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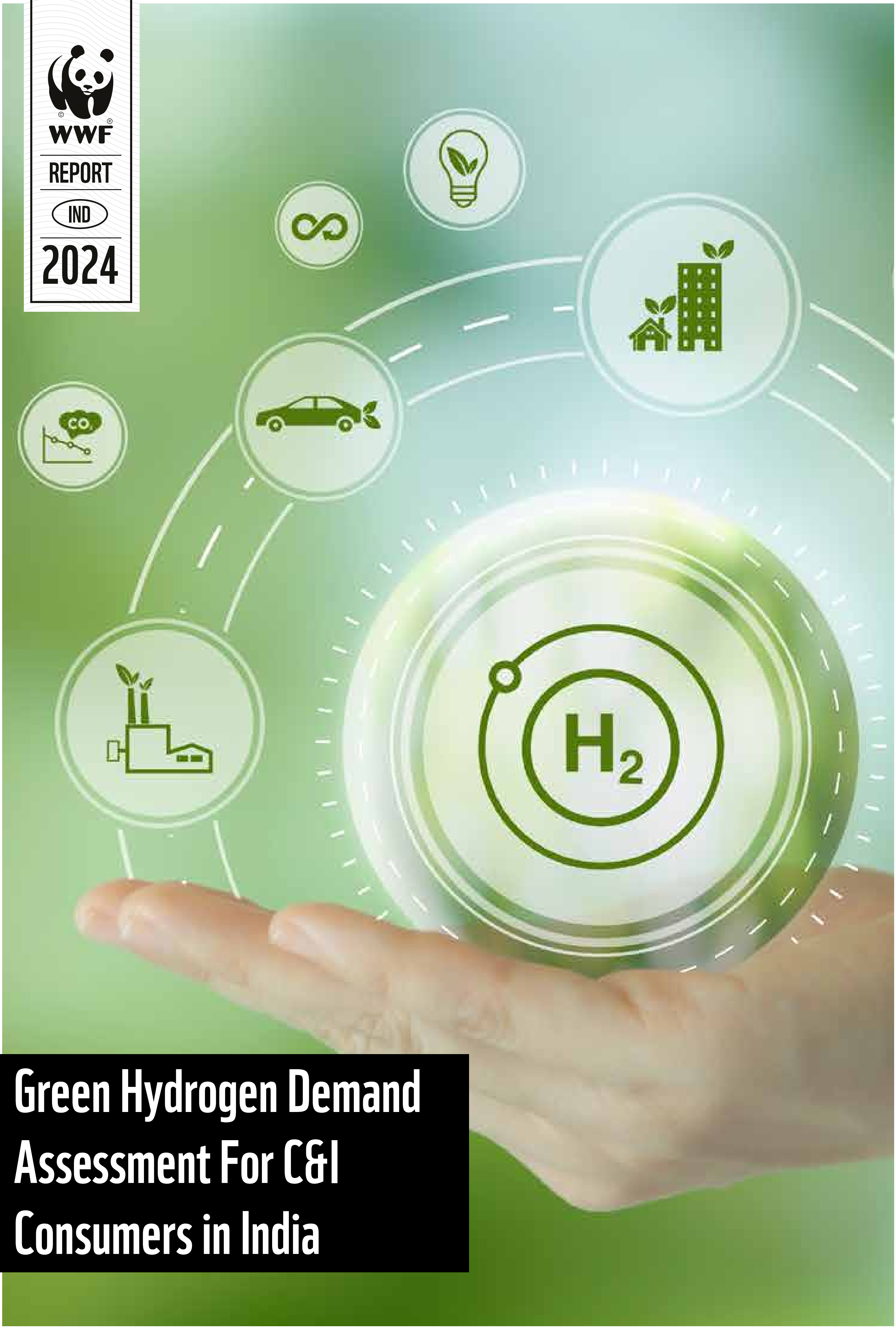

Green Hydrogen Demand Assessment For C&I Consumers in India

CREDITS

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Abbreviations

Acronym	Definition
AEM	Anion exchange membrane
BF-BOF	Blast furnace-Basic oxygen furnace
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCOE	Chief Controller of Explosives
CCOE	Chief Controller of Explosives
CCUS	Carbon Capture, Utilisation and Storage
CCUS	Carbon capture, utilisation and storage
CGD	City Gas Distribution
CII	Confederation of Indian Industry
CNG	Compressed Natural Gas
DAP	Di-ammonium Phosphate
DRI	Direct Iron Reduction
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCEV	Fuel cell electric vehicle
FG	Float Glass
GCR	Gas Cylinder Rules
GDP	Gros Domestic Product
GH	Green Hydrogen
GoI	Government of India
H_2O_2	Hydrogen Peroxide
HCNG	Hydrogen Compressed Natural Gas
HCNG	Hydrogen compressed natural gas
HCV	Heavy Commercial Vehicle
HDV	Heavy Duty Vehicles
HFCV	Hydrogen Fuel Cell Vehicle
HGU	Hydrogen Generation Unit
HGU	hydrogen generation units
IEA	International Energy Agency
ISTS	Inter State Transmission System
KTA	Kilo Tonne per Annum
LCOS	Levelised Cost of Storage
LCV	Light Commercial Vehicle
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquified Petroleum Gas
MCH	methylcyclohexane
MMSCMD	Million Metric standard Cubic Meter Per Day
MMT	Million Metric Tonne
MTPA	Million Tonne Per Annum
OPEX	Operating Expenditure
PEM	Proton Exchange Membrane

PESO	Petroleum and Explosives Safety Organisation
PNGRB	Petroleum and Natural Gas Regulatory Body
PPAC	Petroleum Planning & Analysis Cell
R&D	Research & Development
REC	Renewable Energy Certificate
REDE	Renewable Energy Demand Enhancement
RLNG	Regassified Liquefied Natural Gas
RPO	Renewable Purchase Obligation
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
VGF	Viability gap funding
VKT	Vehicular Kilometres Travelled

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Executive Summary

WWF India and the Confederation of Indian Industry (CII) initiated the Renewable Energy Demand Enhancement (REDE) initiative in India in 2018. REDE represents a collaboration among corporate purchasers with the aim of enhancing their acquisition of renewable energy and propelling efforts to overcome obstacles that are greatly impeding the growth of demand in this sector. It also focuses on expanding the scope of corporate renewable energy procurement, building capacity, influencing policy, networking and and peer-to-peer learning among members.

As the third largest carbon dioxide emitter worldwide, India has a major role to play in curbing the impact of carbon emissions on the environment. The government of India (GoI) has been proactive and has committed to achieve net zero by 2070. The government has also recognised the potential role of green hydrogen in achieving this net zero target, especially in decarbonising the 'hard to abate' sectors. The National Green Hydrogen Mission document released by the GoI in January 2023 comprehensively discusses tapping this potential.

Commercial and industrial (C&I) consumers account for approximately 50 percent[1] of the overall electricity consumption in India, and, as such, have the potential to play a vital role in achieving India's green hydrogen objectives and net zero targets. Therefore, it is crucial for policymakers to consider the challenges faced by the C&I segment while drafting implementation guidelines for green hydrogen policies over the next decade. In this regard, **WWF India** in partnership with **ICF** commissioned a study to understand the trends for hydrogen procurement in India and to forecast when green hydrogen is likely to be commercially viable for C&I use in the country.

1 https://www.mospi.gov.in/sites/default/files/publication_reports/Energy_Statistics_2023/EnergyStatisticsIndia2023.pdf

Key objective of the study

The key objective of the study was to formulate policy recommendations to promote the greater adoption of green hydrogen. Key tasks of the study included:

- Researching India's current hydrogen market
- Identifying key and/or priority industries where hydrogen can replace natural gas
- Assessing the current pricing of hydrogen and future pricing of green hydrogen, and its viability
- Understanding the policy ecosystem and its impact on green hydrogen adoption
- Forecasting future demand for hydrogen and key growth drivers (till 2030), based on an analysis of current growth patterns
- Estimating the cost of green hydrogen that would be considered viable by C&I players for different applications
- Understanding the green hydrogen market from the production and manufacturing perspective

Hydrogen demand in India

Hydrogen consumption in India has increased gradually at a compound annual growth rate (CAGR) of 2.9 percent, from 5.59 million metric tonne (MMT) in 2015 to 6.55 MMT in 2021.[2] Historically, refineries and fertilisers (ammonia) have been the major drivers of hydrogen demand. In 2021, the sectors contributed over 80 percent of India's overall hydrogen

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consumption, with the remaining driven by chemical (methanol and hydrogen peroxide), steel, optic fiber and float glass industries.

In terms of the regional concentration of demand, India's western region accounts for approximately 52 percent[3] of the country's total hydrogen consumption. This is attributable to the concentration of large refineries and fertiliser plants in the region. The states of Maharashtra and Gujarat are the major drivers of hydrogen demand. Further, in FY2021, approximately 90 percent of the hydrogen consumption in India was through the captive route, and only 10 percent of the hydrogen consumption was through merchant market.[4]

To assess future hydrogen demand in India, it is crucial to determine whether it is being used as a direct feedstock or as a heating fuel, and further evaluate the viability of retrofitting existing infrastructure or creating new infrastructure to fulfil the viable demand. Hydrogen serves as a feedstock in industries such as refineries, ammonia production, and the manufacturing of chemicals like methanol and hydrogen peroxide, as well as in the iron and steel sectors. It has lesser applications in float glass production and oil hydrogenation. On the other hand, hydrogen is employed as a fuel in the transportation, city gas distribution (CGD), and significant industries, particularly in power generation.(-minor). In the past, the primary source of hydrogen demand were sectors utilising hydrogen as a feedstock, and it is anticipated this trend is expected to persist in the near future.

The overall demand for hydrogen in India is expected to be in the range of 10 MTPA and 14 MTPA by 2030, with the ammonia and refinery industries projected to account for approximately 78 percent to 81 percent of the hydrogen demand until 2030. Other sectors, such as chemicals, steel and iron, CGD blending, optic fibre, float glass, and hydrogen fuel cell vehicle (HFCV) will also contribute to the demand for hydrogen, accounting for the remaining demand in 2030. Further transition from hydrogen to green hydrogen is expected to be driven by cost effectiveness and the availability of green hydrogen.

In a step towards sustainability and to promote the adoption of green hydrogen, the GoI approved the National Green Hydrogen Mission in January 2023 to replace hydrogen produced from fossil fuels with green hydrogen in ammonia production and petroleum refining, blending green hydrogen in CGD systems, using green hydrogen to produce steel, and replacing fossil fuels with green hydrogen-derived synthetic fuels, such as green ammonia and green methanol in various sectors, such as mobility, shipping, and aviation. Further, the mission aims to build capabilities to produce at least 5 MMT of green hydrogen per annum by 2030, with the potential to reach 10 MMT per annum as the export market grows. Considering this, the sectors with the potential to substitute fossil fuel-based hydrogen with green hydrogen (such as ammonia, refinery, and CGD) can be viewed as the early adopters of green hydrogen.

Further, the use of green hydrogen will likely have a direct impact on the demand for natural gas, as it can act as a substitute for the latter. By 2030, the demand for green hydrogen in non-urea fertiliser production will be equivalent to 1.55 MMSCMD of natural gas, while the demand for green hydrogen in refineries will be equivalent to the natural gas demand of 16.62 MMSCMD. The demand for green hydrogen in CGD will be equivalent to the natural gas demand of 5.04 MMSCMD.

Hydrogen supply in India

Given the captive nature of consumption, fertiliser, petroleum refining, and chemical industries are the major producers of hydrogen. It is produced primarily through steam methane reforming (SMR) of nat-

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ural gas, making it a 'grey hydrogen'. Additionally, hydrogen is also produced as a by-product in the industries that meet the merchant requirements.

Hydrogen sold under the merchant route is either through direct supply contract by the producer, through traders using bilateral agreements, or spot booking. The direct supply radius is usually within 120 km, and transportation is mainly through trucks equipped with cylinder banks, while some suppliers use pipelines for smaller distances. Major players in this segment include Grasim Chemicals, DCM Shriram, Gujarat Alkalies and Chemicals Limited, Tata Chemicals Limited, and GHCL Ltd. Indirect suppliers have a supply radius of around 500 km, and they use similar transportation methods as direct suppliers. Some traders have also established onsite production units for large captive consumers. Key players in this segment include Linde India, Inox Air Products, and Bhuruka gases.

Infrastructure requirements to ensure hydrogen supply

The ecosystem of hydrogen demand is governed by efficient infrastructure at the level of production and distribution. The hydrogen value chain consists of three key components: hydrogen production, hydrogen storage and distribution, and hydrogen utilisation.

Hydrogen distribution infrastructure can be further classified into two categories: central plant and storage, and transportation.

The storage of hydrogen is significantly challenging compared to other fossil fuels due to its low density and high volatility. At present, it is stored mainly as a compressed gas or liquid. In some countries, pilot studies have been conducted to evaluate storing hydrogen in salt caverns. In India, hydrogen is stored mainly as a compressed gas.

The transportation of hydrogen is another challenging area, leading many consumers to install their own hydrogen generating units. Some of the most used transportation modes are:

- Cryogenic liquid tanker trucks or gaseous tube trailers serve as the means for conveying hydrogen from its production site to the intended destination, whereas pipelines are the preferred choice for areas characterised by significant and consistent demand.
- Gaseous hydrogen must be compressed to the required pressure level prior to transportation through pipelines or tube trailers.
- Liquid hydrogen is typically transported through liquefaction plants, and it is useful for high-volume transport when pipelines are unavailable.

In India, hydrogen is transported to very short distances through gaseous tube trailers. A few companies have their own dedicated hydrogen pipelines, but the length is below 2 km. A significant amount of research and development (R&D) is required to evolve the transportation network of hydrogen compared to natural gas.

It is also important to note that while hydrogen production and utilisation stages are currently driven by the willingness of stakeholders to shift to hydrogen, cost-effectiveness, safety, and sustainability are critical for the distribution and storage stages. Further, each step of the hydrogen value chain is currently in the developmental stage. However, of the three stages, hydrogen distribution and storage are the most nascent.

Hydrogen production technologies and pricing

Hydrogen can be produced through various processes. These include thermochemical processes such as SMR, biomass gasification, biomass-derived liquid reforming, and solar thermochemical hydrogen; electrolytic processes; photoelectrochemical processes such as direct solar-water splitting methods; and biological processes, such as microbial biomass conversion and photobiological methods.

Among all production processes, SMR stands out as the most well-established method. In this process, an external heat source supplies high-temperature steam for the reforming reaction that converts a gas source, like methane, into hydrogen and carbon dioxide. In this process, capital expenditure (capex) accounts for about 50 percent of the total production cost. Assuming natural gas costs US$9/MMBTU, the production cost of hydrogen through the SMR process is around US$2/kg (US$17.58/MMBTU).

In the context of India, hydrogen production is mostly for captive consumption, and the by-product of the chloralkali plant is sold in the merchant market. Therefore, thus far, the price of regassified liquefied natural gas (RLNG) has not shown a significant correlation with the cost of hydrogen. At present, hydrogen from chloralkali plants is being sold at a price of ₹220/kg (US$2.7/kg) in the merchant market.

Green hydrogen production and pricing

The production of green hydrogen involves the process of electrolysis, where water is split using electricity from renewable sources. Although the basic principle of water electrolysis is the same across all technologies, there are different physiochemical and electrochemical aspects involved in the construction of each electrolyser. As a result, there are four types of electrolysis technologies currently in use: alkaline electrolysis, proton exchange membrane electrolysis, anion exchange membrane electrolysis, and solid oxide electrolysis.

The alkaline electrolysis process is considered to be the most established technology, while the proton exchange membrane electrolysis process is rapidly developing and is expected to be widely used in the future. In terms of the cost of production, the current cost of green hydrogen production through the proton exchange membrane electrolysis process is calculated at US$3.9/kg, whereas for the alkaline electrolysis process, it is US$3.6/kg. By 2030, the cost of production is expected to reduce to US$2.7/kg for proton exchange membrane electrolysis and US$2.5/kg for the alkaline electrolysis process.

Cost viability of green hydrogen in India for C&I players

The high production cost of green hydrogen poses a significant challenge to its widespread adoption in the C&I sector. To overcome this obstacle and facilitate a smooth transition towards green hydrogen, significant investments from corporate groups and additional incentives from the government and regulators are necessary. Ultimately, to achieve global viability and competitiveness, the cost of green hydrogen must be reduced to US$2/kg or lower, nearly half of its current price.

Key issues and gaps for development of the hydrogen market in India

The GoI's recognition of green hydrogen as a next-generation fuel and its initiative in drafting policies and missions is a proactive approach to establishing green hydrogen as a key energy source. This is a significant step towards achieving a sustainable and carbon-neutral future. The GoI's efforts to promote green hydrogen as a viable alternative to traditional fuels are commendable, and stakeholders in the industry are optimistic about the potential impact of these policies on the growth and adoption of green hydrogen. However, there are still some gaps that need to be plugged for the sustainable growth of the sector.

Some of the key gaps in the regulatory and policy framework are:

- A lack of clarity in the institutional structure regarding ministries/departments for matters relating to green hydrogen.

- Lack of concrete measures towards creating demand for green hydrogen.
- Absence of roadmap for the reduction in cost of production of green hydrogen.
- Insufficient infrastructure development for the storage and transportation of hydrogen.
- The need to promote funding for the development of the hydrogen ecosystem.
- Lack of critical guidelines on safety in hydrogen storage, transport, distribution, and fuel cells.

Stakeholder consultations

Stakeholders were consulted to understand the market sentiment towards the adoption of green hydrogen. The key requirements highlighted during the consultations were:

- The introduction of a carbon tax and the creation of a green hydrogen certification market.
- Incentives to reduce price of renewable energy.
- Updated guidelines from the Petroleum and Explosives Safety Organisation (PESO) for the storage, transportation, and usage of hydrogen.
- Advocacy for hydrogen produced from brine to be defined as green hydrogen.
- Redesigning boilers to accept blended hydrogen gas and defining an allowable blending percentage.
- Green hydrogen mandates for industries.
- Innovative funding from financial institutes to support growth.

Following the individual stakeholder consultations, a roundtable discussion was organised with policymakers, developers, suppliers, and consumers. The roundtable was centred on the critical challenges that could hinder the transition to green hydrogen. The discussions and deliberations in the roundtable highlighted the major gaps and policy recommendations for the desired development of the green hydrogen ecosystem in India. These gaps and recommendations revolved around the current state of policy development in India, the cost of green hydrogen production, infrastructure development for storage and transportation, and the creation of an ecosystem to promote investments and funding for green hydrogen.

Policy recommendations

After conducting a comprehensive study of the hydrogen ecosystem in India and obtaining feedback from stakeholders, a series of policy recommendations were formulated. These are aimed at addressing specific areas, such as R&D, institutional structure, demand creation, the cost of green hydrogen production, transportation and storage, and the spot market for hydrogen.

The key recommendations are:

- Clearly defining a nodal ministry, inter-ministerial governance, and regulatory structure.
- Introducing a green hydrogen obligation for consumers (similar to that of renewable purchase obligation (RPO) to increase the uptake of solar and wind power).
- Developing regulations for safety norms, standards and labelling, dedicated hydrogen pipeline construction norms, retrofitting pipelines, and creating storage.
- Introducing green hydrogen standards and labelling programme.

- Creating hydrogen and/or green hydrogen hubs.
- Conducting research on mainstream and other emerging production technologies such as Proton Exchange Membrane (PEM), Solid Oxide Electrolysis Cells, AEM, and biomass gasifiers.
- Exploring the adoption of hydrogen with minimal retrofitting.
- Encouraging the establishment of state-level policies, including green hydrogen obligation and blending norms.
- Optimising the cost of production of green hydrogen through a reduction in power cost, carbon taxation, and carbon pricing, among others.
- Introducing financial and fiscal incentives through existing and new mechanisms, including viability gap funding (VGF), production-linked incentive scheme (PLI), etc.
- Developing dedicated hydrogen pipelines and associated infrastructure.
- Retrofitting existing pipelines.
- Developing a spot market for hydrogen.
- Introducing appropriate subsidies and schemes at different levels of the value chain.

The increasing global focus on decarbonisation has led to a renewed interest in green hydrogen as a clean energy source. While the technology is still in its early stages of development, the potential benefits of green hydrogen are immense. However, the current high cost of production is a major hurdle in its widespread adoption, particularly in the C&I sectors. It is imperative for the government to assume a pivotal role in designing a sustainable environment for hydrogen by covering the gaps in the entire hydrogen value chain. In addition, the government needs to establish industry-wide standards and benchmarks for the quality, safety, and performance of hydrogen, and support R&D initiatives that aim to lower the costs of hydrogen production, storage, and transportation.

It is also crucial for the government to collaborate with industry stakeholders to create a conducive environment for investment and innovation in the hydrogen sector. By adopting a proactive approach and partnering with industry players, the government can provide the necessary impetus to the hydrogen ecosystem and drive the transition towards a low-carbon economy. With a concerted effort, the cost of green hydrogen can be reduced to a commercially viable level, making it a key player in the future of clean energy.

1

Introduction

In 2021, India, registered an overall annual hydrogen consumption of 6.55 MT,[5] with the refinery, ammonia production, and chemical industries accounting for the bulk of hydrogen consumption. As part of a more comprehensive climate action plan, India has committed to achieve net-zero emissions by 2070 and meet 50 percent[6] of energy requirements through renewable sources by 2030. India's ambition includes positioning itself as a global hub for green hydrogen production., and, therefore, needs to accelerate its path to a green hydrogen economy.

In a significant step towards achieving the country's net-zero targets, the Ministry of Power approved the National Green Hydrogen Mission on 4 January 2023. The document specifies the aim of developing the capacity to produce at least 5 MMT[7] of green hydrogen per annum and creating export opportunities for green hydrogen and its derivatives. The document also talks about facilitating the de-carbonisation of the industrial, mobility, and energy sectors, reducing the dependence on imported fossil fuels and feedstock, and developing indigenous manufacturing capabilities. The document also suggests that India will support pilot projects in emerging end-use sectors and production pathways.

According to a United Nations report, over 70 countries, including major economies such as China, the US, and the EU, have set net-zero targets, covering around 76 percent[8] of global emissions. To achieve this goal, countries are exploring strategies to move towards a sustainable clean energy mix, with green hydrogen as a crucial component. The urgency to reduce greenhouse gas emissions has provided a significant boost to the exploration of clean hydrogen. In 2020, global hydrogen demand was 90 Mt, with approximately 70 Mt used as pure hydrogen and the remaining used as a mixture of gases, such as synthesis gas, for fuel or feedstock.[9] Indeed, according to the Global Hydrogen Review Report 2021 by IEA,[10] the world's largest economies have already laid out plans to move towards a hydrogen economy, with a focus on green hydrogen.

In terms of availability, it is important to note that hydrogen is abundant in the universe but only present in traces in the Earth's atmosphere. However, it can be found in significant quantities in compounds such as water when combined with other elements, as well as in various other carbon-based compounds. Most of the global hydrogen is derived from fossil fuels (natural gas and coal) and biomass, or from water through electrolysis. Natural gas is the primary source for hydrogen production, accounting for approximately 76 percent of the global dedicated hydrogen production. Coal is the second-largest source, contributing an estimated 22 percent of the total production. The remaining 2 percent is produced through the electrolysis of water.[11]

In recent years, various production techniques have been used to produce hydrogen. To differentiate between the hydrogen produced from different sources, a colour-based categorisation system has been adopted:

- Black, grey, or brown hydrogen refers to the extraction of hydrogen from fossil fuels, such as coal or natural gas, using the SMR process.

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6 https://pib.gov.in/PressReleasePage.aspx?PRID= 1768 712

7 https://mnre.gov.in/img/documents/uploads/file_f-167358 1748609.pdf

8 https://www.un.org/en/climatechange/net-zero-coalition

9 https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

10 https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

11 https://www.energypolicy.columbia.edu/sites/default/files/pictures/HydrogenProduction_CGEP_FactSheet_052621.pdf

- Blue hydrogen is produced from fossil fuels with carbon dioxide emissions reduced using carbon capture, utilisation, and storage (CCUS) technology.

- Green hydrogen refers to the production of hydrogen through the electrolysis of water, using electricity from renewable sources. As a result, this is the cleanest form of hydrogen.

- Turquoise hydrogen is produced by the thermal splitting of methane (methane pyrolysis), with solid carbon being produced instead of CO_2.

- Pink hydrogen is produced by the electrolysis of water using nuclear power.

- Yellow hydrogen is generated through the electrolysis of water using electricity sourced from the grid.

- White hydrogen is produced as a by-product of industrial processes.

To accelerate the pace of hydrogen production and the achievement of hydrogen targets in India, there is a pressing need for a greater adoption of clean energy by commercial and industrial (C&I) consumers. Many organisations have already undertaken measures to increase their renewable energy consumption and reduce their carbon emissions by joining the Renewable Energy Demand Enhancement (REDE) initiative. The REDE initiative, started by WWF India and the Confederation of Indian Industries (CII) in 2018, is an alliance of corporate buyers that aims to increase renewable energy procurement, catalyse solutions to address the challenges that are significantly restricting renewable energy demand, expand the scope of corporate renewable energy procurement, build capacity, influence policy, and increase member networking and peer-to-peer learning among members.

Give the growing push for clean fuel and the increasing global attention on green hydrogen, this report seeks to analyse the developments in hydrogen procurement in India and determine the viability of green hydrogen for the country's C&I sector. As such, this report presents an in-depth analysis of:

- Research on the current hydrogen market in India.

- Key/priority industries where hydrogen can replace natural gas.

- Current pricing of hydrogen and future pricing of green hydrogen and its viability.

- The policy ecosystem and its impact on green hydrogen adoption.

- Future demand for hydrogen and key growth drivers (till 2030) based on current growth patterns.

- Estimated green hydrogen cost that would be considered viable in India by commercial and industrial players for different applications.

- Exploring the green hydrogen market from the production and manufacturer view.

Based on the finding of the study and views gathered from stakeholders (including C&I consumers, producers, and manufacturers), This report suggests certain high level policy interventions to increase the uptake of green hydrogen in the commercial and industrial segment.

