhi. <https://pib.gov.in/PressReleasePage.aspx?PRID=1659706> (accessed 16 December 2023).
- Government of India, Ministry of Science and Technology, Department of Science and Technology (DST). 2020c. *India Country Status Report on Hydrogen and Fuel Cells*. New Delhi. <https://dst.gov.in/sites/default/files/Country%20status%20report%20final%20Hydrogen.pdf> (accessed 16 December 2023).
- Government of India, Ministry of Science and Technology, DST. 2021a. *No. DST/TMD-EWO/AHFC-2021*. New Delhi. <https://pib.gov.in/PressReleasePage.aspx?PRID=1762960> (accessed 16 December 2023).

- Government of India, NITI Aayog. 2022b. *Harnessing Green Hydrogen – Opportunities for Deep Decarbonization in India*. New Delhi. https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf (accessed 30 September 2023).
- Gupta, U. 2022. *Hygenco, Jindal Stainless Sign India's First Long-term Green Hydrogen Offtake Deal*. <https://www.pv-magazine.com/2022/08/17/hygenco-jindal-stainless-sign-indias-first-long-term-green-hydrogen-offtake-deal/> (accessed 20 December 2023).
- Gupta U. 2024. *The Hydrogen Stream: ACME, Avaada Begin Work on Green Hydrogen and Ammonia Projects in the Indian State of Odisha*. PV Magazine (14 Feb 2024). <https://www.pv-magazine-india.com/2024/02/14/acme-avaada-begin-work-on-green-hydrogen-and-ammonia-projects-in-odisha/> (accessed 30 September 2024).
- Hall, W., T. Spencer, G. Renjith, and S. Dayal. 2020. *The Potential Role of Hydrogen in India: A Pathway for Scaling-up Low Carbon Hydrogen Across the Economy*. New Delhi: The Energy and Resources Institute (TERI).
- Hazarika, G. 2023. *Ocior Energy to Invest ₹400 Billion in Green Hydrogen Facilities in Gujarat*. MERCOM (28 Feb 2023). <https://www.mercomindia.com/ocior-energy-%E2%82%B9400-billion-in-green-hydrogen-gujarat> (accessed 20 December 2023).
- Indian Oil Corporation Limited (IOCL). 2020. *News Release Details: Shri Dharmendra Pradhan, Hon'ble Minister-MoP&NG and Steel, Inaugurates H-CNG Plant and Launches Rials in Delhi*. New Delhi. <https://iocl.com/NewsDetails/58744> (accessed 20 December 2023).
- International Energy Agency (IEA). 2019. *The Future of Hydrogen Report Prepared by the IEA for the G20, Japan Seizing Today's Opportunities*. Paris. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf.
- . 2021a. *India Energy Outlook 2021*. Paris. <https://www.iea.org/reports/india-energy-outlook-2021>.
- . 2021b. *Global Hydrogen Review 2021*. Paris. <https://iea.blob.core.windows.net/assets/e57fd1ee-aac7-494d-a351-f2a4024909b4/GlobalHydrogenReview2021.pdf>.
- . 2022. *Global Hydrogen Review 2022*. Paris. <https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf>.
- International Renewable Energy Agency (IRENA). 2020. *Green Hydrogen Cost Reduction: Scaling Up Electrolyzers to Meet the 1.5°C Climate Goal*. Abu Dhabi.
- . 2021. *Making the Breakthrough. Green Hydrogen Policies and Technology Costs*. Abu Dhabi.
- . 2022. *Global Hydrogen Trade to Meet the 1.5°C Climate Goal*. Abu Dhabi.
- Jana, A. 2022. *NTPC to Build India's Largest Solar Park of 4.75 GW in Rann of Kutch*. Scholar Lab Foundation (15 September 2022). <https://www.scholarlabfoundation.tech/tech/energy.php> (accessed 30 December 2024).