2

Hydrogen Demand in India

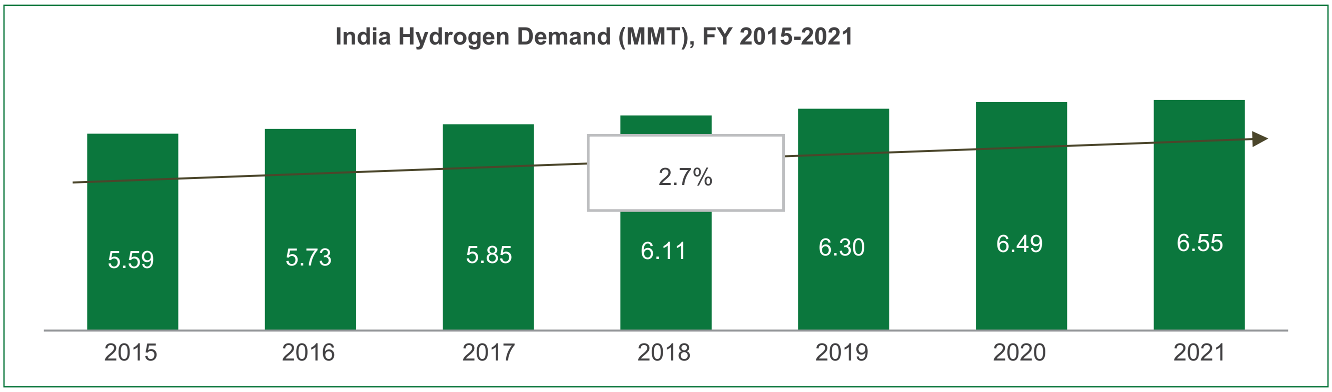
At the 2021 United Nations Climate Change Conference, commonly known as the COP26, India committed to achieving net zero emissions by 2070.[12] Thirty-three countries, including India, and the EU signed the five-point 'Glasgow Breakthroughs' to enhance clean technologies, with the fourth point aiming at making renewable, affordable, low-carbon hydrogen widely available by 2030.[13] In 2021, the total consumption of hydrogen in India stood at 6.55 MMT[14] of hydrogen per annum, approximately 9 percent of the global hydrogen demand.

2.1 Sectors driving hydrogen demand

Hydrogen consumption in India has gradually increased in recent years, from 5.59 MMT in 2015 to 6.55 MMT in 2021, at a CAGR of 2.9 percent.[15] The major driver of hydrogen consumption in India is largely concentrated around industrial usage, primarily in refining and as a feedstock to produce ammonia and methanol. Historically, the majority of the demand comes from refineries, followed by the fertiliser sector in ammonia production, with a small share of consumption coming from methanol production.

The steel industry has consistently been a significant contributor, with a cumulative demand of around 0.12[16] MMT since 2015. A very small share is also being consumed by the glass and optic fibre industries. There is also emerging potential demand for hydrogen in the heavy duty and long-haul freight transportation and power sectors. Our assessment excludes niche applications, such as in industrial forklifts, cell phone towers, and city gas distribution. It also excludes demand potential from aviation, shipping, and cooking industries, which are currently more speculative and technically in the very early stages. A detailed industry-wise consumption trend of hydrogen in India is presented in Table 1.

Figure 1: Hydrogen Consumption in India



Source- Primary survey by ICF India

12 https://www.bbc.com/news/world-asia-india-59125143

13 https://energy.economictimes.indiatimes.com/news/renewable/indias-green-hydrogen-policy-unprecedented-growth-needed-to-achieve-2030- targets/90154361#:~:text=India%2C%20along%20with%2032%20other,hydrogen%20widely%20available%20by%202030

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Table 1: Industry-Wise Hydrogen Consumption (MMT)

Industry	2015	2016	2017	2018	2019	2020	2021
Fertiliser	1.83	1.88	1.91	2.04	2.06	2.13	2.14
Petroleum Refinery	2.56	2.63	2.81	2.94	3.06	3.05	3.12
Methanol	0.52	0.42	0.42	0.35	0.34	0.48	0.53
Hydrogen Peroxide	0.21	0.21	0.22	0.24	0.24	0.24	0.29
Steel	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Optic Fiber	0.02	0.02	0.03	0.03	0.04	0.05	0.05
Float Glass	0.07	0.07	0.07	0.08	0.08	0.09	0.09
Sintered Glass	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Others	0.18	0.29	0.19	0.23	0.27	0.26	0.13
Total Hydrogen Consumption	**5.59**	**5.73**	**5.85**	**6.11**	**6.30**	**6.49**	**6.55**

Source- Primary survey by ICF India

Table 1 shows how hydrogen demand has evolved since 2015. Hydrogen has increasingly been used in the refinery and fertiliser sectors, with CAGRs of 3.4 percent and 2.6 percent,[17] respectively. Similar trends are also visible in the optic fibre and float glass industries, which have recorded a growth rate of over 6 percent since 2015.[18] This increase can be attributed to the development of the domestic manufacturing sector, the introduction of new technologies supporting hydrogen as a feedstock for these industries, and the establishment of new hydrogen peroxide plants across the country.

Table 2: Hydrogen Usage in Different Industries

Refinery	Hydrogen is used for desulphurisation of products such as diesel and petrol.
Fertiliser	Hydrogen is used for manufacturing ammonia, which in turn is used as a feedstock for ammonia-derived fertilisers such as urea and di-ammonium phosphate.
Methanol	Hydrogen is used as a main feedstock to produce methanol, which is currently produced from natural gas.
Hydrogen peroxide	Hydrogen is used in the first step, i.e. hydrogenation of working solution of four-step hydrogen peroxide manufacturing process.
Steel	Hydrogen is used as a reducing agent in steel manufacturing by direct reduced iron process
Float glass	Hydrogen is used as a getter gas to prevent oxidation over the tin baths used in float glass manufacturing process, the glass formed on the baths is made without defects.
Optic fibre	Hydrogen is used for refractive index increment; optical fibre is immersed in a hydrogen environment to absorb hydrogen up to several mol% in advance of UV irradiation to reduce defect formation in cables.

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Table 2 showcases a list of major processes with primary hydrogen usage and the processes in which hydrogen is used.

2.2 Regional concentration of demand centres

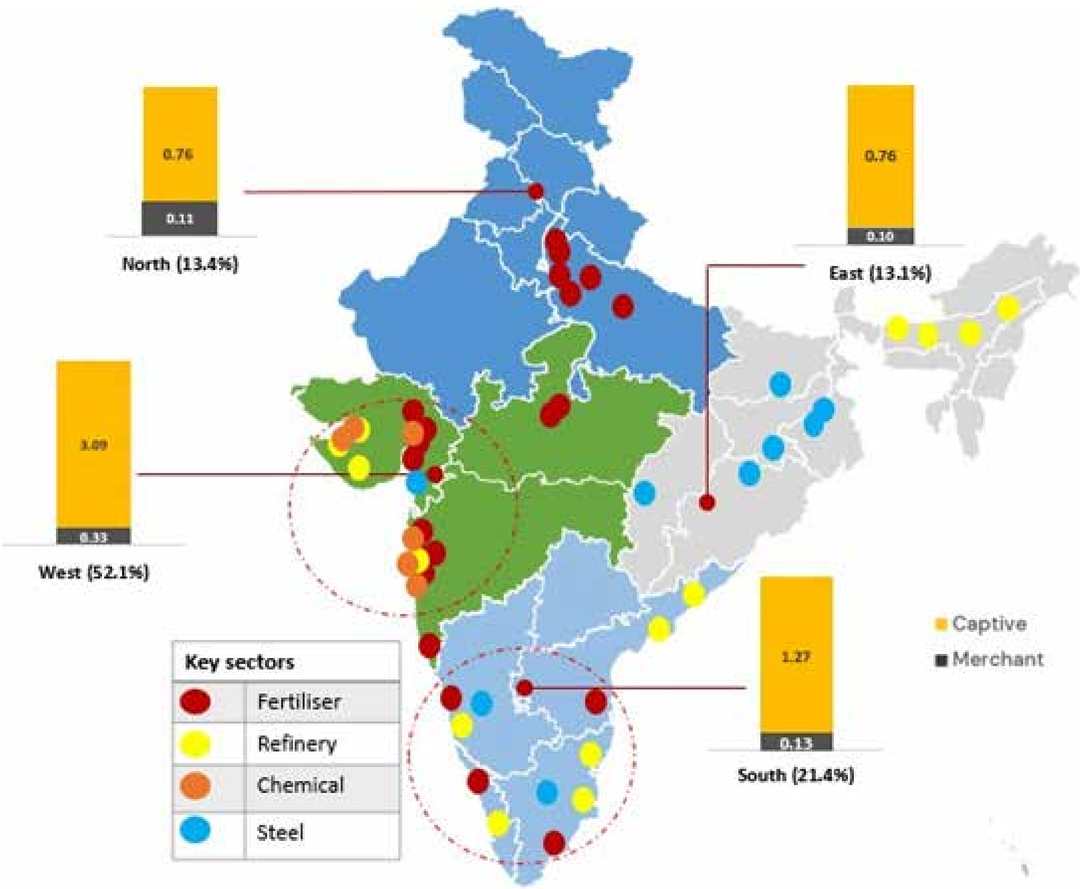
The demand for hydrogen is scattered across India's north, south, east, and west. However, at 52.1 percent[19] of India's total hydrogen demand, the west consumes a significantly higher share than the other three regions. This is because most of the industries using hydrogen as a fuel, such as the fertiliser, refinery, and chemical sectors, are in the western region. However, not all states in the west have similar share—Maharashtra and Gujarat drive the overall hydrogen demand in the region.

The southern region has the next most significant share in hydrogen consumption in India, accounting for 21.4 percent.[20] The industries driving the demand in this region are fertilisers, refinery, and steel.

The remaining demand of hydrogen is split equally between the eastern and northern region, each accounting for 13.1 percent[21] of the total hydrogen demand across India. While the demand in the northern region is driven by the fertiliser sector, the steel industry is the major consumer in the eastern region.

A split of the demand share of each region is provided in Figure 2.

Figure 2: Hydrogen Demand Concentration Across India



Source- ICF primary research

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20 ICF Primary Research

21 ICF Primary Research

The demand for hydrogen in these regions is expected to grow during the forecast period (until 2030), primarily due to the easy availability of natural gas. Approximately 45 percent[22] of the overall consumption of natural gas in India is from imports. The presence of ports in India's western and southern regions makes natural gas procurement and, in turn, hydrogen generation/procurement easy and cost-efficient in these regions. Moreover, the secondary clusters of iron and steel production units and float glass plants in the west and south regions intensify the demand for hydrogen in these regions.

2.3 Key Consumers and Suppliers

In India, hydrogen is mainly produced through SMR process, meaning it falls under the 'grey hydrogen' category. The major producers of such hydrogen are the fertiliser, petroleum refining, and chemical industries. In India, hydrogen is also produced as a by-product in the chloralkali industries.

Most of the hydrogen produced in the country is captive in nature, as a result of which a very small amount is readily available for merchant sale and use. By-product hydrogen from chloro-alkali plants is mainly traded through the merchant route.

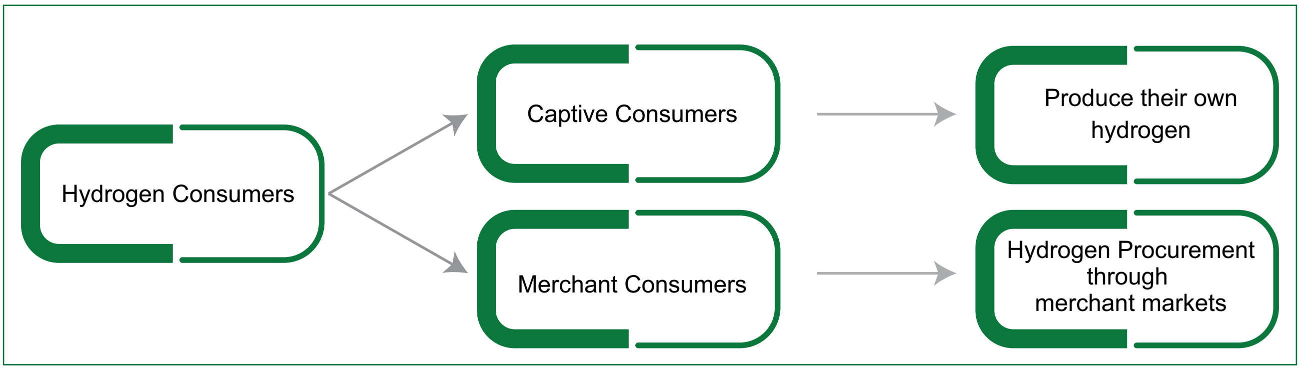
2.3.1 Consumers

Hydrogen consumers can be segregated under two categories based on the mode of hydrogen supply. The first category of consumers is those who set up their own HGU to meet their captive demand. Consumers place these captive units as part of their overall infrastructure plans or through third-party vendors, wherein the investment and the operation and maintenance expenses are borne by the consumers. Another reason for the high dependence on captive generating units is due to the non-availability of hydrogen-linked infrastructure to facilitate merchant supply. The refinery, fertiliser, and steel industries, and some chemical plants instal such hydrogen generation units to meet their large captive demand for hydrogen.

The second category of consumers are those who have a smaller demand for hydrogen and meet their requirements through merchant supplies. These include the food processing, glass, and optic fibre industries.

To understand the consumption pattern of hydrogen, a list of 20 consumers from different sectors along with their current hydrogen demand has been collated and represented below in Table 3.

Figure 3: Types of Hydrogen Users



22 https://economictimes.indiatimes.com/industry/energy/oil-gas/india-begins-importing-lng-from-russia/articleshow/64449583.cms?from=mdr

Table 3: List of Key Consumers

Consumers	Location	Consumption type	Sector	Demand (MMT)
Reliance India Limited	Jamnagar	Captive	Refinery	0.53
Krishak Bharati Cooperative Limited	Hazira	Captive	Fertiliser	0.22
Grasim Industries Limited	Jagdishpur	Captive	Fertiliser	0.11
Indian Oil Corporation Limited	Mathura	Captive	Refinery	0.09
Kanpur Fertilizers and Chemical Limited	Kanpur	Captive	Fertiliser	0.07
Hindustan Petroleum Corporation Limited	Mumbai	Captive	Refinery	0.03
Vinati Organics Limited	Raigad	Merchant	Chemical	0.0070
Indo Amines Limited	Dombivali	Merchant	Chemical	0.0060
Saint Gobain	Bharuch, Navi Mumbai	Merchant	Glass	0.0014
Tata Steel Limited	Palghar	Merchant	Steel	0.0008
Jindal steel works Limited	Raigad	Merchant	Steel	0.0007
Essar Steel	Hazira, Kurla	Merchant	Steel	0.0006
Asahi India Glass Limited	Raigad	Merchant	Glass	0.0006
Hari Orgochem Pvt. Limited	Vadodara	Merchant	Chemical	0.0005
Tata Motors Limited	Pune	Merchant	Automotive	0.0004
Suzuki Motor Gujarat Private Limited	Ahmedabad	Merchant	Automotive	0.0004
Jigs Chemical	Ahmedabad	Merchant	Chemical	0.0003
Finolex Cables Limited	Pune	Merchant	Optic Fibre	0.0003
Indian Peroxide Limited	Bharuch	Merchant	Chemical	0.0003
Deepak Nitrite Limited	Taloja, Vadodara	Merchant	Chemical	0.0002

Source- Primary survey by ICF India

It was observed that more than 90 percent of the overall consumption is through the captive route. Further, there is high variability in the volume of demand, ranging from 0.0002 MMT to 0.53 MMT per consumer.

2.3.2 Suppliers

To understand the hydrogen supply market, it is important to understand the availability of hydrogen through the different modes of production—i.e., whether it is produced as a product, co-product (produced along with the main product and carries equal importance as the main product) or is a by-product (not a planned product and is produced after carrying out the process). This can be further understood from the usage of hydrogen. For captive consumers, most of the hydrogen produced is self-consumed, while the hydrogen produced as a by-product in petroleum refineries and caustic soda plants is sold in the merchant market. The producers either sell the by-product directly to the consumers or through a trader.

The commercial sale of hydrogen in the Indian market is either through bilateral sale by the generating entity (direct supply) or through traders (indirect supply).

Direct suppliers operate through annual contracts, typically for a one-to-three-year period. Such sellers supply hydrogen within 120 km[23] from the point of generation through trucks that are mounted with hydrogen banks. Some suppliers even supply through pipelines for smaller distances (such as in a radius of 1.5 km). The key direct suppliers in the market include Grasim Chemicals, DCM Shriram, Gujarat Alkalies and Chemicals Limited, Tata Chemicals Limited, and GHCL Ltd.

Indirect suppliers include local traders or distributers who operate either on spot booking or on an anual contract basis. Their area of supply is within a range of 500 km from the point of generation, and the mode of transportation is trucks mounted with cylinder banks. However, some traders have also set up onsite hydrogen production units for large captive consumers. The key indirect suppliers are Linde India, Inox Air Products, and Bhuruka Gases.

The list of top merchant suppliers in India, accounting for 66 percent (or 0.443 MMT of the total merchant supply in 2021) are listed in Table 4.

In addition, local traders such as Verni Gastech, Shreeji Carbonic Gases, Shivam Gases, and Nishal Enterprises, among others, act as an aggregator of surplus generation from captive production units.

Table 4: Key Merchant Suppliers in India

Suppliers	Merchant Supply MMT Pan-India	Sales Growth In last 5 Years (%)
Linde India Limited	0.136	3.90
Grasim Industries Limited Including Century Rayon	0.105	3.70
Inox Air Products	0.068	3.80
Gujarat Alkalies and Chemicals Limited	0.002	3.20
Air Liquide India	0.038	2.80
GHCL Limited	0.013	3.70
Tata Chemicals Limited	0.015	3.20
Bhuruka Gases	0.009	2.60
Ellenbarrie Industrial Gases	0.066	3.50

Source- Primary survey by ICF India

23 Stakeholder consultation

3

Hydrogen Demand Projection

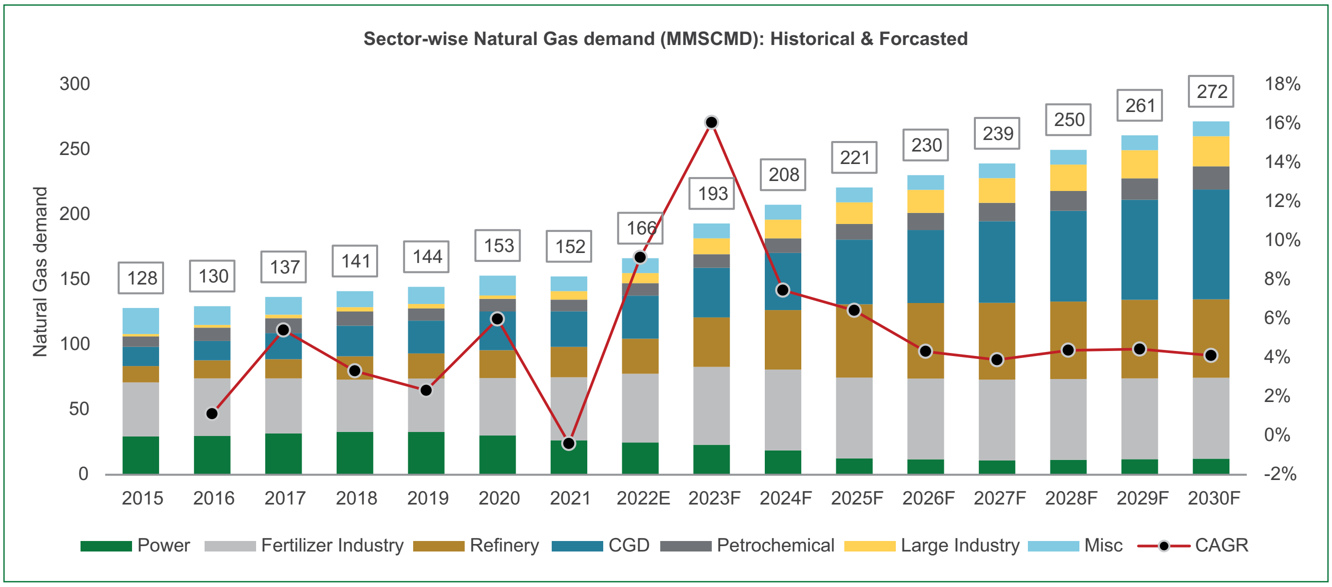
The demand for hydrogen is best determined through two key parameters—first, establishing if it has been utilised as direct feedstock or as a fuel for heating, and next is assessing the viability of adoption in terms of retrofitting existing infrastructure or creating new infrastructure. Still, before assessing the hydrogen demand in India, it is important to understand the natural gas market and the possible impact of hydrogen in its overall demand.

3.1 Natural gas market in India: Historical and forecasted growth

Natural gas demand in India has grown at a steady pace across various industrial segments since 2015. This growth can be attributed to various factors, including the GoI's 'Make in India' initiative that has enabled the growth of the manufacturing sector. A significant factor is also the steady growth of the Indian economy. Further, the growth of the CGD sector, improved pipeline connectivity, CGD firms' infrastructure development plans, the expansion of existing plants, and policy incentives have also spurred the increased use of natural gas in the transport and the industrial sectors.

The estimated demand growth of natural gas, based on sector-wise analysis and requirements, is presented in Figure 4.

Figure 4: Natural Gas Market Growth In India



Source- ICF primary research

Since 2015, the CGD, refinery, and fertiliser industries have seen rapid growth in natural gas consumption, while the power sector has seen a steep decline. This can primarily be attributed to the availability of gas and the steady transition of the power sector to renewable sources of energy. Similar trends are expected in the coming years, with the CGD, refinery, and fertiliser industries continuing to dominate natural gas demand. Natural gas consumption in India is anticipated to increase by 6.6 percent from 2021 to 2030.

3.2 Industries dependent on hydrogen

Hydrogen is currently used either as fuel for the transport and power sectors, as heating fuel for industries such as steel, cement, paper, and food, or as feedstock for fertilisers, refineries, metallurgy, food, steel, and glass, among others.

The possible uses for hydrogen are expanding across multiple sectors, such as in power generation and electricity grid stabilisation, manufacturing processes in industries (such as steelmaking and cement production, fuel cells for electric vehicles, and green ammonia production for fertilisers), and heavy transport, such as shipping. Table 5 summarises the current and potential use of hydrogen across different industries.

Table 5: Use of Hydrogen in Industries

Industry	Uses	End-Use Products
Refinery	• Hydrogen is used for crude oil processing and desulphurisation, with different products allowing different levels of sulphur, based on regulations and industry requirements. • For lower sulphur content, a higher volume of hydrogen is required. • Also used in the hydrocracking process to produce valuable products from heavier oil residues.	Gasoline LPG Fuel Oil Diesel
Fertiliser	• Hydrogen is used to produce ammonia, which is further used to produce urea or other complex fertilisers.	Ammonia Urea and other fertilisers
Metallurgy	• Hydrogen is used as the main reduction agent in the process of making sponge iron through direct iron reduction in a shaft furnace. • The sponge iron obtained is subsequently utilised in the manufacturing of steel within an electric arc furnace.	Steel
	• Atomic hydrogen welding is a type of arc welding that utilises a hydrogen environment.	Welding
Food	• Sorbitol is produced through glucose hydrogenation. The reaction mechanism involves the reduction of carbonyl groups in saccharides under hydrogen pressure, with the assistance of a solid metal catalyst composed of Nickel, Palladium, Platinum, or Ruthenium.	Sorbitol
	• Hydrogen is used for turning unsaturated fats into saturated oils and fats, including hydrogenated vegetable oils, such as margarine and butter spreads.	Vanaspati

Industry	Uses	End-Use Products
Chemical	• Hydrogen is used for methanol synthesis.	Methanol
	• In industrial hydrogen peroxide production, methane or natural gas is employed as a source to supply hydrogen, which is subsequently subjected to a catalytic process involving high temperatures, where it reacts with oxygen.	Hydrogen Peroxide
	• Principally, nitric acid is manufactured through the catalytic oxidation of ammonia.	Nitric Acid
Glass	• A mixture of hydrogen and nitrogen is used to prevent oxidation, and, therefore, defects during the manufacturing process.	Float glass
Communication	• For the refractive index increment of fibre elements, optical fibre is immersed in a hydrogen environment to absorb hydrogen up to several mol% in advance of UV irradiation to reduce defect formation in cables (in a process known as 'hydrogen loading').	Optic Fibre
	• Used as a fuel to provide power backup to telecom towers.	Telecom Tower
Pharma	• Hydrogen is used to produce hydrogen peroxide and active pharmaceutical ingredient, which is used in various medicine manufacturing.	Medicines
Cement	• Hydrogen could be used as a fuel in the manufacturing process to reduce carbon dioxide emissions.	Cement
Transportation	• Hydrogen is used as fuel for long-haul freight and heavy-duty vehicles. • Hydrogen can be used as a fuel in the shipping and aviation sectors.	-
Power generation	• Hydrogen is used to cool power plant generators to transfer heat from the power generating winding enclosure to the heat exchanges known as hydrogen coolers. • Hydrogen can also fuel power generation for the power grid. • Hydrogen fuel cell generators are viable alternatives for backup power generation, such as in hospitals, and for power generation in remote locations where batteries and renewables are unviable due to suboptimal conditions for renewable power generation.	-

While most industries use hydrogen in direct or indirect processes, there are certain end-use sectors, such as fertilisers, refining, steel, and methanol, that consume significant volumes of hydrogen and emit carbon dioxide. The National Green Hydrogen Mission document mentions the possibility of replacing hydrogen produced from fossil fuel sources with green hydrogen in the ammonia production, petroleum refining, steel production, and CGD sectors. Additionally, the GoI also aims to promote the use of green hydrogen-derived synthetic fuels, such as green ammonia and green methanol, in sectors such as mobility, shipping, and aviation as a replacement for fossil fuels.

3.3 Future demand for hydrogen and key growth drivers (C&I)

In 2021, hydrogen demand in India was 6.5 MTPA, majorly driven by captive consumption by refineries (3.1 MTPA), and fertilisers and ammonia (2.1 MTPA) sectors located in the western region.[24] By 2030, demand is projected to be between 10 MTPA and 14 MTPA,[25] primarily driven by the hydrogen-dependent industries, such as ammonia and refinery (amounting to a combined 38-percent share of the total demand).[26] Three different scenarios (realistic, conservative and optimistic) have been assessed to estimate the demand in each sector is summarised in Table 6.