- Money Control. 2023. *NTPC Starts Trial Run of Hydrogen Bus in Leh* Money Control (18 August 2023). <https://www.moneycontrol.com/news/automobile/ntpc-starts-trial-run-of-hydrogen-bus-in-leh-11220261.html#:~:text=State-owned%20power%20giant%20NTPC%20has%20started%20a%20trial,intracity%20routes%20of%20Leh%2C%20a%20company%20statement%20said> (accessed 30 September 2024).
- National Thermal Power Corporation Limited (NTPC). 2022. *NTPC: ESG Progress*. New Delhi. <https://www.ntpc.co.in/sites/default/files/esg/NTPC-ESG-Presentation-10-08-2022.pdf> (accessed 20 December 2023).
- NITI Aayog and RMI. 2022. *Harnessing Green Hydrogen*. New Delhi. https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf.
- Noussan, M., P. P. Raimondi, R. Scita, M. Hafner. 2021. The Role of Green and Blue Hydrogen in the Energy Transition: A Technological and Geopolitical Perspective. *Sustainability*.
- Ohmium. 2024. *Company News: Hero Future Energies and Ohmium International Announce Strategic Partnership for 1000 MW of Green Hydrogen*. [Hero Future Energies and Ohmium International announce strategic partnership for 1000 MW of Green Hydrogen | Ohmium](https://www.ohmium.com/news/hero-future-energies-and-ohmium-international-announce-strategic-partnership-for-1000-mw-of-green-hydrogen) (accessed 20 December 2023).
- Oil and Industry Development Board (OIDB). 2016. *Hydrogen Corpus Fund*. New Delhi. <https://oidb.gov.in/index1.aspx?langid=1&lev=4&lsid=403&pid=36&lid=350> (accessed 16 December 2023).
- Oil and Natural Gas Corporation Limited (ONGC) 2022. *ONGC to Make Green Hydrogen; Inks MoU with India's Leading Renewable Energy Company Greenko ZeroC*. New Delhi. <https://ongcindia.com/web/hi/w/ongc-to-make-green-hydrogen-inks-mou-with-india-s-leading-renewable-energy-company-greenko-zeroc#:~:text=This%20MoU%20is%20in%20line,hydrogen%20per%20annum%20by%202030> (accessed 30 September 2024).
- Ramesh, M. *Renewable Energy*. *Greenko to Invest \$6 b Into Pumped Storage, Green Ammonia Business in Next 3 Years*. The Hindu Businessline (14 Feb 2023) (accessed 20 December 2023). <https://www.thehindubusinessline.com/companies/greenko-to-invest-6-b-into-pumped-storage-green-hydrogen-business-in-next-3-years/article66506985.ece>.
- Renewables Now. 2022. *ABC Cleantech to Invest USD 6bn in Indian Green H2, Ammonia Project*. Renewables Now (3 Nov 2022). <https://renewablesnow.com/news/abc-cleantech-to-invest-usd-6bn-in-indian-green-h2-ammonia-project-803518/> (accessed 20 December 2023).
- Renewable Watch. 2022. *BPCL Calls Bids for Building a 5 MW Green Hydrogen Production Facility*. <https://renewablewatch.in/2022/06/23/bpcl-calls-bids-for-building-a-5-mw-green-hydrogen-production-facility/> (accessed 20 December 2023).
- . 2024. *SECI Announces Winners for 1.5 GW Electrolyser Manufacturing Auction*. <https://renewablewatch.in/2024/09/02/seci-announces-winners-for-1-5-gw-electrolyser-manufacturing-auction/> (accessed 30 September 2024).