Table 6:Forecasted Hydrogen Demand by Scenario (until 2030)

Sectors	Realistic	Conservative	Optimistic
Refineries	Consumption of petroleum products and new-age fuels (electric vehicles, ethanol, CNG, LNG) will continue to grow in line with recent growth trends	Stricter emissions norms across sectors due to climate change will lead to reduced demand of petroleum products	Rapid growth of petroleum products amid growing economy and improved living standards, clubbed with limited adoption of green fuels
Ammonia	Ammonia imports will reach nil by 2028, with exports likely from 2030 onwards	Ammonia imports do not become nil by 2030 and exports do not start	Ammonia imports become nil by 2025 and exports start from 2025
Chemical	Chemicals pick up utilisation across key sectors. hydrogen peroxide growth increases as pulp and paper industry grows, and methanol growth increases with slight blending and additional utilisation in downstream chemical and petrochemical products	Growth of chemicals as per past trends with no additional expansion of industry	Significant expansion due to specific utilisation of chemicals (Eg: Methanol blending is successful, or chemical finds utilisation in more sectors)
Transport	Road Transport · HCNG: Based on stakeholder views and possible plans for higher blending; 6% by 2030 and then to stay constant. · FCEV: Scenario for 0.26% penetration of on-road vehicles by 2030	Road Transport · HCNG: Considering current pilot studies being done by GAIL and CNG blending limit, 2% by 2030 · FCEV: Scenario for 0.27% penetration of on-road vehicles by 2030	Road Transport · HCNG: 6% blending to be achieved by 2030, assuming optimum blending can be achieved. · FCEV: Scenario for 0.91% penetration of on-road vehicles by 2030
Large Industries	Assuming nominal economic growth, balanced fuel mix of renewable and traditional fuels, and moderate uptake of hydrogen blending	Assuming moderate economic growth, fuel mix in favour of traditional fuels, and low uptake of hydrogen blending	Assumed accelerated economic growth, a 2030 fuel mix in favour of renewable fuels and high uptake of hydrogen blending

24 ICF primary research

25 ICF analysis

26 ICF analysis

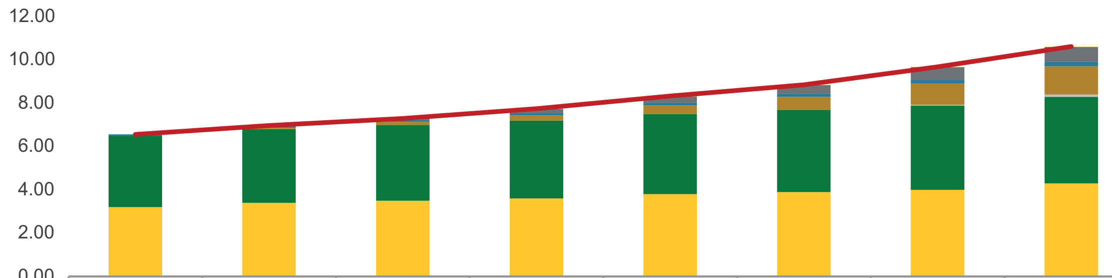
Sectors	Realistic	Conservative	Optimistic
CGD blending	Hydrogen blending trajectory in CGD network from nil to 2% (2026) and 6% in 2030.	Hydrogen blending trajectory in CGD network from nil to 2% till 2026 and 6% in 2030.	Hydrogen blending trajectory in CGD network from nil to 2% (2026) and 6% in 2030.

Source: Assumptions considered by ICF India

Note: The assumptions considered for CGD blending in all the three scenarios are the same until 2030. The diversions are expected to occur after 2030.

The outputs from the scenarios are presented Table 6 in and Figure 6.

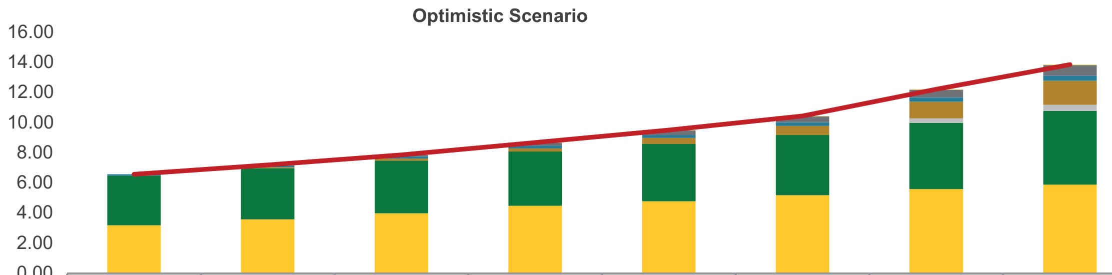
Figure 5: Overall Hydrogen Demand: Realistic Scenario



	2023	2024	2025	2026	2027	2028	2029	2030
Other industries	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.02
H2 Blending	0.00	0.04	0.08	0.20	0.30	0.40	0.60	0.70
Chemical	0.06	0.07	0.08	0.10	0.12	0.14	0.16	0.20
S&I	0.00	0.06	0.14	0.24	0.40	0.60	0.98	1.30
FCEV	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.10
Ammonia	3.30	3.40	3.50	3.60	3.70	3.80	3.90	4.00
Refinery	3.20	3.40	3.50	3.60	3.80	3.90	4.00	4.30
TOTAL	6.56	6.97	7.30	7.75	8.33	8.85	9.68	10.62

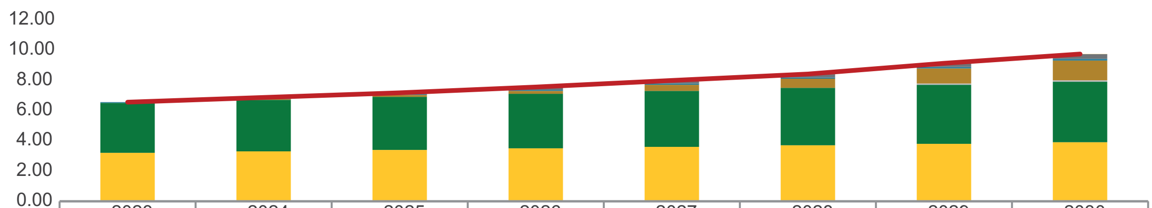
Source- ICF analysis

Figure 6: Overall Hydrogen Demand- Optimistic and Conservative Scenario



	2023	2024	2025	2026	2027	2028	2029	2030
Other industries	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.03
H2 Blending	0.00	0.04	0.09	0.20	0.30	0.40	0.50	0.70
Chemical	0.09	0.11	0.15	0.19	0.20	0.24	0.30	0.34
S&I	0.00	0.06	0.13	0.20	0.40	0.60	1.10	1.60
FCEV	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.40
Ammonia	3.30	3.40	3.50	3.60	3.80	4.00	4.40	4.90
Refinery	3.20	3.60	4.00	4.50	4.80	5.20	5.60	5.90
TOTAL	6.59	7.21	7.88	8.70	9.52	10.46	12.23	13.87

Conservative Scenario



	2023	2024	2025	2026	2027	2028	2029	2030
Other industries	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
H2 Blending	0.00	0.04	0.08	0.18	0.20	0.21	0.23	0.30
Chemical	0.05	0.06	0.06	0.07	0.08	0.09	0.10	0.12
S&I	0.00	0.06	0.13	0.20	0.40	0.60	1.00	1.30
FCEV	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.10
Ammonia	3.30	3.40	3.50	3.60	3.70	3.80	3.90	4.00
Refinery	3.20	3.30	3.40	3.50	3.60	3.70	3.80	3.90
TOTAL	6.55	6.86	7.17	7.55	7.98	8.41	9.12	9.73

Source- ICF analysis

The fastest growth will be observed in optic fibre, float glass, and HFCV, and these sectors will account for 6 percent of the total demand in 2030.

The growth impetus for hydrogen consumption in these industries will be primarily driven by the inherent growth that these sectors are witnessing. The growth trajectory and demand analysis for each sector follows:

3.3.1 Ammonia and fertiliser

India's fertiliser industry has 39 ammonia synthesis units, with production capacity of 19,108 KTPA[27] (as of April 1, 2020). In 2019-20, India imported about 10,000 KTA of urea, 5,000 KTA of diammonium phosphate, and 3,000 KTA of ammonia. The import of fertilisers is expected to fall by ramping up the domestic manufacturing capacity. The GoI has incentivised the fertiliser sector to support domestic production (see Table 7).

Table 7: Incentives provided to fertiliser industry by GoI

Year	Subsidy (₹ Crore)		
	Urea	P&K Fertiliser	City Compost
2013-14	41, 853.00	29, 427.00	NA
2014-15	54, 400.00	20, 667.30	NA
2015-16	54, 600.00	21, 937.50	NA
2016-17	51, 256.50	18, 843.40	NA
2017-18	46, 980.00	22, 237.00	7.26

Source: Annual Report 2018-19, Department of Fertilisers, Ministry of Chemicals & Fertilisers

27 https://www.sciencedirect.com/science/article/abs/pii/S0360319921035448?via%3Dihub

Hydrogen is used as a feedstock for ammonia synthesis. In 2021, the total hydrogen demand in this sector was 1,583 KTA.[28] Almost all ammonia production units are currently producing hydrogen through the SMR method. Ammonia primarily finds application in two major segments: urea and NPK (nitrogen, phosphorous, and potassium) fertilisers. In 2017, these segments collectively accounted for almost 94 percent[29] of India's ammonia demand. Fertilisers, notably the largest end-use sector, prominently drive ammonia consumption in India, constituting roughly 87 percent[30] of the country's ammonia demand in 2020. However, in actual figures, the demand[31] for ammonia in fertilisers remained stagnant, hovering between 36.640 MMT in 2016 and 37.740 MMT in 2021 whereas there has been a noticeable increase in industrial demand for ammonia over the same period.

The demand of ammonia has been analysed with projections of base demand using historic CAGR of 2.8 percent for demand of domestically produced ammonia, and 0.74 percent for ammonia imports. The domestic demand for ammonia (with imports) is projected to grow from 18 MMT per annum in 2022 to 23 MMT per annum in 2030.[32]

According to the three different scenarios explained in Table 6, a reduction in imports and start of exports from different years was assumed to arrive at future ammonia production requirements and hydrogen requirements in India (as listed in the Table 8).

Figure 7: Projected Ammonia Demand for Domestic Usage Including Imports (MMTPA)

Source- ICF analysis

28 ICF primary research

29 https://www.globaldata.com/indias-ammonia-capacity-is-expected-to-witness-double-digit-growth-over-the-next-six-years-says-globaldata/#:~:text=In%20India%2C%20the%20main%20segments%20that%20consume%20ammonia,-from%20%24296.9%2Fton%20in%202017%20to%20%24359.0%2Fton%20i n%202022.

30 https://www.expertmarketresearch.com/reports/indian-ammonia-market#:~:text=The%20Indian%20ammonia%20market%20size,of%20nearly%209.27%20million%20tons – Figures for 2020 are approximate

31 Department of Fertlizers – Annual Report 2021-22

32 ICF Analysis

Table 8: Scenarios for Ammonia Production Requirement till 2030

Year (FY)	Conservative Scenario		Realistic Scenario		Optimistic Scenario	
	Ammonia Import (MMT)	Ammonia Export (MMT)	Ammonia Import (MMT)	Ammonia Export (MMT)	Ammonia Import (MMT)	Ammonia Export (MMT)
2023	2.40	0.00	2.40	0.00	2.40	0.00
2024	2.10	0.00	1.90	0.00	1.20	0.00
2025	1.80	0.00	1.40	0.00	0.00	0.20
2026	1.50	0.00	0.90	0.00	0.00	0.47
2027	1.20	0.00	0.40	0.00	0.00	0.88
2028	0.90	0.00	0.00	0.00	0.00	1.61
2029	0.60	0.00	0.00	0.00	0.00	2.79
2030	0.30	0.00	0.00	0.50	0.00	5.04

Source: ICF analysis

In the realistic scenario, the export of ammonia is expected to start by 2030 and import dependency is assumed to come down to nil linearly till 2028.

In the conservative scenario, imports do not reach net zero and exports do not start until 2030, while in the optimistic scenario, hydrogen imports are assumed

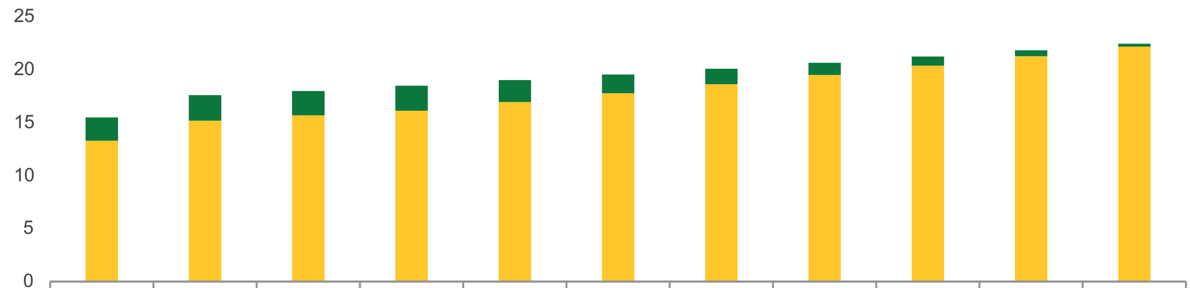
Figure 8: Ammonia Production Requirement – Realistic Scenario (MMTPA)

	FY 16	FY 20	FY 22	FY 23	FY 24	FY 25	FY 26	FY 27	FY 28	FY 29	FY 30
Export	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Import	2.20	2.40	2.30	2.36	1.86	1.36	0.86	0.36	0.00	0.00	0.00
Domestic	13.30	15.20	15.70	16.14	17.16	18.19	19.24	20.30	21.25	21.84	22.46
Total	**15.50**	**17.60**	**18.00**	**18.50**	**19.02**	**19.56**	**20.11**	**20.67**	**21.25**	**21.84**	**22.96**

Source – ICF Analysis

to reduce to nil in 2025 and the export of hydrogen or hydrogen derivatives will start from the same year. The share of fertilisers in the demand of hydrogen is used as the base to derive the share of ammonia in hydrogen exports.

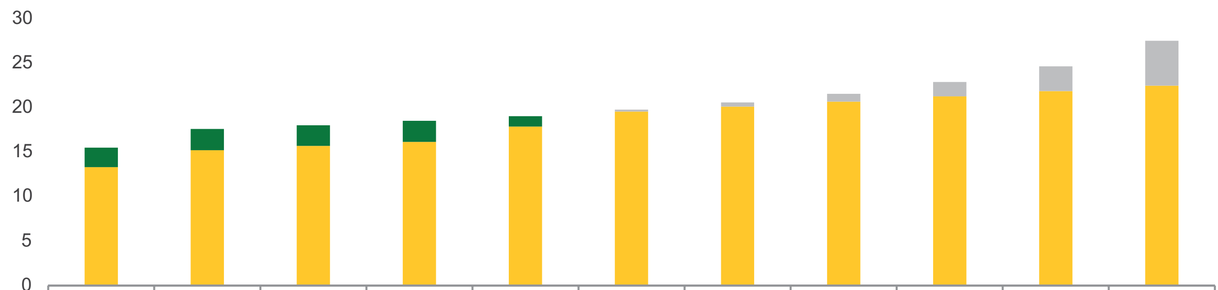
Figure 9: Ammonia Production Requirement – Conservative Scenario (MMTPA)



	FY 16	FY 20	FY 22	FY 23	FY 24	FY 25	FY 26	FY 27	FY 28	FY 29	FY 30
Export	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Import	2.20	2.40	2.30	2.36	2.06	1.76	1.46	1.16	0.86	0.56	0.26
Domestic	13.30	15.20	15.70	16.14	16.96	17.79	18.64	19.50	20.38	21.28	22.19
Total	**15.50**	**17.60**	**18.00**	**18.50**	**19.02**	**19.56**	**20.11**	**20.67**	**21.25**	**21.84**	**22.46**

Source- ICF analysis

Figure 10: Ammonia Production Requirement – Optimistic Scenario (MMTPA)

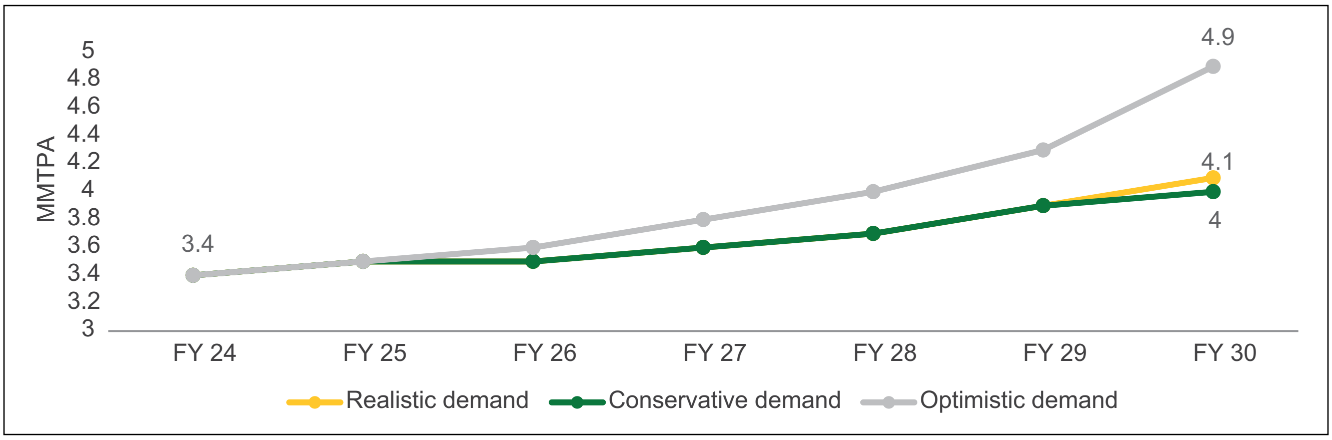


	FY 16	FY 20	FY 22	FY 23	FY 24	FY 25	FY 26	FY 27	FY 28	FY 29	FY 30
Export	0.00	0.00	0.00	0.00	0.00	0.20	0.47	0.88	1.61	2.79	5.04
Import	2.20	2.40	2.30	2.36	1.16	0.00	0.00	0.00	0.00	0.00	0.00
Domestic	13.30	15.20	15.70	16.14	17.86	19.56	20.11	20.67	21.25	21.84	22.46
Total	**15.50**	**17.60**	**18.00**	**18.50**	**19.02**	**19.76**	**20.57**	**21.55**	**22.86**	**24.63**	**27.49**

Source- ICF analysis

The hydrogen requirement is calculated using stoichiometric ratios and molar weight of components in ammonia synthesis reaction (i.e., 6 gm of hydrogen is required to produce 34 gm of ammonia). Thus, the hydrogen demand as shown in Figure 11 is calculated from ammonia production and is expected to be between 4 MMT and 4.9 MMT in 2030. The cumulative annual growth rate is 2.75 percent for conservative, 3.17 percent for realistic, and 6.28 percent for optimistic scenarios in 2024-30.

Figure 11: Hydrogen Demand from Ammonia (MMTPA)



Source- ICF analysis

3.3.2 Refinery

In 2020, India's installed refining capacity was 25041 MTPA.[33] The sector is estimated to record a 4.2-percent growth rate by 2030. In refineries, hydrogen is primarily used as a hydrotreater to remove impurities, such as sulphur from crude oil, and as a hydrocracker to transform heavy gas oil into light distillates by breaking down long hydrocarbon chains. Hydrogen might also find increased use as fuel for heating in refineries, once it reaches price parity with other fuels, such as natural gas.

In terms of hydrogen as feedstock, the demand is currently being met within refineries through the SMR of natural gas, which will have a green hydrogen mandate of 50 percent (indicative demand percentage considered for analysis) by 2030.

The three different scenarios to forecast hydrogen demand from petroleum refineries are shown in Table 9

In the realistic scenario, the demand driver is the growth of petroleum products. In the conservative setting, stricter emissions norms will lead to reduced demand, and in an optimistic case, the rapid growth of petroleum products amid a growing economy with the limited adoption of new age fuels drives refineries' hydrogen demand.

In India, the average hydrogen consumption per unit of refining capacity (MMTPA) is below 12,000 tons.

To assess hydrogen demand, it is assumed that more complex refineries will be added in the years to come due to the increased requirement of processing of heavier fractions of crude oil. As such, the higher the refinery complexity, the greater the hydrogen demand.

The hydrogen requirement inside a refinery is currently close to 1.5 percent of the refinery capacity (up from

<1 percent till a few years ago) and it is expected (based on stakeholder consultations) to plateau at a maximum value of 2 percent in the future. Further hydrogen demand from refineries was calculated using calorific values.

33 https://www.sciencedirect.com/science/article/abs/pii/S0360319921035448?via%3Dihub

Table 9: Scenarios for Forecasting Hydrogen Demand from Refineries

Growth of Economy and Industry		Optimistic Scenario	Realistic Scenario	Conservative Scenario
		Based on Regression with GDP		Based on historical growth rate of petroleum production (lesser than GDP growth rate) in the past 5-6 years and current expansion plans of refineries.
Transport Demand *(High demand for new- age fuels refers to conservative scenario for hydrogen demand)*	CNG demand (2030)	~25 MMSCMD	~30 MMSCMD	~40 MMSCMD
	Demand for heavy duty vehicles	1.91 MMT,	1.91 MMT	3 MMT
	Petrol + Diesel demand replaced by EVs	15 MMT	15 MMT	15.3 MMT
	Ethanol Blending in Petrol	13%	15%	23%
Feedstock	Hydrogen demand per MMTPA for additional refining capacity	18,000 tons	15,000 tons	12,000 tons

Source: ICF Analysis

The assumptions on the growth rate of petroleum products are:

i. Realistic scenario: CAGR of 3.7 percent for refining capacity till 2025 and later 4 percent for the 2025-30 period.

ii. Optimistic scenario: Growth rate of GDP at 8.6 percent till 2026 and 8 percent for 2025-30.

iii. Conservative scenario: A constant CAGR of 3.7 percent has been assumed from 2022 to 2030.

The refining capacity calculated in each scenario has been further lowered due to transport demand of CNG, HDV, EV, and ethanol (as listed in Table 1010).

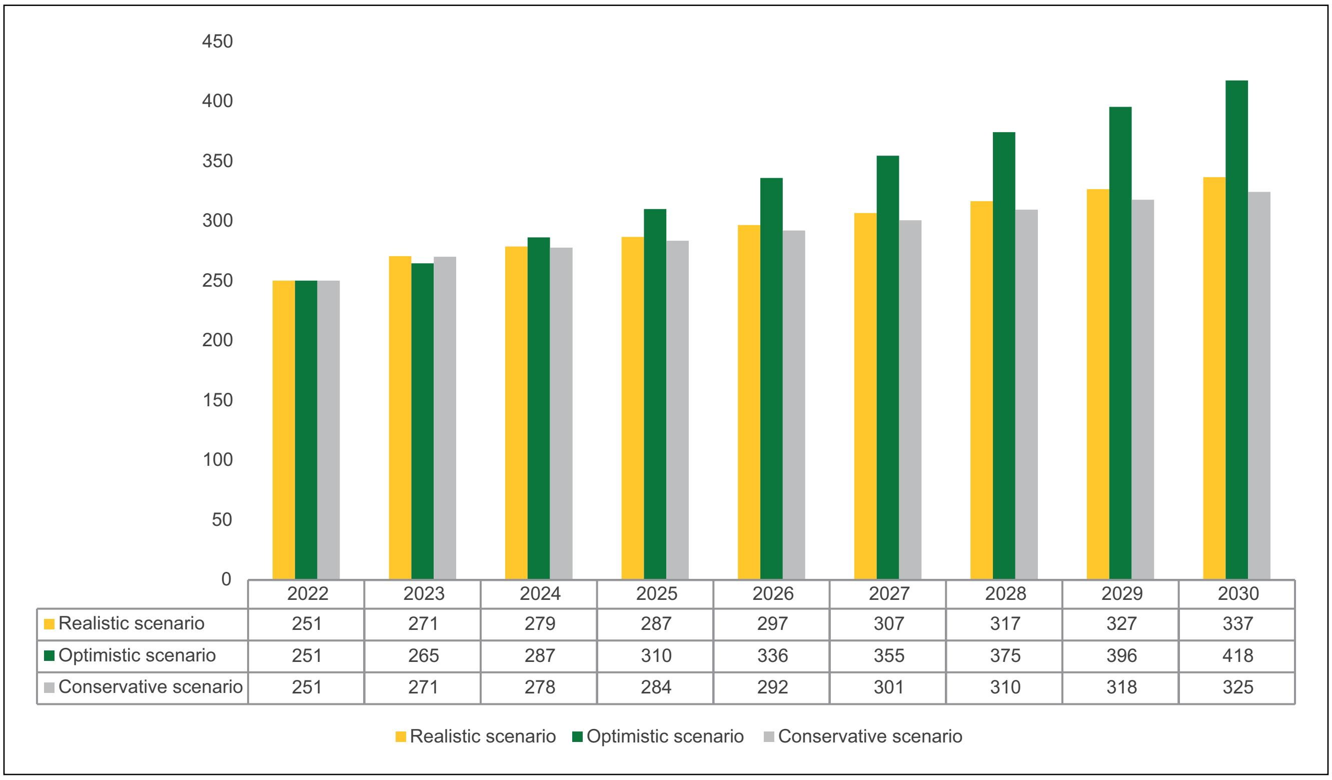
Table 10: Calculated Values for Refining Capacities (MMT)

Year	2023	2024	2025	2026	2027	2028	2029	2030
Refinery Capacity - GDP	276.67	300.59	326.57	354.81	383.19	413.84	446.95	**482.71**
Refinery Capacity – Based on petroleum oils and lubricants production	282.79	293.30	304.19	316.36	329.01	342.17	355.86	**370.10**

Year		2023	2024	2025	2026	2027	2028	2029	2030
Realistic Scenario									
Transport Demand	CNG	4.96	5.59	6.29	6.83	7.34	7.78	8.21	**8.63**
	HDV	0.20	0.33	0.47	0.61	0.76	1.13	1.51	**1.91**
	EV	2.93	4.31	5.82	7.45	9.21	11.11	13.16	**15.38**
	Ethanol	3.53	3.83	4.44	4.77	5.17	5.59	6.26	**6.97**
Optimistic Scenario									
Transport Demand	CNG	4.96	5.59	5.83	6.11	6.39	6.53	6.67	**6.94**
	HDV	0.20	0.33	0.47	0.61	0.76	1.13	1.51	**1.91**
	EV	2.93	4.31	5.82	7.45	9.21	11.11	13.16	**15.38**
	Ethanol	3.53	3.64	4.06	4.37	4.75	5.16	5.36	**5.81**
Conservative Scenario									
Transport Demand	CNG	4.96	5.59	6.29	6.85	7.40	7.96	8.51	**11.11**
	HDV	0.20	0.33	0.47	0.61	0.76	1.00	2.00	**3.00**
	EV	2.93	4.31	5.82	7.45	9.21	11.11	13.16	**15.38**
	Ethanol	4.24	5.47	7.73	8.21	8.82	9.45	10.13	**10.84**

Source: ICF Analysis

Figure 12: Refinery Capacity Forecast (MMTPA)



Source: ICF Analysis

The new hydrogen demand for the 2023-30 period has been calculated by using an assumed per unit of additional refining capacity, for example 15,000 in the realistic scenario (see Table 11). The additional refinery capacity is calculated by the difference in forecasted refinery capacity and installed capacity (250.3 MTPA in 2022).

The total hydrogen demand as feedstock is the sum of this additional hydrogen demand and already installed hydrogen production capacity (2.93 MTPA in 2022). The fuel demand in a refinery is 8 percent of the forecasted refinery capacity. The total hydrogen demand includes hydrogen as feedstock, fuel, and heating source in a refinery.

Table 11: Calculated Values for Hydrogen Demand in Refinery (MMTPA)

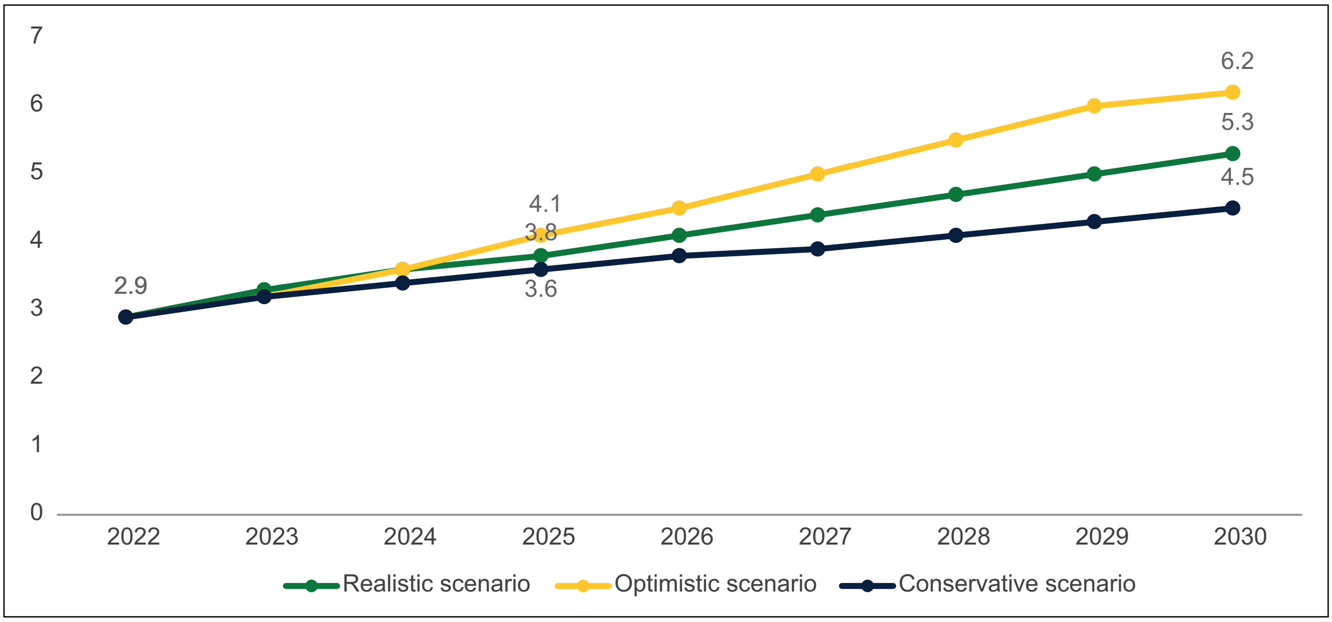
Year		2022	2023	2024	2025	2026	2027	2028	2029	2030
Realistic Scenario	Additional Refinery Capacity	0.20	20.87	28.94	37.06	46.40	54.64	63.67	72.98	82.55
	Hydrogen Demand (New)	0.00	0.28	0.39	0.50	0.62	0.74	0.86	0.99	1.11
	Hydrogen Demand (Feedstock Total)	2.93	3.21	3.32	3.43	3.54	3.66	3.79	3.91	4.04
	Fuel Demand in Refinery	20.04	21.69	22.34	22.99	23.68	24.40	25.12	25.86	26.63
	Hydrogen Demand (For Heating)	0.00	0.13	0.26	0.41	0.56	0.72	0.89	1.06	1.25
	Total Hydrogen Demand	**2.9**	**3.3**	**3.6**	**3.8**	**4.1**	**4.4**	**4.7**	**5.0**	**5.3**
Optimistic Scenario	Additional Refinery Capacity	0.20	6.43	21.62	36.47	49.25	62.58	76.47	91.23	89.67
	Hydrogen Demand (New)	0.00	0.10	0.32	0.55	0.74	0.94	1.15	1.37	1.35
	Hydrogen Demand (Feedstock Total)	2.93	3.02	3.25	3.47	3.67	3.87	4.07	4.30	4.27
	Fuel Demand in Refinery	20.04	20.54	21.75	22.94	23.96	25.03	26.14	27.32	27.20
	Hydrogen Demand (For Heating)	0.00	0.18	0.38	0.61	0.85	1.10	1.38	1.69	1.92
	Total Hydrogen Demand	**2.9**	**3.2**	**3.6**	**4.1**	**4.5**	**4.1**	**5.5**	**6.0**	**6.2**

Year		2022	2023	2024	2025	2026	2027	2028	2029	2030
Conservative Scenario	Additional Refinery Capacity	0.20	20.87	28.94	37.06	45.71	54.57	63.62	72.81	78.98
	Hydrogen Demand (New)	0.00	0.25	0.35	0.44	0.55	0.65	0.76	0.87	0.95
	Hydrogen Demand (Feedstock Total)	2.93	3.18	3.27	3.37	3.48	3.58	3.69	3.79	3.88
	Fuel Demand in Refinery	20.04	21.69	22.34	22.99	23.68	24.39	25.11	25.80	26.34
	Hydrogen Demand (For Heating)	0.00	0.06	0.13	0.20	0.28	0.36	0.44	0.53	0.62
	Total Hydrogen Demand	**2.9**	**3.2**	**3.4**	**3.6**	**3.8**	**3.9**	**4.1**	**4.3**	**4.5**

Source: ICF Analysis

The hydrogen demand in refineries will be between 4.5 MMTPA and 6.2 MMTPA in 2030, with a CAGR of 7.82 percent from 2022 to 2030 in the realistic scenario.

Figure 13: Total Hydrogen Demand in Refineries (MMTPA)



Source- ICF analysis

3.3.3 Iron and Steel

From January to December 2019, India held the position of the world's second-largest producer of crude steel, with a provisional production of 111.25 million tonnes, representing a growth rate of 1.8 percent compared to the corresponding period of the previous year[34]. Further, From January to December 2019, India maintained its position as the top global producer of direct reduced iron (DRI) or sponge iron, with a production of 36.86 million tonnes. This marked a growth rate of 7.7 percent compared to the same period in the preceding year [35]

Hydrogen can replace furnace oil, natural gas, and LPG as the fuel in basic oxygen furnace- and electric arc furnace-based sub processes in the steel sector. It can also be used as a reducing agent in these processes over natural gas and coal.

The historic production of crude steel and finished steel has been analysed through various processes. The future growth trajectory of GDP for different scenarios (as mentioned in Table 12) was used to calculate iron and steel production as per the regression, coupled with forecasted GDP as used to project the natural gas demand. The share of different processes in forecasted iron and steel production, penetration of hydrogen in different processes, and hydrogen-based capacity installation was linearly varied to reach the mix listed in Table 12. The forecast for hydrogen demand from different production processes was calculated using calorific values, to arrive at the trajectories for hydrogen demand under different scenarios.

Table 12:Assumptions for Hydrogen Demand in Iron and Steel Sector for Different Scenario

Demand Driver	BAU
GDP Growth Rates	Three scenarios of GDP growth rate have been considered **Realistic**: GDP growth of 7% by 2030 **Conservative**: GDP growth of 6% by 2030 **Optimistic**: GDP growth of 8% by 2030
Penetration Rate	**For 2030:** BF-BOF: 60%, Electric arc furnace: 32%; Induction furnace: 8%
Penetration Rate: Process Wise	Penetration in existing heating processes (as fuel) is expected to be around 40% in 2030. Penetration in existing reducing processes of coal DRIs is expected to be around 40% in 2030 (use as feedstock) Penetration in reducing processes of additional coal DRIs is expected to be around 100% in 2035 (use as feedstock) Penetration in existing reducing processes of gas DRIs is expected to be around 100% in 2028 (use as feedstock)

34 https://steel.gov.in/sites/default/files/MOSAR_2020.pdf

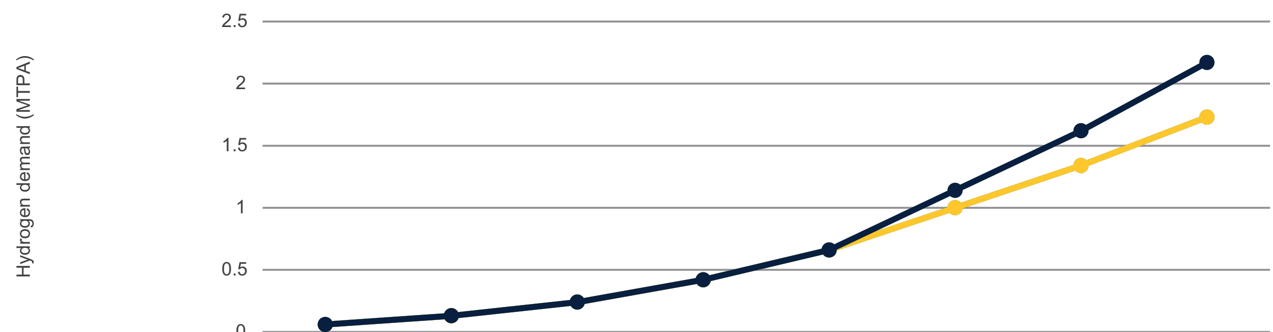
35 https://newsonair.com/2022/04/26/production-of-steel-indias-sterling-performance/

Demand Driver	BAU
Hydrogen-Based Capacity Installation	**Realistic:** All BF-BOF capacity installation post 2030 will be hydrogen-based **Conservative:** All BF-BOF capacity installation post 2035 will be hydrogen-based **Optimistic:** All BF-BOF capacity installation post 2027 will be hydrogen-based
Hydrogen Consumption Per Tonne of Hot Metal (For Gas Steel Plant Capacity)	**28 kg/tonne**

Hydrogen demand in the iron and steel sector is similar in the realistic and conservative scenarios since the technology to use hydrogen in the production of iron and steel is still in the development phase, and a competitive technology is only expected to become commercially viable after 2030.

Therefore, the growth will be gradual. Demand will grow at a CAGR of 62 percent in the realistic scenario.

Figure 14: Hydrogen Demand Projection in Steel and Iron Sectors (MMTPA)



	2023	2024	2025	2026	2027	2028	2029	2030
Realistic scenario	0.06	0.13	0.24	0.42	0.66	1	1.34	1.73
Conservative scenario	0.06	0.13	0.24	0.42	0.66	1	1.34	1.73
Optimistic scenario	0.06	0.13	0.24	0.42	0.66	1.14	1.62	2.17

Source- ICF analysis

3.3.4 Chemicals: Methanol and Hydrogen Peroxide

India's methanol industry is relatively small, with a demand of approximately 2 MT[36] from industrial users to produce chemicals. Nonetheless, the demand is expected to grow rapidly, with the share of methanol imports remaining high. This is primarily a result of a large portion of methanol production coming from natural gas, which is abundantly available in West Asia at extremely low prices. The sector is expected to witness a 6.6-percent growth rate by 2030.[37] The GoI has ambitious plans to expand the domestic methanol industry, using coal-to-methanol technologies. The

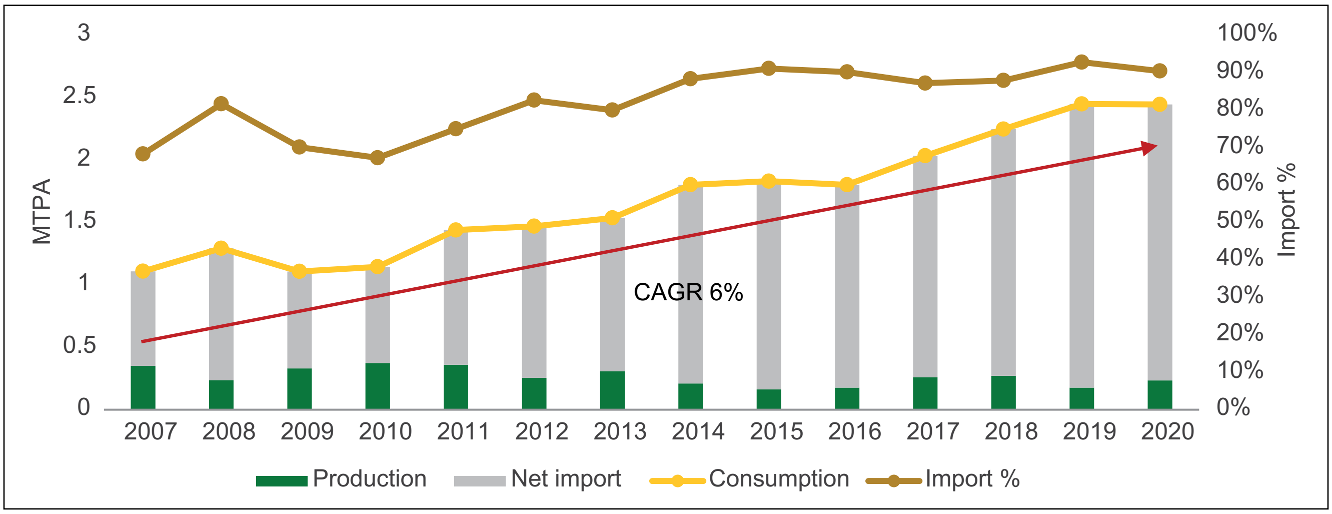
36 The potential role of hydrogen in India 2020

37 ICF primary research

goal is for methanol to displace oil products in major end–use sectors, such as transport (road, rail, and shipping), industry (distributed generators, boilers, heaters), and residential (heating and cooking). According to the plan prepared by NITI Aayog, Indian high ash coal, stranded gas, and biomass can produce 20 MT of methanol annually by 2025.

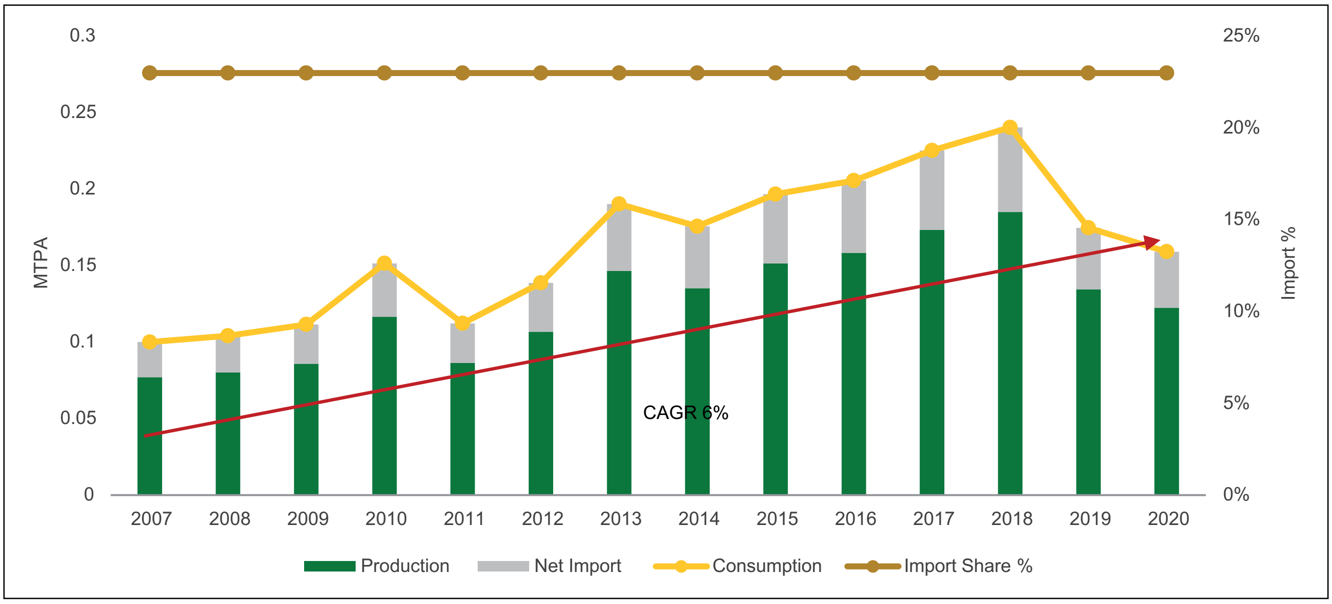
The demand for hydrogen peroxide in India is approximately 165 KTPA, growing at a historical CAGR of 6 percent. As of 2020, India is a net importer, with approximately 23 percent of its demand being met by imports. Hydrogen peroxide demand is expected to grow at 6.9 percent by 2030. The major factors driving this progression include the growing worldwide demand for pulp and paper, along with the increased production of propylene oxide. The increased demand from the textile industry and the paper and pulp sectors is in the form of bleaching agents, where it is used as a raw material for manufacturing propylene oxide.

Figure 15: Status of Methanol Usage in India (MMTPA)



Source- ICF primary research

Figure 16: Status of Hydrogen Peroxide usage in India (MMTPA)



Source- ICF primary research

Three scenarios have been taken to estimate the growth in methanol demand, assuming methanol blending and hydrogen peroxide demand at fixed CAGRs (see Table 13). To reduce import dependencies and reach the targets set by NITI Aayog, different import reduction targets have been assumed in 2030.

Table 13: Assumptions for Hydrogen Demand in Chemicals Sector for Different Scenarios

Scenario		Optimistic	Conservative	Realistic
Methanol	**Growth Assumption**	**8.5%** Assuming a significant uptake in methanol blending	**~6.3%** Assuming past growth trend with no additional growth	**7.5%** Assuming growth starts to pick up and slight blending is achieved
	Import Assumption	Assuming methanol imports reduce to 60% by 2030	Assuming methanol imports reduce to 85% by 2030	Assuming methanol imports reduce to 75% by 2030
Hydrogen Peroxide	**Growth Assumption**	**10%** Assuming hydrogen peroxide finds greater utilisation across sectors with considerable growth in its demand sectors.	**5%** Assuming past growth is replicated in the future as well.	**7%** Assuming the growth is led by the growth of the pulp and paper industry, as it has prominent demand for hydrogen peroxide

Source: ICF Analysis

Hydrogen demand from methanol is calculated taking from the standard factor considered by IEA in its estimations for hydrogen consumption per kilogram of methanol produced. Using the chemical synthesis reaction, hydrogen requirement per kilogram of hydrogen peroxide produced was computed, which was then used to determine the demand.

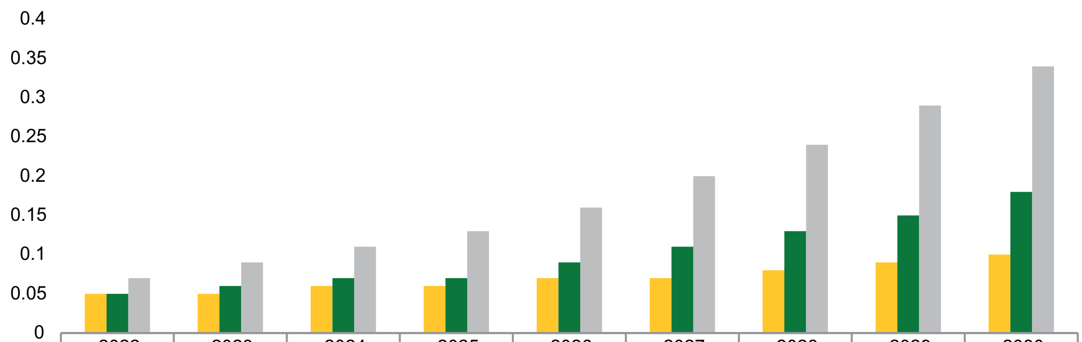
Hydrogen demand in chemicals ranges between 0.1 MTPA in the conservative scenario to 0.34 MTPA in the optimistic scenario. Methanol is responsible for over 80 percent and then over 92 percent of the total hydrogen demand from the chemicals sector in 2030, primarily because of the NITI Aayog's focus on the methanol economy. Additionally, another factor for its higher growth rate is that methanol is a much larger sector than hydrogen peroxide.

Table 14: Hydrogen Demand for Each Chemical (MTPA)

Scenarios	Chemicals	2022	2023	2024	2025	2026	2027	2028	2029	2030
Conservative	**Hydrogen Peroxide**	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Methanol	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.09
Realistic	**Hydrogen Peroxide**	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Methanol	0.04	0.05	0.06	0.06	0.08	0.10	0.12	0.14	0.16
Optimistic	**HydrogenPeroxide**	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
	Methanol	0.06	0.08	0.10	0.12	0.15	0.19	0.23	0.27	0.32

Source: ICF Analysis

Figure 17: Total Hydrogen Demand from Chemicals (MTPA)



	2022	2023	2024	2025	2026	2027	2028	2029	2030
Conservative scenario	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.1
Realistic scenario	0.05	0.06	0.07	0.07	0.09	0.11	0.13	0.15	0.18
Optimistic scenario	0.07	0.09	0.11	0.13	0.16	0.2	0.24	0.29	0.34

Source- ICF analysis

3.3.5 Transport sector

3.3.5 .1 Road transport:

The adoption of hydrogen as a fuel for automobiles has gained traction in India in recent years, with the sector expected to experience a growth rate of 17.3 percent by 2030. The Ministry of New and Renewable Energy is actively supporting hydrogen projects across academic institutions, research organisations, and the industry. Notable initiatives involve the development of internal combustion engines fueled by hydrogen to power two- and three-wheelers and minibuses. Additionally, two hydrogen refueling stations have been established at the Indian Oil R&D Centre in Faridabad and the National Institute of Solar Energy in Gurugram. In 2020, the ministry partnered with NTPC Limited to propose the launch of a pilot fuel cell bus project.[38] Few other initiatives are also underway for instance, in 2019, Tata Motors launched a hydrogen fuel cell bus in collaboration with Indian Oil Corporation Limited.[39]

For this study, the historical growth rates of newly registered vehicles were analysed to forecast the total vehicle registered per district across all states up to 2030. The calculation of vehicle lifespan and the determination of total annual on-road vehicles per district were derived from the 2020 national-level vehicle registration data (sourced from the Ministry of Road Transport & Highways, Government of India (VAHAN)) using the scrappage curves. The demand for liquid (petrol/diesel) fuels was estimated using district-wise kilometres travelled and national average mileage in each vehicle category. For district-wise vehicles using CNG, projected demand was calculated for existing gas and new gas separately with penetration based on a tier-wise classification of districts. Assessing past trends and new technologies, appropriate penetration was applied for future projection for EVs and FCEVs.

The blending of hydrogen with CNG and the use of hydrogen in FCEVs are potential areas of demand.

38 https://energy.economictimes.indiatimes.com/news/renewable/mnre-and-ntpc-to-launch-hydrogen-fuel-cell-bus-project-in-leh-mnre-secy/74242771

39 https://www.fchea.org/transitions/2020/6/9/fuel-cell-and-hydrogen-development-in-india

Using district-wise CNG demand, and based on stakeholder consultations and global studies, the optimistic, conservative and realistic scenarios for hydrogen compressed natural gas adoption were established (see Table 15).

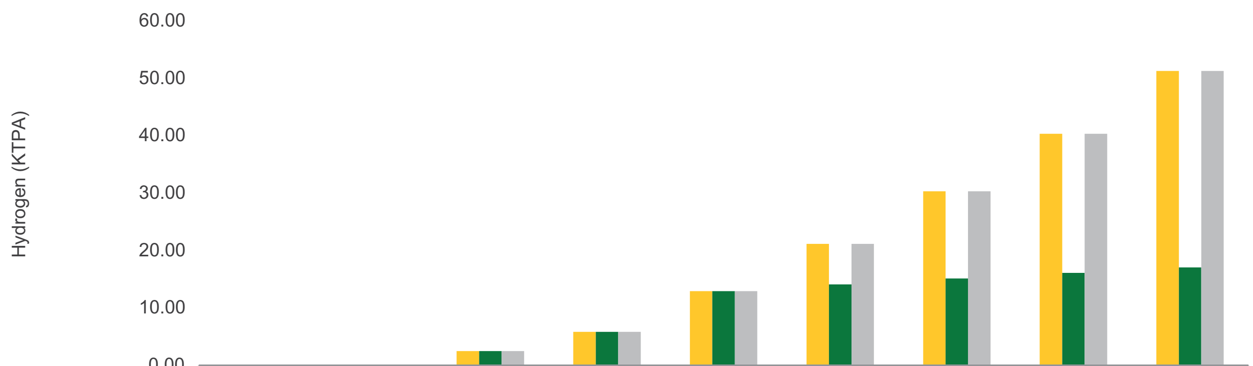
Due to lower blending percentages of hydrogen, the maximum demand for hydrogen in the optimistic scenario will be 0.027 MTPA by 2030. If the BIS 15490 stipulation (a 2 percent hydrogen limit in CNG cylinders) is considered, that will result in hydrogen demand of 0.017 MTPA by 2030. CNG cylinders are the major limitation for blending, but if alleviated through R&D, the realistic scenario of 0.51 MTPA hydrogen demand can be reached.

Table 15: Scenarios for Assessing HCNG Demand

Scenario	Optimistic	Conservative	Realistic
Definition	Optimum blending of 6% to be achieved by 2030	Considering current pilot studies being done by GAIL and CNG blending limit	Based on stakeholder views and possible plans for higher blending
Assumption	Assuming optimum blend can be used in Indian vehicles **Blending to be done at all CNG retail outlets**	Assuming no infrastructure augmentation in the future **Blending at city gate station**	Assuming advanced R&D takes place, and infrastructure augmentation is conducted. **Blending at city gate station**
Blending Targets	2%- 2026 6%- 2030	2% reached by 2026, and then it stays constant	2% - 2026 6% - 2030

Source: ICF Analysis

Figure 18: Hydrogen Demand Scenarios



	2022	2023	2024	2025	2026	2027	2028	2029	2030
Optimistic scenario	0.00	0.00	2.55	5.89	12.99	21.22	30.35	40.38	51.31
Pessimistic scenario	0.00	0.00	2.55	5.89	12.99	14.15	15.17	16.15	17.10
Realistic scenario	0.00	0.00	2.55	5.89	12.99	21.22	30.35	40.38	51.31

Optimistic scenario Pessimistic scenario Realistic scenario

Hydrogen demand from FCEVs was estimated with following assumptions:

i. FCEV Vehicle Category: Cars, buses, LCV, and HCV were chosen as the possible market for FCEVs considering its range of benefits and the Indian market.