- Rivarolo M., Riveros-Godoy G., Magistri L., Massardo A., 2019. *Clean Hydrogen and Ammonia Synthesis in Paraguay from the Itaipu 14 GW Hydroelectric Plant*. *ChemEngineering*, 2019, 3(4), 87; <https://doi.org/10.3390/chemengineering3040087>.
- Solar Energy Corporation of India (SECI). 2023. *Result of Tendering for Selection of Developers for 450 MW Solar PV Projects under Part-B (Open) in Maharashtra under JNNSM Ph-II, Batch-III*. New Delhi. <https://www.seci.co.in/upload/static/files/SECI%20MH%20500%20Result%20website%20upload.pdf> (accessed on 20 December 2023).
- Steel Orbis. 2023. *India's BCCL Hikes Domestic Coking Coal Prices by 10% with Immediate Effect*. <https://www.steelorbis.com/steel-prices/steel-prices-market-analyses/scrap-and-raw-materials/indias-bccl-hikes-domestic-coking-coal-prices-by-10-with-immediate-effect-1286427.htm> (accessed 30 September 2024).
- Tata Motors. 2022. *Press Release: Tata Motors Has Been Making Strides in Developing Hydrogen Fuel Cell Technology in India*. Mumbai. [https://www.tatamotors.com/press-releases/tata-motors-has-been-making-strides-in-developing-hydrogen-fuel-cell-technology-in-india/#:~:text=It%20has%20built%20a%20dedicated,Oil%20Corporation%20Limited%20\(IOC\),Oil%20Corporation%20Limited%20\(IOC\)](https://www.tatamotors.com/press-releases/tata-motors-has-been-making-strides-in-developing-hydrogen-fuel-cell-technology-in-india/#:~:text=It%20has%20built%20a%20dedicated,Oil%20Corporation%20Limited%20(IOC),Oil%20Corporation%20Limited%20(IOC)) (accessed 10 November 2024).
- The Economic Times*. 2021. *BPCL Green Hydrogen Unit to be India's Largest*. <https://economictimes.indiatimes.com/industry/renewables/bpcl-green-hydrogen-unit-to-be-indias-largest/articleshow/87878954.cms> (accessed 6 January 2024).
- . 2024. *ReNew mulls Rs 26,400 Core Green Hydrogen Project in Kerala: Report*. <https://economictimes.indiatimes.com/industry/renewables/renew-mulls-rs-26400-crore-green-hydrogen-project-in-kerala-report/articleshow/107221020.cms> (accessed 30 September 2024).
- TotalEnergies. 2022. *India: TotalEnergies and Adani Join Forces to Create a World*. Paris. <https://totalenergies.com/media/news/press-releases/india-totalenergies-and-adani-join-forces-create-world-class-green> (accessed 20 December 2023).

ANNEXURE 1: R&D AND KNOWLEDGE-SHARING INITIATIVES BY INDIA'S PUBLIC AND PRIVATE ENTITIES

No.	Agency/Institution	Details
1	India H2 Alliance (IH2A)	<ul style="list-style-type: none"> Reliance Industries Limited (RIL) formed the India H2 Alliance with Chart Industries. The alliance was later joined by JSW Steel, CSIR-National Chemical Lab (CSIR-NCL), and Scottish Development International (SDI). Additionally, The Energy and Resources Institute (TERI), Council on Energy, Environment and Water (CEEW), and World Resources Institute (WRI) India will collaborate with IH2A. The objective of the alliance is to collaborate with the government to develop a blueprint for commercializing hydrogen technologies and systems. The alliance aims to build net-zero carbon pathways in India. The alliance would work closely with the government in five areas: <ul style="list-style-type: none"> developing a national hydrogen policy and roadmap for 2021–2030 establishment of a national hydrogen task force and mission via a public-private partnership identification of large hydrogen demonstration projects helping create a national India hydrogen fund and creation of capacity covering hydrogen production, storage and distribution, industrial use, and transport IH2A has submitted a six-point agenda to the NITI Aayog and MNRE to create a domestic “Bharat H2” supply chain and build scale hydrogen systems. The submission was on the following lines: <ul style="list-style-type: none"> Constituting a public-private Bharat H2 task force to prepare a milestone-based national hydrogen roadmap and building a hydrogen economy at scale Taping India's potential to create a national electrolyzer installed capacity of 15–20 GW and promote domestic manufacturing through a national electrolyzer manufacturing mission, aligned with the government's Faster Adoption and Manufacturing of (hybrid) Electric Vehicles (FAME) II Scheme Creating a national H2-themed Energy Transition Fund, with cofunding partnerships with sovereign partners, multilateral agencies, clean energy funds, and industry, with the aim of raising \$1 billion by 2030 for deployment towards national hydrogen projects of a certain scale A uniform set of globally harmonized and interoperable Bharat H2 standards for hydrogen storage, transport, and dispensation need to be finalized quickly, so that hydrogen adoption is accelerated across different sectors and use cases India should prioritize pre-feasibility studies of at least ten national Bharat H2 green hydrogen valleys or H2 hubs—large-scale demonstration stage projects with participation from industry consortia, incentives, and offtake agreements guaranteed by the government India should form a Bharat H2 Industrial Group to leverage hydrogen for decarbonization efforts in steel, refineries, fertilizers, and cement industrial clusters, and a separate Bharat H2 Heavy-Duty Freight Transport Group for hydrogen commercialization.