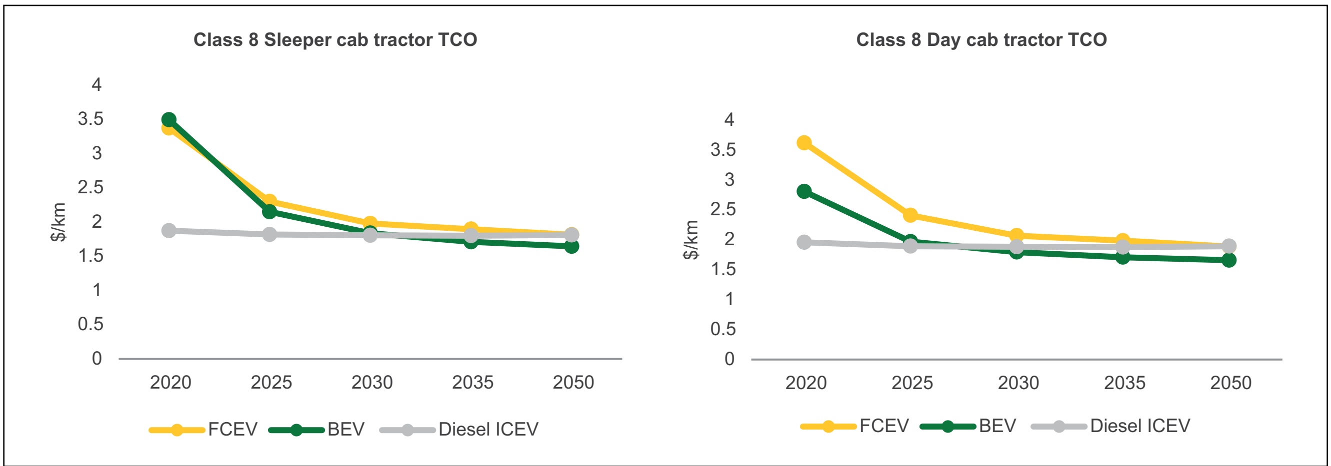
ii. FCEV Growth Trajectory: As a new alternative fuel vehicle, FCEV is will likely face challenges initially, but will eventually witness exponential growth due to technology development.

iii. Similar Driving Pattern: FCEVs are assumed to have the same vehicle kilometres travelled (VKT) as current diesel/petrol vehicles.

iv. Final Demand: Considering fuel consumption from available global models, the final hydrogen demand is calculated.

Based on the total cost of ownership (TCO) projection until 2050, EVs will continue to undercut FCEVs due to the first mover advantage (see Figure 19). The TCO projection follows a similar trajectory for EVs and FCEVs and will be in close range to each other by 2030. TCO comparison shows that to promote FCEVs over EVs, the focus needs to be on capitalising on the technical benefits of FCEVs over EVs, such as longer range and less refuel time. These benefits are extremely important for long range transport.

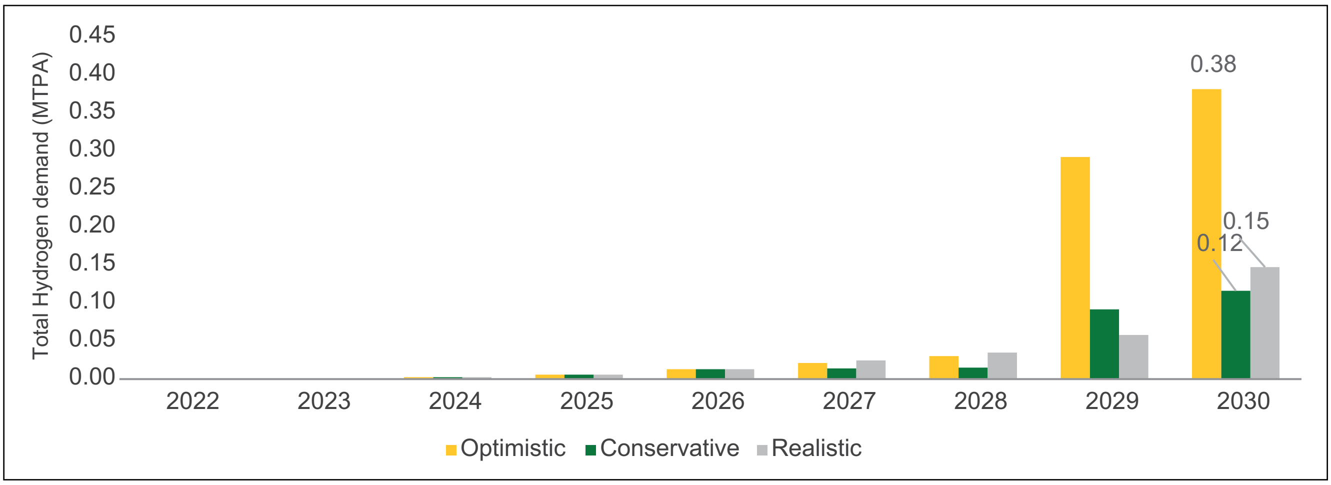
Figure 19: Total cost of ownership projection till 2050



Source- ICF analysis

Hydrogen demand of 0.1 MTPA is possible with around 0.26 percent FCEV penetration in cars, buses, LCVs, and HCVs in 2030. A 0.35 percent FCEV penetration in on-road vehicles by 2030 will result in a hydrogen demand of 0.33 MTPA. According to ICF research, FCEVs are set to be on the road as early as 2027.

Figure 20: Total Road Transport Hydrogen Demand (MTPA)



Source- ICF analysis

3.3.6 Large industries

The industries covered under this section include steel, chemicals, automobile, engineering, pharmaceutical, glass, and refineries, among others (see Table 16).

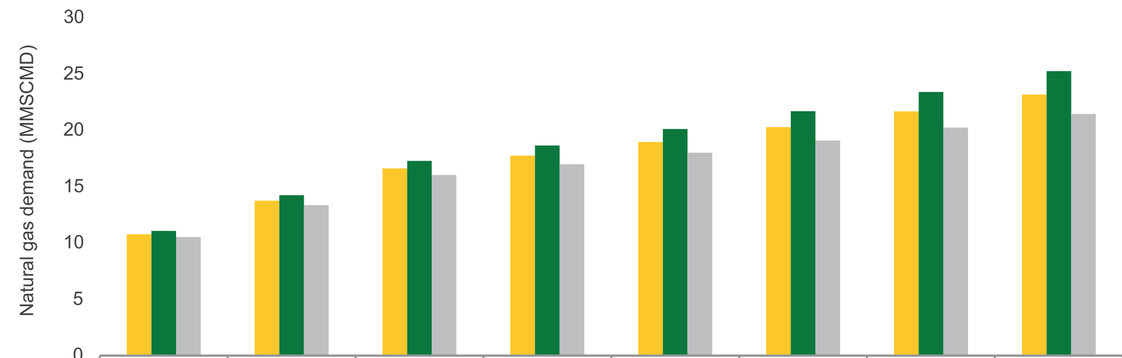
Table 16: Number of Industries

Sector	Number of industries
Steel	43
Chemicals	20
Automobile	4
Engineering	6
Pharmaceutical	2
Glass	19
Refinery	23
Others (including minerals, refractory, paper, dairy, metals and aluminium)	6

Source: ICF Analysis

To assess hydrogen demand (for blending with natural gas), this study first estimated natural gas equivalent *demand* using information from previous interactions with selected industrial units and then projecting the demand based on industry/state level manufacturing growth indicators. Assuming linear progression of replacement level based on the year of pipeline connectivity and final future mix, the future replacement of fuels by natural gas was projected in three scenarios. For refineries, where hydrogen might directly be used for heating, penetration rates on fuel demand were taken, which is typically 8-10 percent of the refinery capacity. The projected trajectory of natural gas demand across large industries in India is shown in Figure 21.

Figure 21: Total Natural Gas Demand in Large Industries (MMSCMD)



	2023	2024	2025	2026	2027	2028	2029	2030
Realistic scenario	10.78	13.77	16.62	17.76	18.98	20.29	21.69	23.19
Opportunistic scenario	11.07	14.25	17.3	18.66	20.13	21.71	23.42	25.26
Pessimistic scenario	10.53	13.37	16.04	17	18.02	19.1	20.25	21.47

Source- ICF analysis

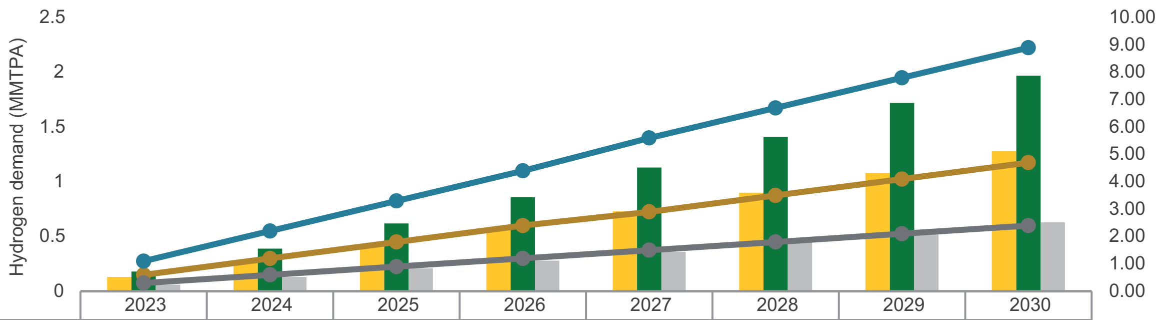
Although hydrogen is currently not a go-to fuel for heating due to its high cost, it may witness high levels of consumption directly and through blending with gas in the future. To project this trajectory of hydrogen demand across large industries in India, this study factored in the uptake of hydrogen blending for different scenarios.

Table 17: Assumptions on Hydrogen Demand in Large Industries

Scenario	Blending in Natural Gas (Till 2030)
Hydrogen Blending - Realistic Scenario	4.7%
Hydrogen Blending - Optimistic Scenario	~8.9%
Hydrogen Blending - Conservative Scenario	~2.4%

Source: ICF Analysis

Figure 22: Hydrogen Demand in Large Industries (MMTPA) And Blending %



	2023	2024	2025	2026	2027	2028	2029	2030
H2 demand-Realistic	0.13	0.27	0.41	0.57	0.73	0.9	1.08	1.28
H2 demand-Optimistic	0.18	0.39	0.62	0.86	1.13	1.41	1.72	1.97
H2 demand-Conservative	0.06	0.13	0.21	0.28	0.36	0.45	0.54	0.63
Blending %-Realistic	0.60	1.20	1.80	2.40	2.90	3.50	4.10	4.70
Blending %-Optimistic	1.10	2.20	3.30	4.40	5.60	6.70	7.80	8.90
Blending %-Conservative	0.30	0.60	0.90	1.20	1.50	1.80	2.10	2.40

3.3.7 City Gas Distribution Blending

The CGD network is scattered across India. Figure 23 depicts the network up to the 10th CGD bidding round (2021)[40] of the PNGRB.

To utilise hydrogen across CGD networks in India, the first step is to blend hydrogen with natural gas. Infrastructure connectivity across CGD networks is required for quick ramping up of hydrogen blending across CGD networks.

Hydrogen blending in CGD networks is limited by the pipeline material used, and limitations in the end-use applications. GAIL (India) Limited's pilot project in Madhya Pradesh is aiming for 2 percent blending and raising it to 5 percent by circumventing the CNG refiling stations. Technical studies are also underway to determine the limitation of hydrogen blending in India's city gas pipeline networks based on the type of steel used. The result of these studies will determine the future percentage of CGD blending. The end-use limitations of hydrogen blending as per secondary technical reports for industrial use is 10 percent (without technological augmentation) and is 30 percent for commercial and industrial use.

For CGD, the demand projections have been categorised into industrial, domestic, and commercial categories. The assumptions for each category are listed in the Table 18.

40 The 11th bidding round was held in 2021. So, the map is an accurate depiction till 2021.

Figure 23: CGD Network in India (MoPNG and PPAC stats)

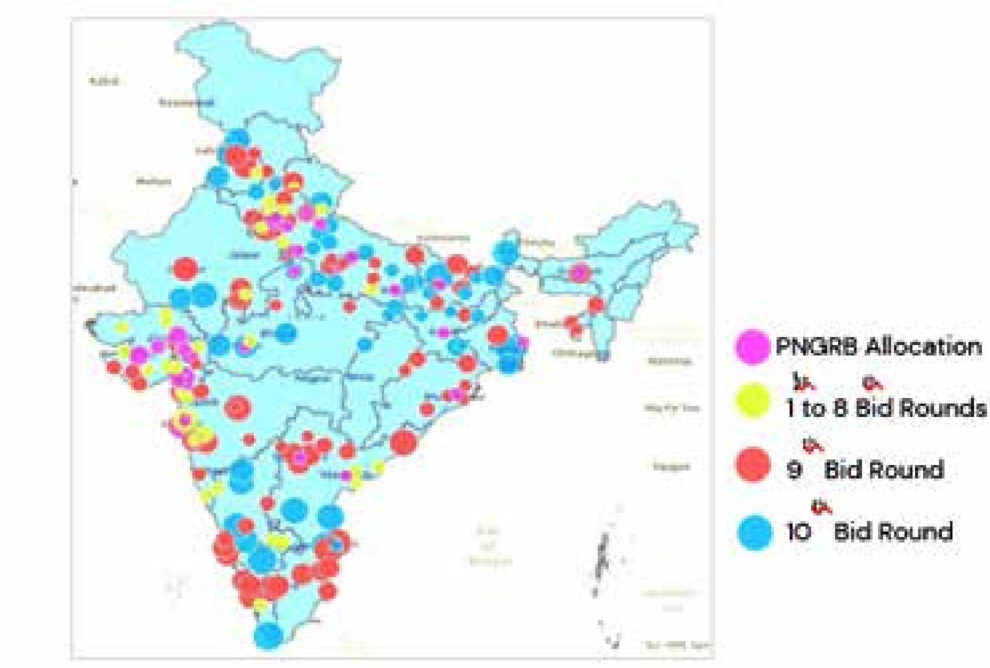
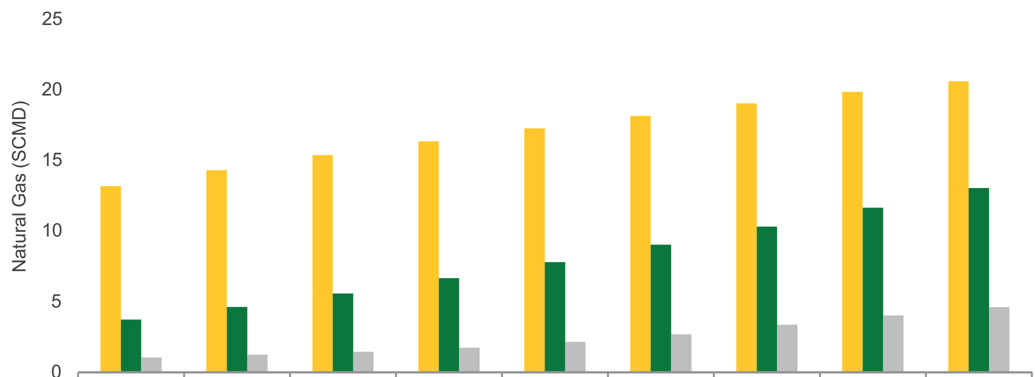


Table 18: Key Assumptions

<table>
<tr><th>Industrial demand</th><th>Domestic demand</th><th>Commercial demand</th></tr>
<tr>
<td>Analysing historic growth of fuel demand and projecting future demand based on it assuming:
Replacement of fuels by natural gas to start from the year of pipeline connection.
Reach the following penetration levels in next 20 years:
Up to 33% for furnace oil, 62% for LPG, 7% for diesel, and 41% for Light Diesel Oil + Low Sulphur Heavy Stock in the realistic scenario, following a linear trajectory</td>
<td>Analysing historic growth of domestic LPG demand based on population growth forecast assuming:
Replacement of domestic LPG demand by natural gas to start from the year of pipeline connection to the district.
Reach the penetration levels of 5.5% (tier 7 districts) and 10% (tier 1 districts) till 2030, following a linear trajectory</td>
<td>Analysing historic growth of commercial LPG demand and projecting future demand assuming:
Replacement of commercial LPG demand by natural gas to start from the year of pipeline connection to the district.
Reach the following penetration levels till 2030, following a linear trajectory:
~31% in the realistic scenario,
~41% in the optimistic scenario, and
~21% in the conservative scenario</td>
</tr>
<tr><td colspan="3">The extent of hydrogen blending is assumed to start from nil to linearly reach:
2% under the conservative scenario (considering current pilot studies by Gail India and no infrastructure augmentation)
5% under the realistic scenario (based on stakeholder views, possible plans and technical test reports)
~9% under the optimistic scenario (based on infrastructure augmentation) by 2030.</td></tr>
</table>

Source: ICF Analysis

Figure 24: Expected Natural Gas Demand Without H2 Blending (SCMD)

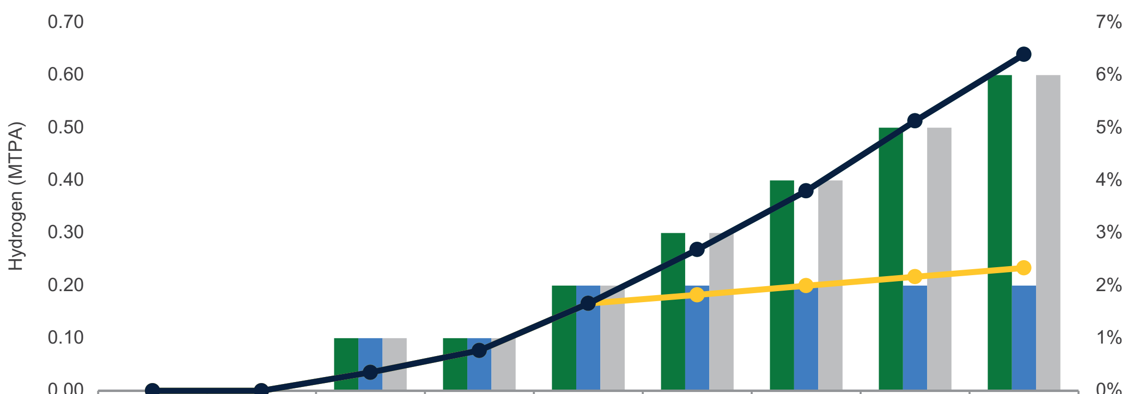


	2022	2023	2024	2025	2026	2027	2028	2029	2030
Natural Gas Demand - Industrial	13.21	14.32	15.41	16.38	17.29	18.18	19.06	19.88	20.64
Natural Gas Demand - Domestic	3.74	4.64	5.59	6.68	7.81	9.05	10.33	11.67	13.07
Natural Gas Demand - Commercial	1.06	1.25	1.45	1.74	2.16	2.70	3.38	4.03	4.63

Source- ICF analysis

The hydrogen demand forecast from CGD blending is calculated using calorific values and volumes of hydrogen compared to natural gas. Considering inputs from stakeholders that only 2 percent blending of hydrogen in CGD network is currently being done in India, the conservative scenario leads to an approximate hydrogen demand of 0.23 MTPA by 2030. In the realistic scenario, approximately 0.64 MTPA hydrogen demand could be achieved if technical feasibility for 6 percent blending is achieved in India.

Figure 25: Consolidated Hydrogen demand in CGD (MTPA)

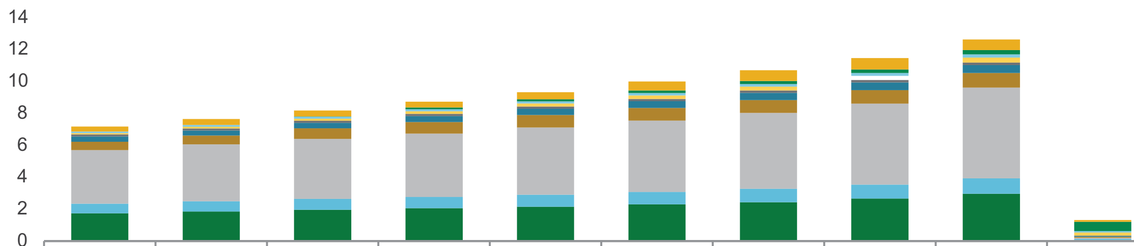


	2022	2023	2024	2025	2026	2027	2028	2029	2030
Realistic demand (%)	0%	0%	1%	1%	2%	3%	4%	5%	6%
Conservative demand (%)	0%	0%	1%	1%	2%	2%	2%	2%	2%
Optimistic demand (%)	0%	0%	1%	1%	2%	3%	4%	5%	6%
Realistic demand	0.00	0.00	0.03	0.08	0.17	0.27	0.38	0.51	0.64
Conservative demand	0.00	0.00	0.03	0.08	0.17	0.18	0.20	0.22	0.23
Optimistic demand	0.00	0.00	0.03	0.08	0.17	0.27	0.38	0.51	0.64

Source- ICF analysis

Figure 26: Forecasted Sectoral Hydrogen Demand Till 2030

Sector wise hydrogen demand (MMT), FY 2022-2030



	2022	2023	2024	2025	2026	2027	2028	2029	2030	CAGR
Others	0.31	0.37	0.37	0.37	0.44	0.56	0.67	0.72	0.66	0.11
HFCV	0	0	0.02	0.11	0.13	0.16	0.19	0.22	0.27	58.06%
FG	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.18	0.2	9.07%
OF	0.08	0.11	0.13	0.16	0.19	0.22	0.24	0.26	0.32	18.83%
Steel	0.13	0.13	0.13	0.14	0.14	0.14	0.15	0.15	0.16	2.62%
H2O2	0.33	0.31	0.34	0.37	0.39	0.43	0.45	0.48	0.49	5.15%
Methanol	0.53	0.55	0.66	0.72	0.78	0.79	0.81	0.85	0.91	7.05%
Petroleum Refinery	3.35	3.57	3.76	3.97	4.21	4.47	4.75	5.06	5.68	6.81%
Fertlizers	0.6	0.64	0.68	0.7	0.75	0.77	0.84	0.88	0.97	6.15%
Ammonia	1.74	1.85	1.96	2.06	2.15	2.30	2.43	2.66	2.96	6.89%

Source- ICF analysis

3.3.8 Demand from other potential industries

- **Cement:** Hydrogen has limited use in the production of cement. It cannot be used as an ingredient or reactant in the conventional method of cement production, but it can be used as a substitute of some fossil fuels used in the sector.

- **Aviation:** Sustainable fuels are being considered globally to decarbonise the aviation industry. At present, technological constraints, infrastructure challenges, hydrogen availability, high cost, and public perception remain among the leading challenges for adoption of hydrogen in aviation.

- **Railways:** The Indian Railways' '100 percent electrification' mission can potentially create a demand for hydrogen. As of March 31, 2022, Indian Railways has electrified 52,247 route kilometers (RKMs), encompassing approximately 80 percent of the entire broad-gauge network spanning 65,141 RKMs.

- **Shipping:** The EU has introduced new rules for the use of hydrogen as a fuel in shipping, which will require the development of a significant number of hydrogen refuelling stations along the coast. The regulations, which came into effect on 1 January 2023 set out a framework for the use of hydrogen in ships, including safety and technical requirements. The goal is to encourage the shipping industry to transition away from fossil fuels and towards more sustainable energy sources. Similarly, for the integration of green hydrogen into the shipping sector, India would require updated regulations governing the utilisation of hydrogen as a shipping fuel. Moreover, the establishment of dedicated bunkering infrastructure is crucial. This entails the creation of hydrogen refueling stations and the implementation of bunkering facilities at ports.

3.4 Identifying green hydrogen 'early adopter' sectors

The industries that currently use natural gas as a feedstock can be the ideal sectors to become the early adopters of green hydrogen. However, while assessing the shift to green hydrogen in these industries, it is important to understand the drivers of demand for green hydrogen in each. The two key factors that are expected to drive the shift to green hydrogen are cost effectiveness and a greater availability of green hydrogen.

The National Green Hydrogen Mission was approved in January 2023, and will be implemented in a phased manner, with an initial focus on deploying green hydrogen in sectors already using hydrogen, and evolving an ecosystem for R&D, regulations, and pilot projects. The idea is to increase the utilisation of hydrogen in sectors such as refineries, fertilisers and CGD, which will also create a sustained demand to support new investments in green hydrogen production.

The three sectors have been considered as the potential demand drivers for green hydrogen as a replacement for natural gas (see Table 19)

Table 19: Proposed Trajectory for replacement of Natural Gas to Green Hydrogen

Sector	2025-26	2029-30
Refining	10%	50%
Fertiliser Production	15%	50%
City Gas Distribution	5%	10%

3.4.1 Fertiliser

The fertiliser industry utilises natural gas to produce ammonia, which acts as the main intermediary in providing nitrogen to all nitrogen-containing fertilisers. Among the nitrogenous fertilisers, urea is the most commonly used fertiliser constituting around 60 percent[41] of the total fertiliser demand. However, there are other various grades of complex fertilisers as well with different nitrogen contents. Diammonium phosphate is the most used complex fertiliser in India, with approximately 18 percent[42] nitrogen content.

The production methodology of urea using natural gas as the input is described below:

$CH_4 + H_2O$ + Heat -> $CO_2 + 3\ H_2$ (Hydrogen Production)
N2 + 3 H2 -> 2 NH3 (Ammonia production – Haber-Bosch Process)
CO2 + 2 NH3 -> CH4N2O + H2O (Urea Production)

The production of urea requires 0.74 MT carbon dioxide per MT of urea produced. The carbon dioxide produced as the by-product in the process is further utilised internally for urea production. Further, the GoI's subsidy outgo compensates about 76 percent[43] of the urea production cost.

It further appears that the production of urea through green hydrogen will require an additional source of carbon dioxide along with some configurational changes in the plant, which can have a higher cost impact on the overall production. This might further lead to an increase in the subsidy burden on the government. Given these concerns, urea has been excluded from the purview of the proposed targets.

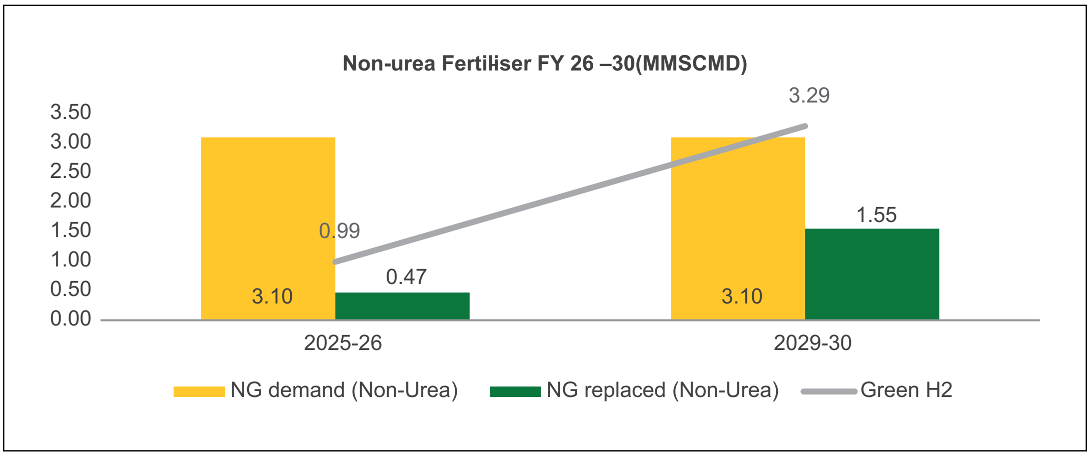
The trajectory proposed for non-urea fertilisers is shown in the Figure 27.