continued on next page

Annexure 1 table continued

No.	Agency/Institution	Details
2	US-India Green Hydrogen Task Force	<ul style="list-style-type: none"> As part of US-India Strategic Clean Energy Partnership (SCEP), the US DOE, —Government of India, and the US-India Strategic Partnership Forum (USISPF) have formed the US-India Green Hydrogen Task Force. The objective is to assess technology status, study innovative policy options, and make recommendations to enable access, affordability, and deployment of critical hydrogen technologies in India.
3	IOCL and Greenstat Green Hydrogen India Pvt. Ltd. (a subsidiary of Greenstat Norway)	<ul style="list-style-type: none"> A Statement of Intent has been signed between two entities to set up a Center of Excellence on hydrogen, including Carbon Capture, Utilization, and Storage (A), and Fuel Cells. The aim is to develop clean energy in cooperation with Indo-Norwegian green hydrogen cluster companies/organizations by facilitating the transfer and sharing of technology, know-how, and experience through the green hydrogen value chain, including hydrogen storage and fuel cells.
4	TERI and Greenstat Green Hydrogen India Pvt. Ltd.	<ul style="list-style-type: none"> Two entities have announced a research partnership to accelerate the deployment of hydrogen technologies in India The MOU covers policy and research activities: <ul style="list-style-type: none"> Collaboration on the establishment of a Norwegian Center of Excellence on green hydrogen in India; and Knowledge sharing to support the development of hydrogen technologies in India.
5	India Energy Storage Alliance (IESA) and Greenstat Green Hydrogen India Pvt. Ltd.	<ul style="list-style-type: none"> An MoU has been signed between two entities to accelerate hydrogen technology development and establish a center of excellence in India. The aim is to support the development of green hydrogen technologies in India.
6	IOCL and IISc, Bengaluru	<ul style="list-style-type: none"> The objective is to generate affordable fuel cell-grade hydrogen. To explore the production of green hydrogen through biomass gasification, IOCL R&D has joined up with IISc, Bengaluru, to develop biomass gasification technology. An MoU has been signed between two entities to develop and demonstrate the production of green hydrogen through biomass gasification technology. The process will help produce hydrogen suitable for fuel cells at an affordable price. The entities will also work together to optimize biomass gasification and hydrogen purification processes.
7	ONGC Energy Center (OEC)	<ul style="list-style-type: none"> The OEC has been undertaking research on the development of thermochemical processes for the generation of hydrogen by splitting water. Development of closed-loop Copper-Chlorine (Cu-Cl) and closed/open-loop Iodine-Sulphur (I-S) cycles has been undertaken as part of research initiatives. The OEC successfully completed the indigenous development of the process as well as the equipment required for Cu-Cl and I-S cycles. The OEC, in association with ICT Mumbai, has also set up a laboratory-scale engineering plant with a 25 LPH capacity. The objective was to develop and demonstrate an indigenous integrated facility for closed-loop operation of the process for hydrogen generation on a laboratory scale.
8	Thermax	<ul style="list-style-type: none"> Thermax is exploring hydrogen generation via a catalytic route from liquid organic compounds such as formic acid, methanol, etc.

continued on next page

Annexure 1 *table continued*

No.	Agency/Institution	Details
9	NMRL, Mumbai	<ul style="list-style-type: none"> • Bio-hydrogen with chemical fuel cells for electricity generation. • Green hydrogen generation by auto thermal reforming. Focus areas of research include PAFC and PEMFC. • Developed and demonstrated 700–1000 W capacity PAFC-based Uninterruptible Power Supply (UPS). • 1.2 kW PAFC system integrated in an electric vehicle developed under the Defence Research and Development Organization (DRDO)-REVA joint project. • Development work on PEMFC and SOFC.
10	BHEL	<ul style="list-style-type: none"> • Research focus areas include PAFC, PEMFC, and SOFC to develop technology for long-term fuel cell stack. • Developed a 50 kW PAFC power plant. • Developed 1 kW PEMFC modules and a 3 kW PEMFC power pack.
11	Nissan India	<ul style="list-style-type: none"> • Focus areas of research include PEMFC technology for automobile applications. • Working on membrane development for PEMFC technology and studying membrane degradation.
12	Eden Energy (India) Pvt. Ltd.	<ul style="list-style-type: none"> • The focus area of research includes hydrogen for the transport sector. • Partnered with Ashok Leyland to develop Hythane-powered engine and commercialize the same for buses.
13	Mahindra and Mahindra, Chengalpattu	<ul style="list-style-type: none"> • Development and demonstration of diesel hydrogen dual-fuel SUV.
14	R&D Center, IOCL, Faridabad	<ul style="list-style-type: none"> • Development of hydrogen refueling facility for demonstration of fuel cell vehicles.
15	HPCL/IITD/ CeNS	<ul style="list-style-type: none"> • Scale up studies and process development by hydrogen production through catalytic decomposition of natural gas.
16	IOCL R&D	<ul style="list-style-type: none"> • Solar-based H₂ production system and dispensing station for refueling H₂ fuel cell vehicle. • Setting up of compact reformer unit of 4 tons per day (TPD) capacity for producing green hydrogen blend HCNG and trials demonstration at Rajghat Bus Depot in Delhi.

ANNEXURE 2: ASSUMPTIONS OF FINANCIAL AND ECONOMIC ASSESSMENTS

Value	Assumptions	Source
Capital Expenditure Assumptions		
Project Start Year	2025	Market Estimates
Project Life	25 Years	Market Estimates
Construction Period	2 Years	Market Estimates
Electrolyzer Refurbishment	10 Years	Market Estimates
Alkaline Electrolyzer Capital Expenditure (Capex)	\$700 per kWh	Market Estimates
Cooling Plant and Water Treatment Capex	\$50 per kWh	Market Estimates
Electrolyzer Stack Cost	35% of electrolyzer cost	Market Estimates
Other Soft Costs, Preconstruction Expenses, Startup Expenses	6.5% of Capex cost	Market Estimates
Civil Construction Expenses	3.5% of Capex cost	Market Estimates
Alkaline Electrolyzer Minimum Load Range	50%	Market Estimates
Operational Expenditure Assumptions		
Electrolyzer Electricity Consumption	53 kWh per Kg	Market Estimates
Solar capacity utilization factor (CUF)	25%	Market Estimates
Wind CUF (on-site)	25%	Market Estimates
Wind CUF (off-site)	37%	Market Estimates
Project CUF with Banking	67%	Market Estimates
Water Cost	₹55 per kilo liter	Market Estimates
Solar Banking Charges	₹1.5 per kWh	Gujarat Solar Policy, Gujarat Electricity Regulatory Commission (GERC)
Wind Transmission Charges	₹4,047/MW/day	Gujarat Energy Transmission Corporation (GETCO) tariff order
Manpower Cost	₹ 0.55 Crore. per year	Market Estimates
Transmission Loss for Wind Energy	3.72%	GERC
Demineralized/Deionized Water Requirement	10 liter/green hydrogen kg	Market Estimates
Repair Maintenance Costs	2% of gross block	Market Estimates
Admin and Other Expenses	1% of revenue	Market Estimates
Insurance Expense	0.5% of gross block	Market Estimates
Financial Assumptions		
Debt: Equity	70:30	Market Estimates
Long-Term Loan Rate	9%	State Bank of India (SBI) base rate
Short-Term Loan Interest	9.50%	SBI Short-term loan rate
\$ to Indian rupee (₹)	₹80	Market Estimates
Repayment Period	18 Years	Market Estimates
Escalation on Operating Costs and Prices (WPI)	5%	Market Estimates
Equity Rate of Return	14%	Market Estimates
Salvage Value of Machinery	5%	Market Estimates
Depreciation Rate	As per Companies and Income Tax Act	Market Estimates
Corporate Taxation Rate (all inclusive)	17.16%	Market Estimates