41 https://www.teriin.org/sites/default/files/2021-07/Report_on_The_Potential_Role_of_%20Hydrogen_in_India.pdf

42 https://www.teriin.org/sites/default/files/2021-07/Report_on_The_Potential_Role_of_%20Hydrogen_in_India.pdf

43 Draft NHEM

Figure 27: Volume Replacement in Fertiliser[44]



Source- ICF Analysis

As indicated in Figure 27, by 2030, green hydrogen demand in non-urea fertiliser will be equivalent to 1.55 MMSCMD of the natural gas demand. This is expected to replace approximately 4 percent of the total natural gas demand in the fertiliser sector.

3.34.2 Refinery

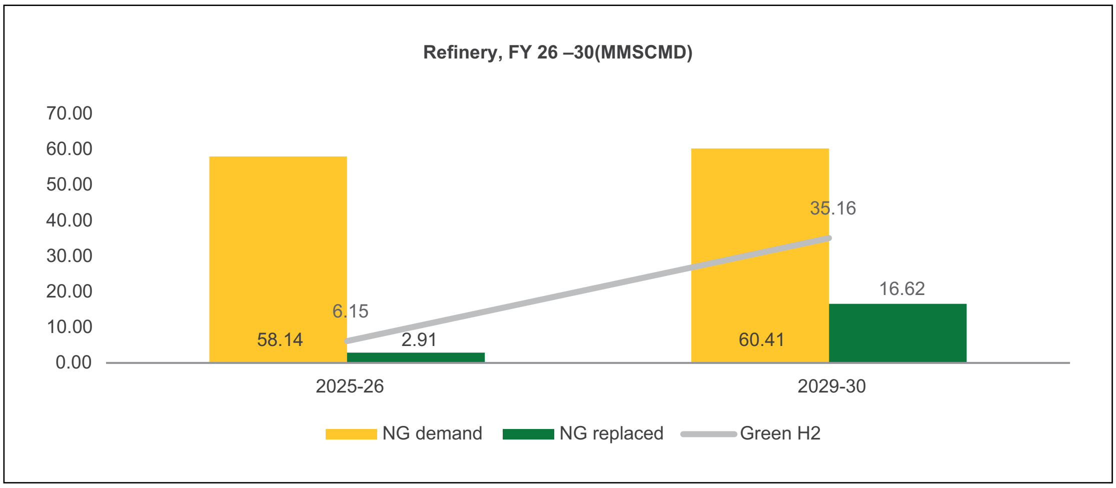
In refineries, hydrogen is mainly used for processing crude oil into refined products and for desulphurisation. Historically, naphtha was used to produce hydrogen through onsite catalytic reformation, which required hydrotreating and hydrocracking processes. With the growing demand for naphtha in petrochemical refineries to maximise profits, natural gas reformation gradually supplanted the previous method over time. Further, hydrogen is also produced as a by-product during the refining process. However, the volume of the by-product hydrogen is insufficient to meet the total refinery hydrogen demand. All the refineries have onsite hydrogen production units using natural gas or naphtha reforming.

Further, only the production of hydrogen from a hydrogen generation unit (producing on-demand hydrogen) has been considered for the green hydrogen trajectory. Accordingly, the proposed target for refineries is provided in Figure 28.

By 2030, green hydrogen demand in refineries will be 35.16 MMSCMD, which is equivalent to natural gas demand of 16.62 MMSCMD. The share of natural gas demand in hydrogen generation units have been considered at 50 percent (2026) and 55 percent (2030). The increase in the share of hydrogen generation units between 2026 and 2030 is because of a lower sulphur content and the shift from diesel to petrol. This will replace approximately 28 percent of the total natural gas demand in refining.

44 Natural Gas Consumption per Ton of H2 production is 4 Ton. Natural Gas supply to non-urea fertiliser is considered as 5% of total supply

Figure 28: NG Volume Replacement in Refinery



Source- ICF Analysis

3.4.3 City Gas Distribution

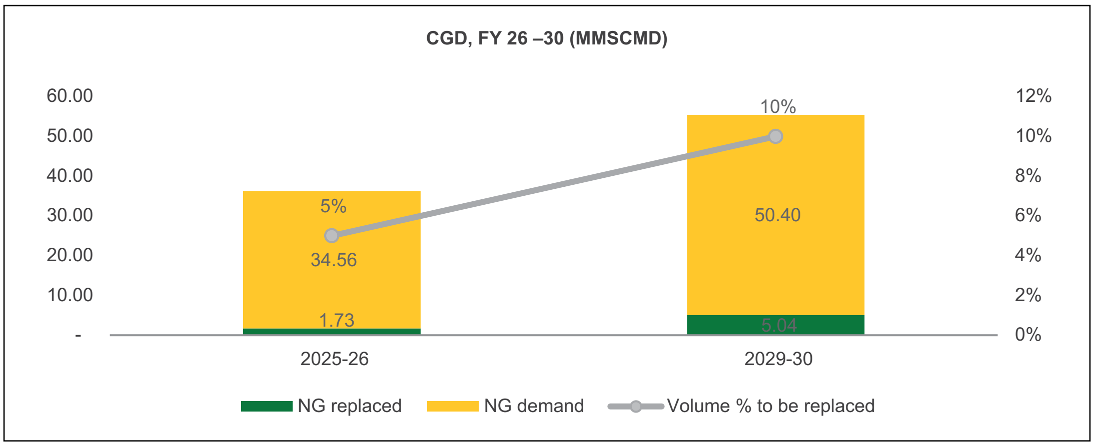
This sector is expected to uptake hydrogen in the form of blending. The proposed trajectory green hydrogen in CGD is shown in the Figure 29.

By 2030, CGD will have 10 percent blending of green hydrogen by volume, replacing 5.04 MMSCMD of natural gas.

3.5 Ongoing developments, tie-ups, and pilot projects

With the green energy movement growing, many companies have already forayed into the sector (see Table 20 and Table 21)

Figure 29: Ng Volume Replacement in CGD



Source- ICF Analysis

Table 20:Green Hydrogen Projects Under Development

Company	Segment	Development/Plans	Location	Year
Oil India Limited	Green Hydrogen Pilot Plant	Grade: 99.999%[45] pure Production: 10 kg per day (plans to increase to 30 kg per day in future) Technology: Anion exchange membrane electrolyser array	Jorhat Pump Station, Assam	Apr 2022 (Within 3 Months)
HPCL	Green Hydrogen	The goal is to establish a green hydrogen capacity of 24,000 tonnes[46] annually and to achieve the commissioning of a green hydrogen plant with a capacity of 370 tonnes per year.	Andhra Pradesh	December 2022
Ohmium	Electrolyser	In 2021, the manufacturing capacity was approximately 0.5 GW per year[47], with plans for swift expansion to reach 2 GW per year.	Karnataka	2022
GAIL (India) Ltd	Green Hydrogen	Has floated a recent tender to procure an electrolyser. They are looking at locations to finalise a 10 MW[48] plant with the capability of generating 4.5 tonnes of green hydrogen daily	2-3 locations, including Madhya Pradesh	2023
Indian Oil Corporation Limited	Green Hydrogen	Has floated tender to develop green hydrogen generation facility with 7,000 MT[49] annual capacity planned to build India's first green hydrogen plant at its Refinery	Mathura, Panipat	2025
BPCL	Electrolyser	Has announced to float a tender for a 20 MW electrolyser[50] to build the country's largest green hydrogen plant	Madhya Pradesh	Not Revealed

Source- ICF secondary research

45 https://economictimes.indiatimes.com/industry/renewables/oil-india-limited-commissions-indias-first-99-999-pure-green-hydrogen-pilot-plant/articleshow/90963593.cms

46 https://energy.economictimes.indiatimes.com/news/oil-and-gas/indian-refiner-hpcl-eyes-net-zero-carbon-emissions-by-2040/89260403

47 https://www.ohmium.com/news/ohmium-launches-indias-first-green-hydrogen-electrolyzer-gigafactory-

48 https://www.business-standard.com/article/companies/gail-seeks-to-procure-india-s-largest-hydrogen-electrolyser-121102101207_1.html

49 https://mercomindia.com/indian-oil-floats-tender-green-hydrogen/

50 https://economictimes.indiatimes.com/industry/renewables/bpcl-green-hydrogen-unit-to-be-indias-largest/articleshow/87878954.cms?from=mdr

Table 21: Announcement on Segment-Wise Major Collaborations

Company	Segment	Vision	Target Year
Statkraft and Aker Horizons	Green Hydrogen and Ammonia Production	Explore joint development opportunities for fully integrated renewable power generation and green hydrogen production in India, targeting domestic hard-to-abate industries, such as the steel and ammonia for domestic use and export	Not Revealed
Greenko Group and Belgium's John Cockerill	Electrolyser Factory	Set up 2 GW[51] alkaline electrolyser factories in India over the next 12-18 months to make hydrogen for industrial use in the country at the lowest cost	2023
SFC Energy and FC TecNrgy	Green Hydrogen and Methanol Fuel Cells	Plans to set up a manufacturing unit, R&D and a repair centre in Gurugram, Haryana. They have also revealed their introduction of the EFOY Hydrogen Fuel Cell in the Indian market.	Not Revealed
L&T and Hydrogen Pro	Electrolyser Factory	The large-scale production of alkaline water electrolysers utilising HydrogenPro technology for the Indian market in gigawatt capacity.	Not Revealed
IOCL, L&T and Renew	Green Hydrogen	Recently signed a binding term sheet for the formation of a joint venture company to develop India's nascent green hydrogen sector	Not Revealed
Technip Energies and Greenko ZeroC Private Ltd	Green Hydrogen	Examine the prospects for green hydrogen project development in various sectors within India, such as refining, petrochemicals, fertilisers, chemicals, and power plants, with the aim of expediting the nation's energy transition.	Not Revealed
JSW and Fortescue Future Industries	Green Hydrogen	Announcement on green hydrogen for steelmaking and hydrogen mobility. Plans to announce first green hydrogen project soon	2030
Reliance Industries Limited	Green Hydrogen/ Electrolyser Factory	At the 2021 International Climate Summit, outlined a 1-1-1 vision to trim the cost of hydrogen to under US$1 per 1 kg in 10 years[52]. The company is developing four giga factories, which include an integrated solar PV module factory, an advanced energy storage battery factory, an electrolyser factory for the production of green hydrogen, and a fuel cell factory. In January 2022, announced plans to invest US$75 billion[53] in renewables infrastructure, including generation plants, solar panels, and electrolysers.	2025

51 https://economictimes.indiatimes.com/industry/renewables/greenko-john-cockerill-to-set-up-2-electrolyser-giga-factories-for-green-hydrogen/articleshow/90784080.cms

52 https://www.business-standard.com/article/economy-policy/mukesh-ambani-sees-green-hydrogen-costs-coming-down-to-1-per-kg-in-10-yrs-121090300540_1.html

53 https://economictimes.indiatimes.com/industry/renewables/mukesh-ambanis-75-billion-plan-aims-to-make-india-a-hydrogen-hub/articleshow/89215398.cms

Company	Segment	Vision	Target Year
Acme	Green Hydrogen	Aims to be a major producer with annual capacities of about 10 million tonnes by 2030[54] Plans to invest US$6.7 billion[55] in green hydrogen project in Karnataka	2030
NTPC	Electrolyser	Develop a 5 MW hydrogen generation plant. It is running a pilot project at its Vindhyanchal unit, where the cost of hydrogen is estimated to be around US$2.8-3/kg[56]	Not Revealed
NTPC	Electrolyser	Invited bids to select electrolyser technology provider(s) for a period of two years for Proton Exchange Membrane and non-Proton Exchange Membrane technology of 400 MW and 600 MW, respectively[57]	Not Revealed

Source- ICF secondary research

54 https://www.eqmagpro.com/acme-eyes-10-million-tonnes-green-hydrogen-ammonia-capacity-by-2030-chairman-manoj-upadhyay-says/
55 https://www.livemint.com/industry/energy/acme-group-to-invest-6-7-billion-in-green-hydrogen-project-in-karnataka-11654512422437.html
56 https://www.livemint.com/industry/energy/five-indian-companies-leading-the-green-hydrogen-revolution-11636369476063.html
57 https://mercomindia.com/ntpc-invites-bids-from-electrolyzer-technology-providers/

4

Hydrogen production technologies and pricing

4.1 Hydrogen production methods

Hydrogen can be produced from different processes using both conventional and alternative energy resources, such as natural gas, coal, nuclear, biomass, solar, and wind. The most common methods used in industries to produce hydrogen are SMR and electrolysis. Some of the most common techniques currently being used or researched to produce hydrogen are listed in the Table 22.

Table 22: Production Processes of Hydrogen

S. No.	Processes	Description
1	**Thermochemical Processes**	
1.1	SMR (also called Natural Gas Reforming)	• Natural gas contains methane (CH_4) that can be used to produce hydrogen through thermal processes, such as SMR and partial oxidation. • About 95%[58] of the hydrogen produced in the US is through natural gas reforming in large central plants.
1.2	Biomass Gasification	• Gasification is a process that converts organic or fossil- based carbonaceous materials at high temperatures (>700°C). • This is a regulated procedure that utilises heat, steam, and oxygen to transform biomass into hydrogen and other substances, all without involving combustion.
1.3	Biomass-Derived Liquid Reforming	• Fluids sourced from biomass materials, such as ethanol and bio-oils, can be reformed to generate hydrogen through a process akin to SMR.
1.4	Solar Thermochemical Hydrogen	• Thermochemical water splitting uses high temperatures (from concentrated solar power or from the waste heat of nuclear power reactions) and chemical reactions to produce hydrogen and oxygen from water.
2	**Electrolytic Processes**	
2.1	Electrolysis	• Electrolysis presents a viable prospect for producing carbon-free hydrogen using renewable and nuclear resources. • It employs electricity to separate water into hydrogen and oxygen. • This technology is mature and accessible in the market, with ongoing developments in systems that can effectively harness intermittent renewable energy.

58 https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

S. No.	Processes	Description
3		**Direct Solar Water Splitting Processes**
3.1	Photoelectrochemical	· Hydrogen is derived from water by harnessing sunlight and specialised semiconductors known as photoelectrochemical materials. These materials utilise light energy to directly break down water molecules into hydrogen and oxygen.
4		**Biological Processes**
4.1	Microbial Biomass Conversion	· Microbial biomass conversion methods leverage the capacity of microorganisms to consume and break down biomass, liberating hydrogen in the process.
4.2	Photobiological	· This process utilises microorganisms and sunlight to convert water, and occasionally organic material, into hydrogen.

Source- ICF secondary research

4.2 Cost of producing hydrogen through SMR method

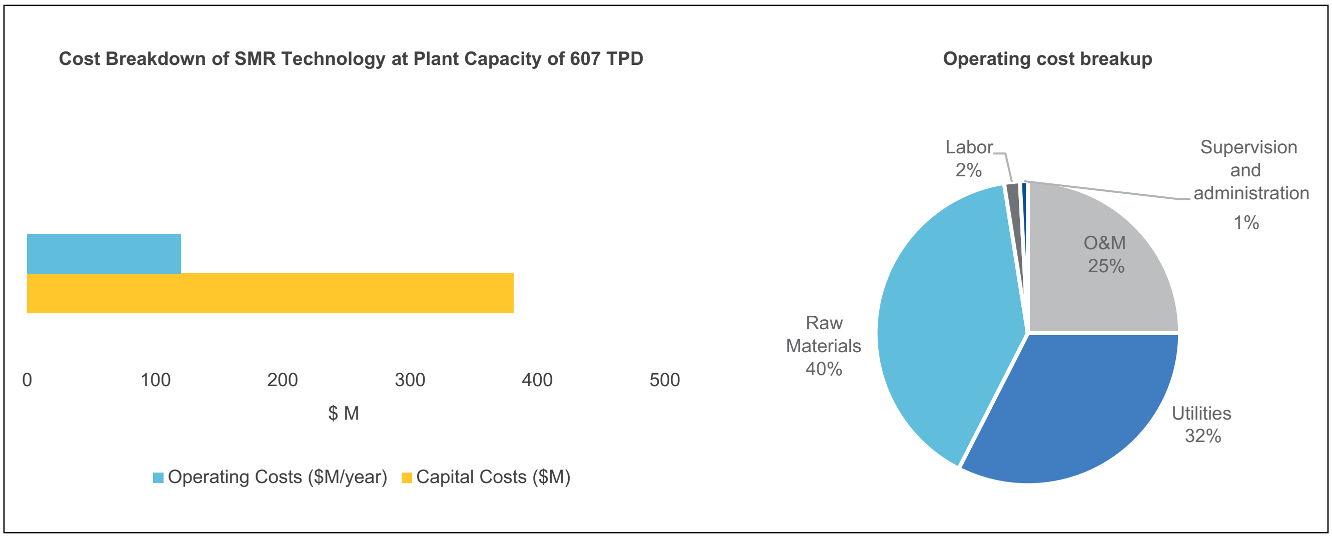
SMR represents a well-established production method, where an external heat source supplies high-temperature steam for the reforming reaction that generates hydrogen and carbon dioxide from a gas source, like methane. Any excess steam can be used to generate power, which is sufficient to meet the power demand of the overall plant.

The overall cost of producing hydrogen through SMR consists of three major components:

- Natural gas price
- Capex, which includes reformer unit, power island (steam turbine), balance of plant, civil works, electricity (where relevant), and gas grid connection
- Operating expenditure, which includes water, chemicals, and catalysts, direct labour, administration/supervision, utilities, and maintenance

The capital costs, operating and maintenance cost, and performance characteristic were accessed through secondary research and stakeholder consultations. During our research and subsequent stakeholder consultations, it was found that capex accounted for over 50 percent of the total cost. The cost breakdown is shown in Figure 30.

Figure 30: Grey Hydrogen Production Cost Breakdown



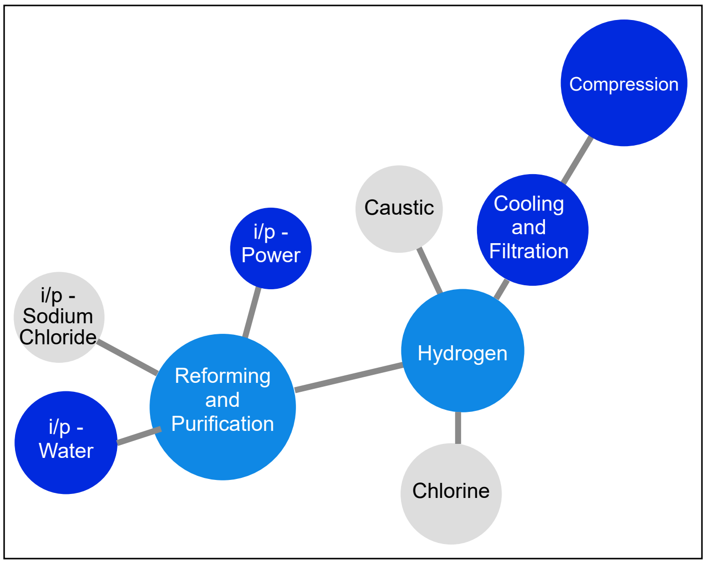
Source- https://doi.org/10.1016/j.enconman.2022.115245

It was further found that the natural gas required for grey hydrogen production is 0.18 GJ/kg, which costs around US$9/MMBTU. The average cost of producing grey hydrogen is around US$2/kg (about INR 160/kg).[59]

4.3 Cost of producing hydrogen in Chloralkali plants

In India, natural gas-based hydrogen production is captive in nature, whereas the hydrogen produced through electrolysis is generally produced in chloralkali plants in the form of a by-product, which is then sold in the merchant market. Hence, the current hydrogen price in India for merchant sale has no correlation with RLNG.

Figure 31: Chlor-alkali manufacturing process



59 Stakeholder interaction

During stakeholder consultation with one of the largest chloralkali manufacturers in India, it was found that although hydrogen is produced as a by-product, it is considered a 'co-product' (and not a 'by-product') when calculating the production cost because the produced hydrogen is conditioned further to make it storable and saleable.

It was also found that in 2021, the average cost of producing hydrogen was estimated to be INR 14-15/ Nm^3 (~INR 155-166/kg), including the cost of conditioning hydrogen (cooling, filtration, and compression costs).

The selling price of hydrogen is currently at a premium of 40-50 percent of the production cost. The current price of hydrogen in the merchant market is around INR 20/Nm^3 (~INR 220/kg). This price is decided based on the overall cost of production, which is further driven by certain market factors, such as the market price of competitors in the catchment area, demand, and supply.

4.4 Cost of producing green hydrogen

Green hydrogen is produced through the process of electrolysis. The electrolyser used in the process of electrolysis is composed of two key components: the stack and the system. The stack is where the water is split, while the system comprises of the power supply, water supply, purification, and compression.

While the core principle of water electrolysis remains consistent among all technologies, the construction process incorporates varying physiochemical and electrochemical factors. Consequently, four distinct technology types are available for generating green hydrogen: alkaline electrolysis, proton exchange membrane electrolysis, anion exchange membrane electrolysis, and solid oxide electrolysis. See Table 23 for the characterisation of the four types of water electrolysis.

Table 23: Characterisation of Electrolyser Technologies

Technology	Efficiency (%)	H2 Purity (%)	Operating Hours	Capital Cost ($/ kW)
Alkaline Electrolysers	70	99.5	60,000-90,000	430–900
Polymer Electrolyte Membrane	66	99.9999	30,000-90,000	667–1,450
Solid Oxide Electrolyser	55	99.9	10,000-30,000	2,300–6,667
Anion Exchange Membrane	69	99.99	-	>931

Source- ORF[60]

Electrolysis processes are technologically advanced; for instance, alkaline electrolysis and proton exchange membrane electrolysis have a technology readiness level exceeding 7.[60] The alkaline electrolyser is a well-established technology with a stack life of 60,000-90,000 operational hours. Its stack composition makes it the cheapest available technology. The proton exchange membrane electrolysis process has higher capital costs due to the requirement of more expensive catalyst materials. The quick ramp-up and

60 https://www.orfonline.org/expert-speak/indias-leadership-in-green-hydrogen/

ramp-down sequences makes proton exchange membrane electrolysis the most suited for coupling with proprietary renewable sources. The anion exchange membrane electrolysis and solid oxide electrolysis stack stability and durability are still unclear.

There are four key cost drivers of these systems: stack, power electronics, gas conditioning, and balance of plant. The stack involves about 50–60[61] percent of the total cost. The projected cost of producing green hydrogen through alkaline electrolysis and proton exchange membrane electrolysis at large capacities (1 GW) have been evaluated based on the following common assumptions and the key assumptions mentioned in Table 24.

i. Capacity utilisation rate = 98%

ii. Water use = 15 kg/ kg H2

iii. Water cost= US$0.28 / kg H2

iv. Purchased electricity use = 50 kWh/kg H2

v. Cost of electricity= US$ 0.056 /kWh

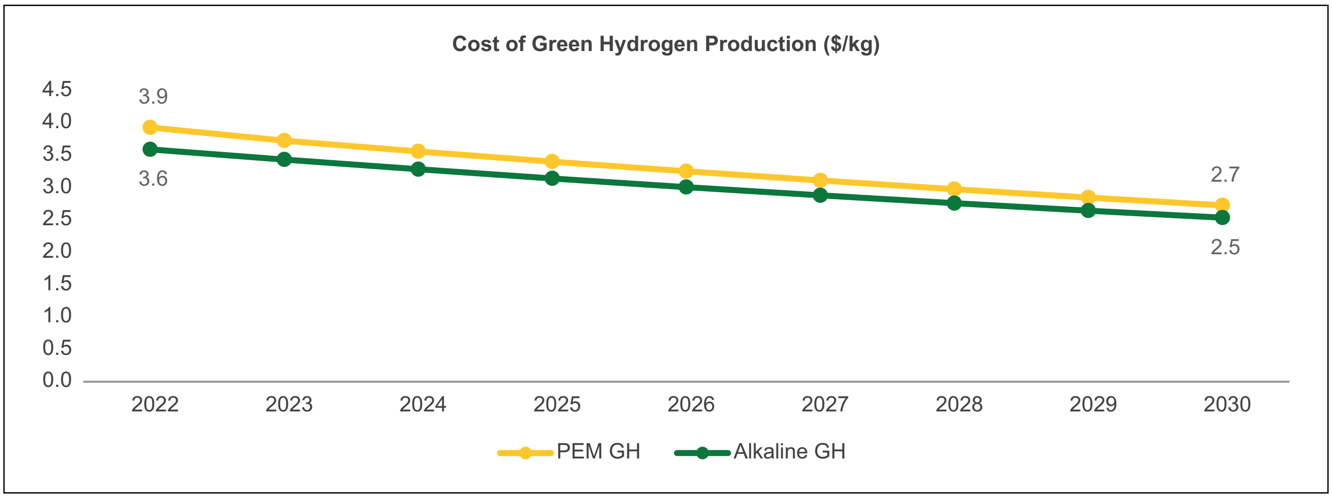
Table 24: Key Assumptions for Green Hydrogen Cost Projection

Assumptions	Units	Large PEM	Large Alkaline
Capacity	MW	1,000	1,000
Life of Plant	Years	20	20
Capex	$/kW	670	437
Stack Cost (to be replaced after 10 years)	$/kW	400	200
Operating expenditure	% of capex	0.5	0.5
Annual Hydrogen Production	KTPA	113.31	120.19
Electrolyser Efficiency	%	66	70
Electricity Requirement (per kg of H2)	kWh	50	50
Water Requirement (per kg of H2)	Kg	15	15
Electrolyser Efficiency Escalation	%	0.36	0.1
Yearly Escalation of Capital Cost	%	-2.5	-1.5
Yearly Escalation of Electricity Cost	%	-5	
Yearly Escalation of Water Cost	%	1	
Electricity Requirement Escalation	%	-0.35	

Based on the assumptions above, the green hydrogen cost has been projected till 2030 in Figure 32.

61 https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/01/Cost-competitive-green-hydrogen-how-to-lower-the-cost-of-electrolysers-EL47.pdf

Figure 32: Green Hydrogen Cost Projection at Factory Gate in India



Source- ICF analysis

We estimate that, until 2030, hydrogen from alkaline electrolysis will remain economical as compared to the proton exchange membrane electrolysis process, with the cost differential between the two decreasing, from US$0.3/kg (2022) to US$0.2/kg (2030).

4.5 Cost viability of green hydrogen for C&I players in India

Preliminary findings suggest that the widespread adoption of green hydrogen in India's C&I sector is challenging due to its high cost of production. It is essential to reduce the production cost of green hydrogen to make it a commercially viable fuel source or feedstock. For a smooth transition to green hydrogen and to overcome the primary obstacles, significant investments from the corporate sector and additional incentives from the government and regulators are required. For green hydrogen to become cost-competitive and globally viable, the cost needs to be reduced to US$2/kg or lower, which is nearly half its current price.

To better understand the current market sentiment towards green hydrogen in India's C&I sector and to identify the challenges and support required for a smooth transition, meetings were conducted with stakeholders across the value chain. Details of the consultations are presented in Chapter 6.

The key highlights from the stakeholder consultations are:

- Given the declining costs for solar PV and wind generation, building electrolysers alongside renewable energy sources could provide a low-cost supply option for hydrogen.
- The prevailing elevated LNG prices will contribute to boosting the competitiveness of green hydrogen. Nevertheless, a substantial reduction in prices primarily hinges on innovations in electrolyser technology, which is unlikely to be achieved in the near future to the extent of halving the current green hydrogen costs. It was also emphasised that, for such viability in the immediate future, the introduction of carbon taxes can exert pressure on other industries, potentially making green hydrogen prices more economically viable.
- An important renewable energy developer said that one of the biggest challenges in the development of green hydrogen and its derivatives is the lack of adequate government policy support. Currently, there is lack of policy initiatives on the demand side. Clarity and/or a waiver is needed

to make tangible progress on reducing the price of renewable energy power, such as a methodology for providing 24X7 banking provision in line with the GoI's intention. Also, levies such as the goods and services tax (at 18 percent), the basic customs duty of 25-40 percent, and the electricity duty (varies from INR 0.2 to INR 1.5 per unit across different states) are major hurdles to reducing the price of renewable energy.

- There is a strong need for an incentive on the supply side to make green hydrogen a viable fuel source. It was further stressed that the reduction in renewable power cost by one or two cents can facilitate a reduction in green hydrogen price to US$1/kg or US$2/kg.

5

Infrastructure requirements for hydrogen supply

There are three major components in the hydrogen value chain—production, storage and distribution, and utilisation (see Figure 33)

Although each part of the hydrogen value chain is at a relatively early stage of development, the production and utilisation parts are majorly driven by the willingness of relevant stakeholders to adapt to hydrogen than the technical feasibility of the hydrogen infrastructure. The government's push for a net zero economy and the idea of using a clean fuel with economic benefits is expected to play a major role in the production and usage of hydrogen in the country.

When it comes to the distribution and storage of hydrogen, stakeholders' focus is on cost effectiveness, safety, and sustainability. While the different stages in the hydrogen value chain have different driving factors, the economic feasibility and sustainability of a hydrogen-based economy is heavily interlinked to the production and distribution methodology of hydrogen. For instance, the production of grey hydrogen in the current scenario is comparatively economical, while green hydrogen stands out from other sources of hydrogen in terms of sustainability.

Notably, India's hydrogen infrastructure is still at a nascent stage of development for large-scale distribution and consumption. In the current context, hydrogen production and consumption have substantial geographic limitations. For instance, India's western region has better access to hydrogen due to its proximity to the production sources. Given these gaps in the hydrogen production and storage infrastructure, this section explores the supporting infrastructure currently used by hydrogen producers and consumers globally and documents the evolving technologies that will make the large-scale distribution of hydrogen feasible in the future.

The infrastructure required in hydrogen distribution can be divided into two broad categories: central plant and storage, and transportation.

5.1 Central Plant and Storage

Hydrogen stands out as a fuel with the highest energy-to-mass ratio among all fuels. Nevertheless, its relatively low ambient temperature density leads to

Figure 33: The Hydrogen Value Chain

a reduced energy per unit volume, necessitating the advancement of storage methods with the potential to achieve higher energy density. On a weight basis, hydrogen has nearly three times the energy content of natural gas (120 MJ/kg for hydrogen versus 44 MJ/kg[62] for natural gas). However, hydrogen has a lower volume than natural gas (8 MJ/litre for liquid hydrogen versus 32 MJ/litre[62] for natural gas).

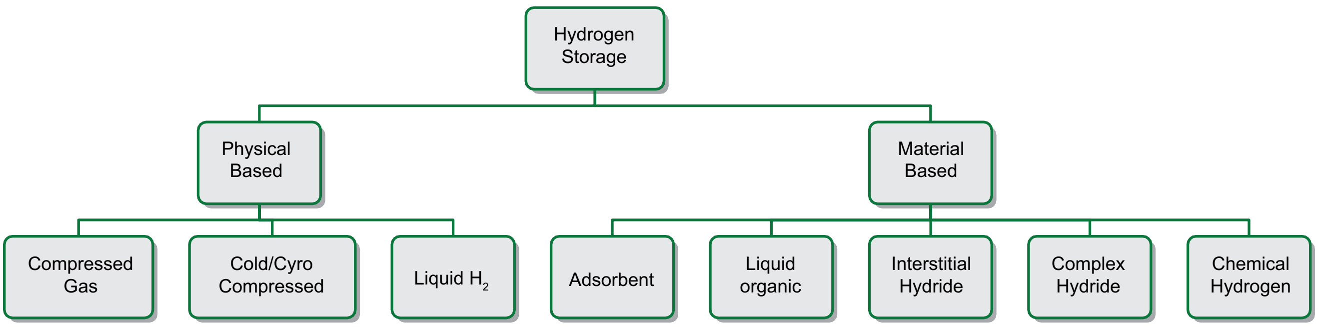
Hydrogen's low density makes it considerably harder to store as compared to fossil fuels. If hydrogen were to substitute natural gas in the global economy at present, approximately three to four times[63] more storage infrastructure would have to be constructed. This would come at a cost of around US$637[64] billion by 2050, to maintain an equivalent level of energy security. Thus, hydrogen storage in large quantities is expected to pose a major challenge to a hydrogen-based economy.

According to the US Department of Energy, hydrogen can be stored using different technologies either under the physical-based or material-based mode (see Figure 34)

For industrial purposes, hydrogen is generally stored in its physical form, which is considered to be the most mature hydrogen storage technology. In the physical form, hydrogen can be stored as either a gas or a liquid. Usually, the storage of hydrogen as a gas necessitates the use of high-pressure tanks, with tank pressures typically ranging from 350 to 700[65] bar. Storing hydrogen as a liquid requires cryogenic temperatures, because the boiling point of hydrogen at one atmosphere pressure (1 atm) is very low, i.e., −252.8°C.[66]

Further, onsite hydrogen storage is used at central hydrogen production facilities, transport terminals, and end-use locations. Current storage options include insulated liquid and gaseous storage tanks. See Table 25 for the four types of common high pressure gaseous storage vessels[67].

Figure 34: Hydrogen Storage Technologies



62 https://www.energy.gov/eere/fuelcells/hydrogen-storage

63 https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf

64 https://about.bnef.com/blog/hydrogen-economy-offers-promising-path-to-decarbonization/

65 https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=Hydrogen%20can%20be%20stored%20physically,pressure%20is%20%E2%88%92252.8%C2%B0C.

66 https://www.mdpi.com/2571-8797/3/4/51/htm#:~:text=In%20comparison%2C%20hydrogen%20storage%20as,20.3%20K)%20%5B11%5D.

67 https://www.energy.gov/eere/fuelcells/site-and-bulk-hydrogen-storage

Table 25: Type of Storage Vessels

Type I	All-metal cylinder
Type II	Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament
Type III	Non-load bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament
Type IV	Non-load bearing, non-metal liner axial and hoop wrapped with resin-impregnated continuous filament.

Although compressed hydrogen is typically stored at temperatures near ambient, there is ongoing exploration of 'cold' (sub-ambient, but above 150 K) and 'cryogenic' (below 150 K) compressed hydrogen storage options. These approaches are being considered due to the higher hydrogen densities that can be achieved at lower temperatures.

In the present scenario, large-scale, cost-effective alternatives like salt caverns have limited geographic availability, and the expense associated with using alternative liquid storage technologies often exceeds the cost of hydrogen production. Table 26 details the various storage options available globally and the associated costs.

Table 26: Hydrogen Storage Infrastructure

	Gaseous State				**Liquid State**	
	Salt Caverns	**Depleted Gas Fields**	**Rock Caverns**	**Pressurised Containers**	**Liquid Hydrogen**	**Ammonia**
Main Usage (Volume and Cycling)	Large Volumes - Months, Weeks	Large Volumes – Seasonal	Medium Volumes - Months, Weeks	Small Volumes – Daily	Small-Medium Volumes - Days, Weeks	Large Volumes - Months, Weeks
Benchmark levelised cost of storage (LCOS) ($/kg)[68]	0.23	1.90	0.71	0.19	4.57	2.83
Possible Future levelised cost of storage (LCOS) ($/kg)	0.23	1.07	0.23	0.17	0.95	0.87
Geographical Availability	Limited	Limited	Limited	Not Limited	Not Limited	Not Limited

Source- https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar- 2020.pdf

68 Benchmark levelised cost of storage (LCOS) at the highest reasonable cycling rate. Source: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy- Outlook-Key-Messages-30-Mar-2020.pdf

Of all the listed options, compressed hydrogen is the most widely used. In India, hydrogen is also transported as a compressed gas.

Hydrogen produced as a by-product from the chloralkali industries is usually sold through merchant routes, which requires long-haul transport. In such facilities, the hydrogen is produced at a very high temperature (90^{O}C), which is then cooled and brought down to ambient temperatures. Once the temperature is stabilised, it is made to pass through washing towers to filter out impurities and come down to the desired grade (99.9%) of hydrogen. The hydrogen gas then flows to the gas holder, which works as a buffer vessel. In the gas holder, the gaseous form of hydrogen is taken to hydrogen compressors, where it is compressed to a pressure of 150 Kg/cm^2 at the required ambient temperature. The gas holder reacts as a buffer to maintain the pressure inside the line so there is no high rejection. Further, the compression of hydrogen gas is done in multistage compressors.

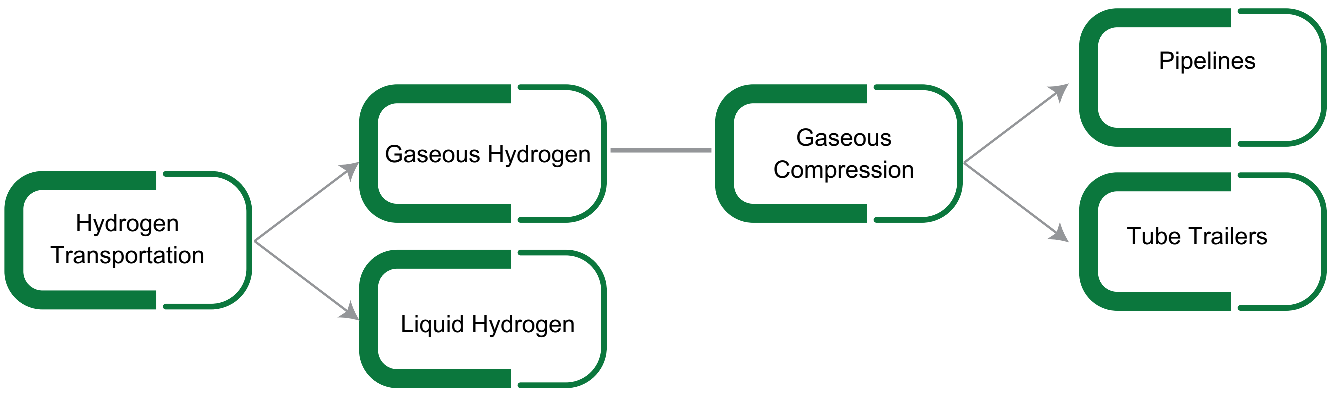
5.2 Transportation

Hydrogen is presently conveyed from its production site to the consumption point using pipelines, as well as through cryogenic liquid tanker trucks or gaseous tube trailers for road transport. Pipelines are typically employed in areas with substantial and expectedly stable demand. In regions where demand is either emerging or on a smaller scale, liquefaction plants, liquid tankers, and tube trailers are utilised. At the point of hydrogen utilisation, additional infrastructure components, such as compression, are frequently implemented.

The most common approach to transport gaseous hydrogen is either by trucks or through pipelines. Since gaseous hydrogen is generally produced at relatively lower pressures (20–30 bar), it is necessary to compress it to the required pressure level prior to its transport. However, the more conventional method to transport hydrogen is through trucks. Gaseous hydrogen is compressed to pressures of 180 bar (~2,600[69] psig) or higher into long cylinders, which are then stacked on the truck trailers. This gives the appearance of long tubes and is hence called tube trailers.

Liquid hydrogen transportation is most opted for when high-volume transport is needed in the absence of pipelines. To transform hydrogen into a liquid state, it needs to undergo a liquefaction process, which involves cooling it to cryogenic temperatures. The various modes of transportation of hydrogen are detailed below.

Figure 35: Hydrogen Transportation Technologies



69 https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers#:~:text=Gaseous%20hydrogen%20is%20compressed%20to,hence%20the%20name%20tube%20trailer.

5.2.1 Pipelines

Pipelines are widely considered to be one of the most cost-effective and efficient methods of transporting hydrogen over long distances. Compared to other modes of transport, such as trucks or ships, pipelines offer several advantages, including lower transportation costs, reduced emissions, and a more stable and secure supply chain. Additionally, pipelines can be used to transport hydrogen in large volumes, thus making them ideal for transporting hydrogen from production sites to consumption centres. Gaseous hydrogen is transported through pipelines in much the way that natural gas is transported today. These pipelines are owned by hydrogen producers, and are located where large hydrogen users, such as petroleum refineries, ammonia plants, and chemical plants, are concentrated.

Hydrogen transportation through pipelines could be facilitated by either repurposing the existing natural gas pipelines, or by constructing new hydrogen pipelines. Repurposing existing natural gas pipelines for the transportation of hydrogen is one of the cheapest transportation techniques for delivering large volumes of gaseous hydrogen. This option leverages existing infrastructure, thus reducing the need for new investment, and minimising the environmental impact of pipeline construction. In addition, repurposing existing pipelines can reduce the time required to establish a hydrogen transportation network, as pipelines can be retrofitted and adapted for hydrogen transportation relatively quickly. Another advantage of repurposing natural gas pipelines for hydrogen is that it offers a secure and stable supply chain. Pipelines are known for their reliability and safety, compared to other modes of transportation, and repurposing existing pipelines reduces the risk of leaks or spills that can be a cause for concern when transporting hydrogen.

Further, the cost of hydrogen transportation through pipelines is influenced by various factors, including the compression and diameter of the pipeline. Hydrogen is typically transported through pipelines at high pressure to minimise its volume and reduce the cost of transportation. The amount of compression required to transport hydrogen is directly proportional to the cost of transportation. Higher compression requires more energy, and, therefore, it increases the cost of transportation. The diameter of the pipeline is another factor that affects the cost of hydrogen transportation. Larger pipelines can transport hydrogen at lower pressure and lower compression, which reduces the cost of transportation. However, larger pipelines are more expensive to construct and instal, which also increases the overall cost of hydrogen transportation.

According to the International Energy Agency, the cost[70] of new hydrogen pipelines with 48 and <36 inches diameter will be around US$0.21/kgH2/1,000km and US$0.86/kgH2/1,000km (INR 17/kgH2/1,000km ad 67/kgH2/1,000km), respectively, whereas the cost of a repurposed pipeline is between US$0.11/kgH2/1,000km and US$0.32/kgH2/1,000km (or INR 8.4/kgH2/1,000km and 25/kgH2/1,000km)[71]

5.2.2 Tube Trailers:

The vehicles responsible for transporting gaseous hydrogen are known as tube trailers. Currently, steel tube trailers are the most frequently used and have

70 European Hydrogen Backbone, Bloomberg New Energy Forum, Agora Energiewende, IEA

71 https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Presentations/20210827_Knowledge_Session_Transport_of_Green_Hydrogen/01_Matthias_Schimmel.pdf

a carrying capacity of around 380 kg[72]. However, the weight of the steel tubes restricts their carrying capacity. Recently, composite storage vessels, with capacities of 560–900[73] kg of hydrogen per trailer, have been developed. Such tube trailers are currently being used to deliver compressed natural gas in some countries.

For compressed hydrogen of 50 tpd capacity, the transportation cost accounts for approximately 60 percent of the total landed hydrogen cost. For liquid hydrogen of 50 tpd capacity, the conditioning and storage at production site accounts for approximately 40 percent of the total landed hydrogen cost[74].

Further, for 50 tpd transportation, i.e., distances up to 500 km, gaseous hydrogen will incur higher costs of approximately US$4/kg against US$0.93/kg for liquid hydrogen. For distances up to 50 km, the transportation cost of gaseous hydrogen is competitive at US$0.96/kg, compared to US$0.22/kg for liquid hydrogen.

At present, the export and import of hydrogen is not technically feasible, but hydrogen can be shipped in form of derivatives.

5.2.2.1 Liquid Hydrogen

Liquefaction: Gaseous hydrogen is liquefied by cooling it to below −253°C (−423°F). Once hydrogen is transformed into a liquid form, it can be stored in well-insulated tanks at the liquefaction plant. Liquefying hydrogen requires energy. Using current technology, liquefaction consumes over 30 percent[75] of the energy contained in hydrogen, and it is a costly process. Moreover, some amount of stored hydrogen is lost due to evaporation or 'boil off' of liquefied hydrogen, particularly when small tanks with a high surface-to-volume ratio are used.

Liquid Tankers: Over longer distances, hydrogen is conveyed in a liquid state using highly insulated, cryogenic tanker trucks. Following the liquefaction process, the liquid hydrogen is transferred to delivery trucks and then transported to distribution sites where it is converted back into a high-pressure gaseous product for dispensing. When it comes to long-distance transport, using liquid hydrogen in tanker trucks proves to be a more cost-effective option than transporting gaseous hydrogen because liquid tanker trucks can carry a significantly larger quantity of hydrogen by mass compared to gaseous tube trailers. However, there are challenges associated with liquid transportation, including the potential for boil-off during delivery.

Chiyoda Corporation (Japan)[76]: Chiyoda initiated research and development efforts on a high-performance dehydrating catalyst as far back as 2002. By 2011, they had achieved successful development of their LOHC methylcyclohexane (MCH), which they named SPERA. In 2013, a demonstration plant was established in Yokohama, and the SPERA technology has since reached a maturity level estimated at TRL 9. Aligning with the Japanese government's Strategic Roadmap for Hydrogen and Fuel Cells (2016), SPERA technology facilitates the large-scale import of hydrogen from abroad, such as from Australia.

72 www.energy.gov/eere/fuelcells/hydrogen-tube-trailers

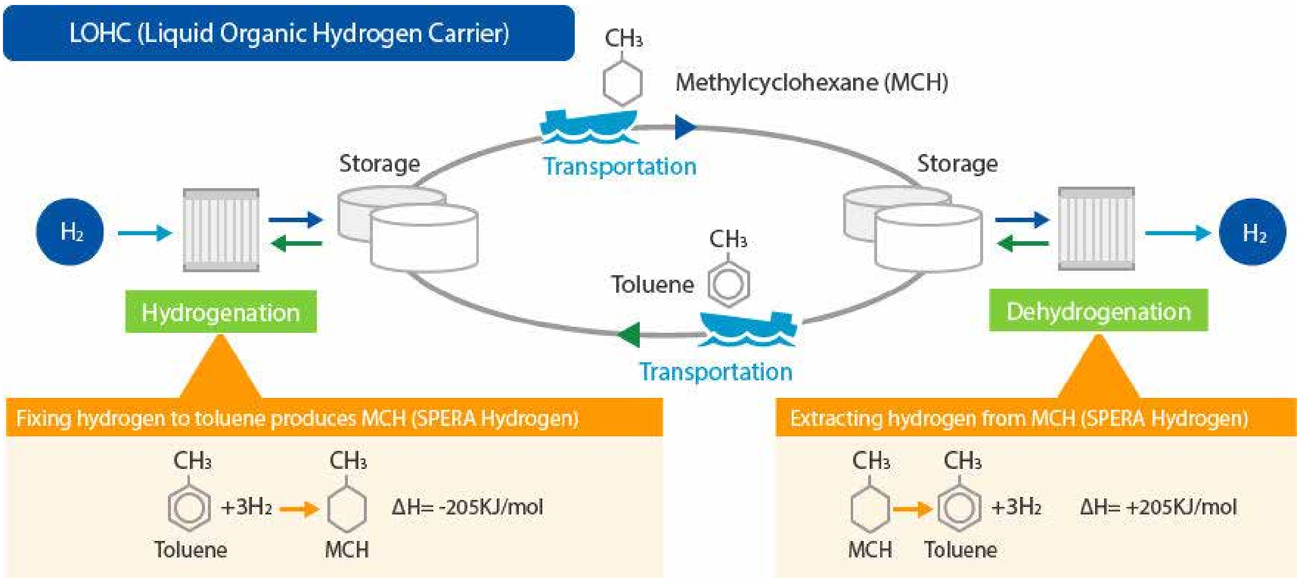
73 https://www.energy.gov/eere/fuelcells/hydrogen-tube- trailers#:~:text=Recently%2C%20composite%20storage%20vessels%20have,natural%20gas%20in%20other%20countries.

74 https://www.energyforum.in/fileadmin/user_upload/india/media_elements/Presentations/20210827_Knowledge_Session_Transport_of_Green_Hydrogen/05_Anish_Paunwala.pdf

75 https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery#:~:text=Gaseous%20hydrogen%20is%20liquefied%20by,the%20hydrogen%20and%20is%20expensive.

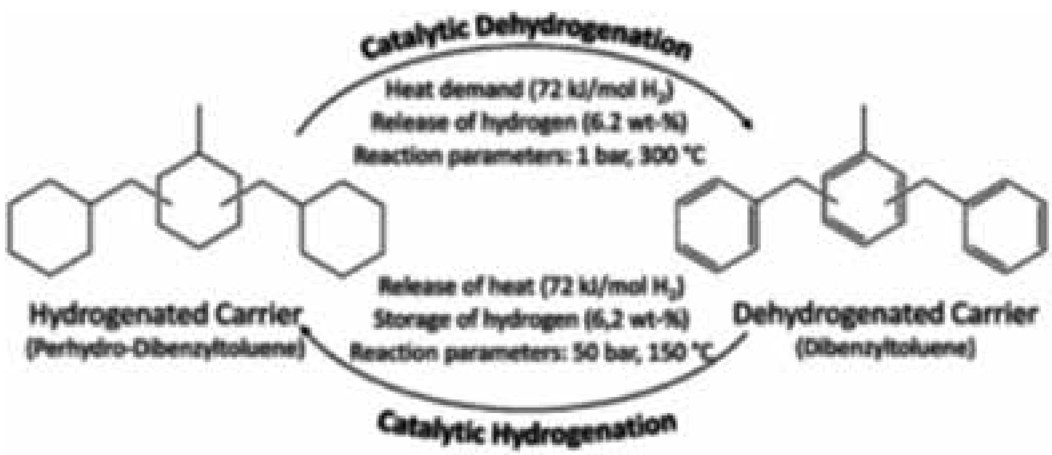
76 https://transitionaccelerator.ca/wp-content/uploads/2020/07/HollandInnovationNetworkinChina-Hydrogendevelopments.January2019-1.pdf

Figure 36: SPERA LOHC technology from Chiyoda Corporation

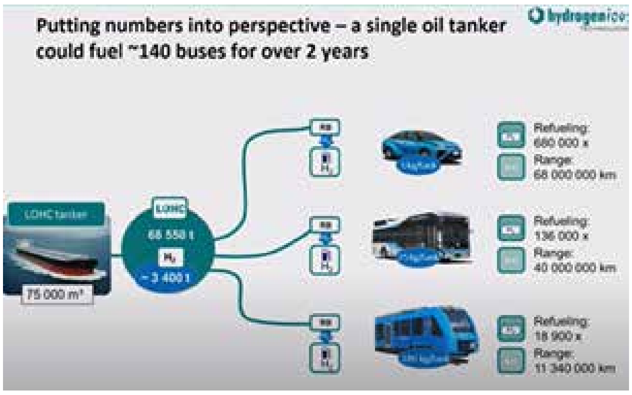


Hydrogenious (Germany)[76]: Hydrogenious has entered into a collaborative agreement with Zhongshan Borad-Ocean Motor Co., Ltd. to establish the first pilot hydrogen refueling station utilising Liquid Organic Hydrogen Carrier (LOHC) technology for buses in China. Hydrogenious's technology employs dibenzyl toluene as a carrier, which is presently available at a cost of approximately US$4 per kilogram. Platinum and palladium serve as catalysts to separate the carrier and hydrogen within the Release BOX. Hydrogenious has also collaborated with Hy-Gear from the Netherlands and VTT from Finland as part of the HySTOC project, funded by Fuel Cells and Hydrogen Joint Undertaking (FCH-JU), which ran from January 2018 until the end of 2020. The HySTOC project aims to demonstrate the distribution of high-purity hydrogen (in accordance with ISO 14687:2-2012) to commercial hydrogen refueling stations in Finland.

Figure 37: LOHC Technology of Hydrogenious[77]



77 China Storage and distribution.pdf



Hynertech (China)[76]: Hynertech was established in 2014 through a collaboration between the China University of Geosciences (Wuhan) and various partners in Jiangsu province. While specific details about the carrier and catalyst materials used by Hynertech are not publicly disclosed, it is known that their LOHC desorption temperature is lower, around 200 degrees Celsius, as compared to Chiyoda (above 350 degrees Celsius) and Hydrogenious (above 320 degrees Celsius). Hynertech's technology provides 99.99% pure hydrogen, eliminating the need for additional purification devices when used in PEM fuel cells. In 2018, Hynertech made announcements about constructing two new production bases for its LOHC technology. During the same year, they introduced the first fuel cell logistics vehicle operating at normal temperature and pressure in Wuhan, in collaboration with the Tri-Ring Group and Wuhan Jinhuang Industry.

5.3 Modes of hydrogen supply

The demand for hydrogen in India can be categorised as 'captive demand' and 'merchant demand'. At present, the infrastructure for hydrogen supply is still in its infancy, leading to a prevalent captive demand. This demand category accounts for around 90 percent[78] of the total hydrogen consumption in India.

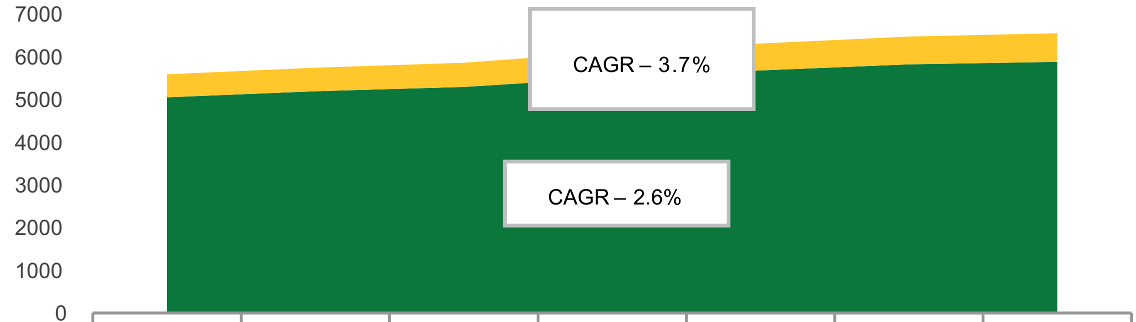
With the continued development of hydrogen infrastructure and a growing emphasis on clean energy,and the establishment of local manufacturing industries across the country, there is potential for an increase in merchant demand. While the captive demand for hydrogen has increased at 2.6 percent annually since 2015, the merchant demand is growing at a CAGR of 3.7 percent[79]. By improving the hydrogen supply chain and making hydrogen more widely available, it could further become a key player in the transition to a low-carbon economy.

The major contributors to captive demand are industries such as refining, fertilisers, and chemical plants, while merchant demand has primarily been driven by growing demand in optic fibre, float glass, sorbitol, and others.[80]

78 ICF research
79 ICF Research
80 ICF Research

Figure 38: Modes of Hydrogen Supply73F73F

Total Hydrogen demand (KTA)



	2015	2016	2017	2018	2019	2020	2021
Merchant supply	540	550	570	600	630	650	670
Captive supply	5050	5190	5290	5510	5680	5820	5880

6

India's policy ecosystem and the impact on green hydrogen adoption

According to the IEA's Global Hydrogen Review 2023,[81] less than 0.1 percent of the hydrogen currently produced worldwide is green hydrogen. It is safe to assume that a similar situation prevails in India as well. Currently, the production cost of green hydrogen in India is around US$7 per kg, whereas the production of blue and grey hydrogen using fossil fuels costs approximately US$2 per kg.[82] As such, the present scenario poses two major challenges for the Indian government—incentivising the production of green hydrogen and ensuring a smooth transition from the current blue and grey hydrogen producing capacity to producing green hydrogen. The government has already introduced several schemes and missions to develop the green hydrogen sector. The Green Hydrogen Policy launched in February 2022, the Green Hydrogen Mission, and the aim of the Ministry of Power to produce[83] 5 MT of green hydrogen by 2030 showcase the government's commitment to boost the country's green hydrogen sector.

6.1 Green Hydrogen Policy, 2022

The Ministry of Power released the Green Hydrogen Policy[84] in February 2022, identifying the need and advantages of using green hydrogen. It also laid down a few regulations that need to be followed. The main aim of the policy is to combat climate change and transform India into a green hydrogen hub. The key highlights of the policy include:

- Green hydrogen is to be defined as the hydrogen produced by the electrolysis of water using renewable energy.
- The government will waive inter-state transmission charges for a period of 25 years for the producers of green hydrogen/ammonia, but this scheme is valid only for projects commissioned before June 30, 2025.
- The government will also allow the charges for the renewable energy used to make green hydrogen to be fixed by the state commission for a period of 30 days.
- Priority will be given to the connectivity of green hydrogen stations to the inter-state transmission system.
- Green hydrogen producers will be permitted to establish storage bunkers in close proximity to ports.
- The renewable energy used for the production of green hydrogen will count for the producer's renewable purchase obligation compliance.
- Distribution licensees will also be allowed to supply renewable energy for the supply of green hydrogen.

81 https://www.downtoearth.org.in/blog/energy/biohydrogen-s-role-in-india-s-green-hydrogen-pathway-92267#:~:text=Despite%20increasing%20global%20political%20support,International%20Energy%20Agency%20(IEA)

82 https://www.thethirdpole.net/en/energy/india-new-hydrogen-world-order/

83 https://www.reuters.com/business/energy/india-plans-produce-5-mln-tonnes-green-hydrogen-by-2030-2022-02-17/

84 https://powermin.gov.in/sites/default/files/Green_Hydrogen_Policy.pdf

- The Ministry of New and Renewable Energy will establish a single portal for all statutory clearances and permissions required for the manufacture, transportation, storage, and distribution of green hydrogen and/or green ammonia. The relevant agencies or authorities will be asked to grant clearances and permissions in a timely manner, with a preference for completing the process within 30 days from the date of application.

- The Ministry of New and Renewable Energy may aggregate demands from different sectors and invite bids for the procurement of green hydrogen or ammonia.

6.2 National Green Hydrogen Mission

In January 2023, the Union Cabinet approved the National Green Hydrogen Mission. The key goal of the mission is to transform India into a "global hub for green hydrogen production, usage, and export". The mission is planned to be implemented in a phased manner, aims to replace fossil fuels and feedstock with green hydrogen, and evolve an ecosystem for R&D, regulations, and pilot projects. It will involve using green hydrogen in ammonia and petroleum refining, blending it in CGD systems, producing steel, and using green hydrogen-derived fuels to replace fossil fuels in mobility, shipping, and the aviation sectors. The mission also seeks to position India as a frontrunner in the technology and production of electrolysers and other supporting technologies for green hydrogen.

The Ministry of New and Renewable Energy has been identified as the nodal agency, and an initial financial outlay of INR19,744 crore has been proposed for the mission.

The key highlights of the mission document include:

- Development of green hydrogen production capacity of at least 5 MMT per annum with potential to reach 10 MMT per annum with the growth of export markets.

- Addition of renewable energy capacity of about 125 GW.

- Cumulative reduction in fossil fuel imports over INR 1 trillion.

- Reduction of approximately 50 MMT of annual greenhouse gas emissions.

The mission will be implemented in two phases:

6.2.1 PHASE I (2022-23 to 2025-26)

- The emphasis will be on stimulating demand and simultaneously facilitating sufficient supply by enhancing domestic electrolyser manufacturing capacity.

- Incentives will be developed to support increasing green hydrogen production and uptake. Usage in the refinery, fertiliser, and urban gas sectors will also generate a consistent demand, promoting fresh investments in green hydrogen production.

- Furthermore, it will establish the groundwork for forthcoming energy transitions in other challenging-to-decarbonise industries by generating the necessary research and development momentum.

- Pilot initiatives will be launched to kickstart a shift toward green practices in steel manufacturing, long-haul heavy-duty transportation, and shipping.

- It is expected that the scaling up of green hydrogen production and use, and the proposed measures under the mission in the first phase will drive down the costs while allowing for the greater and wider deployment of green hydrogen in the next phase.

6.2.2. PHASE II (2026-27 to 2029-30)

- During this stage, the feasibility of implementing large-scale green hydrogen projects in the steel, transportation, and shipping sectors will be assessed.

- Pilot initiatives will be commenced in other promising sectors, including railways and aviation. Research and development efforts will be expanded to ensure the ongoing progress of products.

- The second phase activities will enhance penetration across all potential sectors to drive a deep decarbonisation of the economy.

The mission's proposed financial outlay has been assigned to five key areas:

- **Strategic Interventions for Green Hydrogen Transition (SIGHT):** An outlay of INR 17,490 crore has been proposed for the basket of incentives under SIGHT to support green hydrogen production and indigenous manufacturing.

- **Pilot projects:** An outlay of INR 1, 466 crores has been proposed for pilot projects that will be undertaken for initiating green transition in steel production, long-haul and heavy-duty mobility, and shipping in the first phase. Pilot projects in other potential sectors, such as railways and aviation, may be initiated in the second phase.

- **Research and development:** An outlay of INR 400 crore has been proposed for this sector, which will be supported with an aim to increase the affordability of green hydrogen production, storage, transportation, and utilisation, as well as to enhance the efficiency, safety and reliability of the relevant systems and processes.

- **Others:** An outlay of Rs 388 crore has been proposed for this sector for skill development, public awareness, and stakeholder outreach.

6.3 Review of current regulations for supply of hydrogen (PESO rules)

The Petroleum and Explosives Safety Organisation (PESO) was established in 1898 to serve as the nodal agency for regulating the safety of hazardous substances. Since hydrogen is highly flammable, it poses a threat to property and life in the event of any negligence. Thus, PESO has provided certain rules and regulations that should be followed while dealing with gases such as CNG, LPG, and hydrogen. However, as of now, PESO has not mandated a separate set of rules for the supply of hydrogen, but hydrogen has been mentioned in several reports.

PESO[85] has been in operation even before the new green hydrogen policy was framed and had in 2015 granted permission to Indian Oil to set up a hydrogen manufacturing plant in Haryana. The following are the key PESO rules that will have an impact on green hydrogen:

6.3.1 PESO regulations for gas cylinders 2016 under Explosive Act, 1884

6.3.1.1 Technical provisions of Gas Cylinder Rules 2016 (GCR-2016) under Explosive Act, 1884[86]

6.3.1.1.1 *Cylinders used for filling compressed hydrogen gas*

The type and standards of approved cylinder and valve are described in the schedule I of GCR-2016. Provisions under the schedule are:

85 https://www.business-standard.com/content/b2b-chemicals/peso-grants-permission-to-indian-oil-to-set-up-hydrogen-plant-115051100485_1.html

86 https://peso.gov.in/web/gas-cylinder-rules-2016

- **Testing and Filling:** Cylinders are tested and inspected by the inspection authority, and thereby approved by chief controller. The filling is only done by the licensee.

- **Valves and Cylinder Safety:** Under this schedule, the cylinder valves are required to be compiled to the IS:3224 standard. For safety provisions of these cylinders, the manufacture and maintenance of safety relief devices fitted in the bodies of Indian manufactured cylinders should comply with IS:5903 standard.

- **Colour:** The schedule requires the colour of the cylinders to be according to those mentioned in the IS:4379 standard.

- **Chemical Properties:** The gas contained is mandated to be free from hydrogen sulphide and other sulphurous impurities to the extent possible, and the moisture is mandated to be less than 0.02 g/m^3 of gas at normal temperature and pressure.

6.3.1.1.2 Handling and use of compressed H_2 gas cylinders

- **Valves:** Conveyors, trolleys, and cradles of adequate strength are suggested to be used in the valves thereby avoiding any damage.

- **Safety Guidelines:** For safety purposes, the cylinders should not be allowed to fall upon one another. Further, sliding, dropping, and playing with cylinders is prohibited. Also, cylinders used for storage and transportation of hydrogen should not be used for filling with any other gas, except a mixture of hydrogen gas with inert gases.

- **Transportation:** Cylinders or cascades are required to be transported as per provisions of Schedule 6 of GCR-2016.

6.3.1.1.3 Storage of compressed hydrogen gas cylinders

- **Ideal Storage:** Storage of compressed hydrogen gas cylinders is required to be in a cool, dry, and well-ventilated place that is under cover. Additionally, the storage is suggested to be done away from boilers, open flames, steam pipes or any other potential sources of heat. The hydrogen cylinders are also suggested to be kept away from those cylinders that contain other toxic gases.

- **Properties:** The storage room for the compressed hydrogen gas cylinder is also recommended to a room that is fire resistant. Furthermore, the electrical fittings in the filling and storage area should be constructed in a flame-proof location while conforming to IS or IEC-60079-1, IS or IEC-60079-11 or any other standard that must be approved by the Chief Controller.

6.3.1.2 Legal implications for using hydrogen cylinders under GCR-201686

- **Ownership of Cylinder:** The hydrogen cylinder is not authorised to be filled with a compressed gas and transported unless it was charged by or with the written consent of the owner of the cylinder.

- **Testing:** The hydrogen cylinders are mandated to be tested periodically in accordance with provisions of Schedule I of GCR-2016. The testing should be done within the period, as specified in IS:15975, or the timeline/ duration approved by the Chief Controller of Explosives (CCOE).

- **Re-testing of Cylinder:** A cylinder for which the prescribed periodical re-test is due is recommended to not be charged and transported, until the re-rest is properly carried out in accordance with the codes accepted by the Chief Controller.

- **Owner's Record:** The owner of a cylinder is required to keep record of the life of each cylinder owned. The record must contain the following information regarding each cylinder:
  - ◇ The cylinder manufacturer's name and the rotation number,
  - ◇ The specification number to which the cylinder is manufactured,
  - ◇ The date of original hydrostatic test or hydrostatic stretch test or pneumatic test
  - ◇ The cylinder manufacturer's test and inspection certificate
  - ◇ Number and date of letter of approval granted by the Chief Controller.
- **Filling:** The filling of hydrogen cylinders requires a mandatory license as specified under GCR-2016.
- **Transportation:** A license is not necessary for transporting cylinders filled with a compressed gas, by a carrier or any other person if it is done in accordance with the provisions of these rules. However, this is applicable only if it does not withstand Rule 43, stating that 'No person shall fill any cylinder with compressed gas and no cylinder filled with compressed gas shall be possessed by anyone except under and in accordance with the conditions of a licence granted under these rules.'
- **Approval:** A prior approval of specification and plan of premises that is proposed to be license should be obtained from the CCOE/COE.

6.3.1.3 Licensing:

- An applicant for a licence in Form "F" for storage of flammable, toxic, or corrosive gases for the purpose of sale or trading and not for own use, is required to apply to the district authority.
- The requirement of "no objection certificate" under the sub rule (1) is not applicable for a licence in form "F" for storage of flammable, toxic, or corrosive gases forming part of the cylinder filling plant.
- A licence in Form 'F' for filling or storage of compressed gases granted or renewed under rules remains in force till the 30th day of September of the year up to which the licence is granted or renewed, subject to a maximum of 10 years.

In addition to the Gas Cylinder Rules, 2016, the country has also the defined the Indian Standard Code of Safety (IS 15201: 2002)[87] for the storage, handling, and transport of hydrogen. In June 2021, the Ministry of Petroleum and Natural Gas suggested amendments to the Oilfield (Regulation and Development Act), 1984[88] to include hydrogen in the definition of "mineral oils".

87 https://archive.org/details/gov.law.is.15201.2002/mode/2up

88 https://economictimes.indiatimes.com/industry/energy/oil-gas/petroleum-min-proposes-changes-in-law-to-include-hydrogen-in-mineral- oil/articleshow/83604610.cms?from=mdr

7

Policy recommendations

7.1 Key issues/gaps

Despite the government presenting a detailed National Green Hydrogen Mission t`o bolster the energy sector, India's regulatory framework still has many gaps. For instance, India's regulatory framework lacks many critical guidelines on safety in hydrogen storage, transport, distribution, and fuel cells. India is yet to develop comprehensive national regulations, codes, and infrastructure and workplace safety standards governing hydrogen production, transportation, storage, and use. Table 27 covers some of the identified gaps in the sector that need to be addressed.

Table 27 : Key Gaps Within Hydrogen Regulatory Framework

Key Gaps	Description
Hydrogen Demand	• Lack of incentivisation for green hydrogen demand • No green hydrogen consumption obligation targets • Lack of robust carbon taxation and carbon pricing policy to incentivise adoption of cleaner fuels
Cost of Production	• No clear pathway to reduce production cost of green hydrogen • Lack in clarity of actual incentives for different components in the green hydrogen value chain
Institutional Structure	• No clarity on institutional set-up for the development of hydrogen and/or hydrogen-related activities • Clarity required on nodal agencies administering regulatory framework related to hydrogen • Clarity required on nodal agencies to introduce/modify/update safety-related laws in hydrogen value chain
Infrastructure	• Lack of infrastructure for storage and transportation of hydrogen • Lack of clarity on development of CCUS technology in the country • Lack of policy support around the development of new infrastructure or retrofitting of existing gas pipelines for transportation of hydrogen
Funding	• Need for a hydrogen ecosystem. Lending institutions have little or no confidence in financing hydrogen projects. • Push for green hydrogen certificates similar to Renewable Energy Certificates is lacking
Regulation	• Requirement of filling regulatory gaps for a sustainable hydrogen market • Categorisation required for production of green hydrogen produced from by- products (chloralkali) • Requirement of modifications in PESO guidelines to fill in gaps regarding long- distance hydrogen transportation using pipeline

As such, there is a need to review national regulations that define the roles of utilities and grid operators. At present, certain aspects of the market structure warrant regulatory frameworks that keep these entities separate. If hydrogen deployment is successful, it can concurrently become an integral part of the gas network, and support electricity grid resilience and the reliability of the electricity grid. Hydrogen will, thereby, facilitate sector coupling between electricity and gas utilities, thus creating a new role requiring specific regulations. There is also a need to ensure that a standardisation framework based on national or international norms is implemented and is appropriately applicable to the use of hydrogen and its carriers.

7.2 Stakeholder Consultations

Consultations with stakeholders across the hydrogen value chain were aimed at identifying the challenges that pose hurdles to a smooth transition to this clean fuel, while also gathering valuable insights on the needs and concerns of various stakeholders.

Two different approaches were used for the stakeholder consultations:

1. One-on-one interactions with key stakeholders, and
2. Roundtable discussion among the key stakeholders on sectoral challenges

These stakeholder meetings were structured around the following key areas:

- Views on the existing hydrogen market, including international bilateral programmes, demand, supply, and infrastructure, among others
- Green hydrogen financing in India
- Opportunities and challenges in manufacturing electrolysers in India
- Necessities, opportunities, and R&D for infrastructure development
- Policy support for green hydrogen in terms of regulatory strengthening, demand creation, gaseous hydrogen production, and electrolyser manufacturing, funding, infrastructure development, and R&D

A summary of the key points from the discussions with various stakeholders is provided below:

Trading Platform:
It was deliberated that due to the declining costs for solar PV and wind generation, building electrolysers with co-located renewable energy sources may become a low-cost supply option for hydrogen. Further, if the current high LNG prices persist, it will improve the competitiveness of green hydrogen vis-à-vis grey hydrogen (SMR). However, for the green hydrogen production cost to reach the expected level (i.e., around half of the current cost), major electrolyser technology innovation is required. It was further highlighted that for viability in near future, the applicability of carbon tax can create a push on other industries, which can make green hydrogen prices viable.

Renewable energy developer:
It was highlighted that one of the biggest challenges in the development of green hydrogen and its derivatives is the lack of adequate government policy support. As of now, there is a lack of policy initiatives to spur the demand for hydrogen. Clarity and/or a waiver is required for a reduction in the price of renewable energy power. These could be in the form of methodology for providing 24X7 banking provisions, restructuring applicability of taxes (18 percent GST and/or Basic Customs Duty of 25-40 percent) for reducing cost of renewable energy, and the removal of electricity duty, which is an extra burden on the cost of renewable power. There is also a strong need for an incentive push on the supply side to make green hydrogen adoptable for the C&I sector. It was further mentioned that the reduction in renewable power cost by 1-2 cents can facilitate a reduction in green hydrogen price by up to US$2 per kg.

By-product hydrogen producer:
The key challenges highlighted during the stakeholder meeting include the lack of updated PESO

guidelines for the storage, transportation, and usage of hydrogen, the lack of regulation on the number of storage days of hydrogen, the lack of clarity on the treatment of hydrogen produced from the chloralkali industries in India's hydrogen policy, and the absence of a trading platform for hydrogen certificates.

A few suggestions were presented, such as the introduction of an incentive scheme for potential hydrogen consumers to set up plants near hydrogen producers to ensure easy transportation using pipelines, and the production of hydrogen using renewable energy power (through rooftop model), which can be directly utilised in vehicles (FCEVs), or any other energy consumption points, so that it becomes a complete renewable energy package for domestic customers.

It was also deliberated that boilers can be designed to use hydrogen/blended hydrogen as a fuel. Once such boilers are designed to accept blended hydrogen, such initiatives will not only promote usage of hydrogen but also help in reducing emissions.

Natural gas producer:
A few key aspects will need to be addressed to enable the development of the green hydrogen sector. Some of these include mandates for ongoing industries like refinery and fertiliser, and new-use cases like blending, and iron and steel. The mandate also includes applicable and implementable policy to boost demand and a roadmap for the next 15 years, including clarity on the mandate for each sector that will act as a key driver for investors. This approach will drive demand and the necessary infrastructure, necessitating complementary policies for both upstream and downstream activities. For example, a robust carbon pricing system is essential for promoting sustainable chemicals.

Furthermore, it was emphasised that the issue may not lie with the infrastructure, but rather in determining the permissible blending percentage. There is a pressing requirement for a comprehensive approach that encompasses all aspects of infrastructure within the hydrogen policy.

7.2.1 Roundtable discussion:

A roundtable discussion was held that brough together members from WWF India and representatives spanning the entire hydrogen value chain, including multilateral/donor agencies, trading platforms, renewable developers, pipeline infrastructure, and others.

The discussions centred around the critical challenges that have the potential to impede the transition to green hydrogen in the future, including:

- Generating hydrogen demand in key sectors through incentivisation
- Defining a clear and effective institutional structure
- Providing infrastructure support for hydrogen storage and transportation
- Securing funding support from relevant agencies
- Establishing a clear regulatory framework that makes the hydrogen market more feasible for commercial and industrial consumers

The roundtable discussion yielded extensive deliberation on some critical points:

1. International bilateral programmes:
Two of the international bilateral programmes discussed during the roundtable were the strategic initiatives between India and the UK, and India and Germany.

The India-UK programme for the development of hydrogen, power, and renewables is a joint initiative launched by the two countries. The programme aims to promote the development of low-carbon energy systems and technologies, and encourage collaboration between Indian and UK businesses and research institutions in the energy sector. Three major programmes launched under this initiative are:

- India-UK joint partnership programmes on renewables and power.

- Climate compatible growth programme
- India-UK hydrogen hub

The India-Germany programme is a joint initiative launched by the two countries to promote the development of hydrogen technologies and systems. The programme aims to foster collaboration between Indian and German stakeholders in the hydrogen sector, including businesses, research institutions, and government bodies.

2. Current state of policy development in India

The discussants noted that the National Green Hydrogen Mission document provides only limited information regarding the current status and the pathway for progress of hydrogen development in the country. The mission document falls short in elaborating several crucial points, including:

- The development of a comprehensive institutional framework for hydrogen-related matters, such as the creation of an empowered group to encompass people from various ministries
- The need to expand research and development efforts in the hydrogen sector
- Consumption obligation to encourage widespread adoption of green hydrogen
- Ideas to be explored for establishing a robust hydrogen market

It was further deliberated that a more exhaustive and comprehensive hydrogen policy is required, one that focusses on all aspects of the hydrogen market in India (from production to supply and storage to transportation), with an equal focus on creating an environment for research and development in India.

- Cost of hydrogen production
- It was emphasised that the cost of decentralised hydrogen generation could significantly decrease to below US$2 if the cost of round-the-clock power reduces in the future.
- It was further suggested that significant cost-reduction measures in renewable energy generation is imperative to bring down the cost of producing green hydrogen, as the cost of power constitutes a major share of the overall cost. In addition, there is an urgent need to issue procedural guidelines for interstate banking.

3. Infrastructure for storage and transportation

The need for clarity on infrastructure support for hydrogen storage and transportation was stressed during the discussion, and it was emphasised that action must be taken to address this issue.

During the discussion, it was suggested that the liquid form of hydrogen may be a more efficient method of transportation than the current compressed gaseous form. Infrastructure initiatives are needed to support this transition.

It was also highlighted that the option of utilising existing natural gas infrastructure may be explored, as the cost for repurposing is much lower. If new infrastructure is needed, the timeframe, capacity, and utility of such infrastructure will require extra attention.

One suggestion put forth was to view ammonia as a potential mode of transportation rather than solely as a component for fertilisers.

4. Investment and funding

- To establish 160-180 GW of electrolysing capacity and procure electrolysers at an estimated price of US$500-US$700/kilowatt, an investment of between US$250 billion and US$400 billion will be required over the next decade.
- Creating a hub for green hydrogen will require additional public capital investment, particularly for infrastructure, such as pipelines and common goods, with approximately 20 percent of the total investment directed to this purpose. Unlike grey hydrogen, most of the investments for green hydrogen will need to be frontloaded. The

projects will require a guarantee of diversified, stable, and long-term demand to ensure success.

- Capacity development in existing financial institutions is crucial to meet the investment requirements for green hydrogen projects. Ensuring diversified, stable, and long-term demand from projects is necessary. Early-stage innovation financing over the next five-ten years is also vital.

7.3 Policy Recommendations

Based on the individual stakeholder consultations and the roundtable discussion, several key policy recommendations have been developed to make green hydrogen a viable option for the C&I sector in India. These recommendations are listed below:

Table 28: Policy Recommendations

KEY AREAS	TIMEFRAME	KEY DECISION-MAKERS/ STAKEHOLDERS	ACTION PLAN	POLICY RECOMMENDATIONS
RESEARCH AND DEVELOPMENT	• Medium Term	• Ministry of New and Renewable Energy	• International bilateral programme	• Creation of hydrogen/ green hydrogen hubs to encourage research and collaboration. • International institutions to spur innovation
	• Short Term • Medium Term	• Department of Science & Technology, Ministry of Science & Technology	• Funding of hydrogen research by the Indian government under the Hydrogen Mission	• Research on mainstream production technologies like electrolysers • Research on other emerging production technologies like pyrolysis and biomass/waste gasification • Hydrogen can be employed in drop-in biofuels, which are liquid fuels derived from sources like biomass, agricultural residues, and various wastes such as municipal solid waste, plastic waste, and industrial waste. These fuels must meet Indian standards for petrol (MS), high speed diesel (HSD), and jet fuel and can be used, either in their pure form or as blends, in vehicles without necessitating any engine system modifications. Furthermore, they can be seamlessly integrated into the existing petroleum distribution system. • Exploring the adoption of hydrogen across various industrial processes with minimal retrofitting.
INSTITUTIONAL STRUCTURE	• Short Term	• Government of India	• Development of regulatory structure for hydrogen, defining the roles and responsibilities for institutionalising hydrogen as a fuel similar to that of natural gas	• Nodal ministry, inter- ministerial governance, and regulatory structure for development and regulation of all activities related to green hydrogen value chain to be clearly defined • Creating an empowered group for smooth and efficient decision-making • State level policies to be encouraged

KEY AREAS	TIMEFRAME	KEY DECISION-MAKERS/ STAKEHOLDERS	ACTION PLAN	POLICY RECOMMENDATIONS
	• Short Term	• Nodal agency as defined by the Indian government	• Defining appropriate laws and regulation • for hydrogen production, distribution, and pricing	• Development of specific regulations to define safety norms, dedicated hydrogen pipeline construction norms, retrofitting of pipelines, storage of hydrogen, among others. • Creation/identification of specific institutions to certify the production of green hydrogen and ensure that its life cycle emissions have been nil.
DEMAND CREATION	• Short Term	• Nodal agency as assigned by the Indian government	• Mandatory demand creation	• Green hydrogen obligation for consumers (similar to that of renewable purchase obligation (RPO) to increase the uptake of solar and wind power) • Introduction of green hydrogen standards and labelling programme
	• Medium Term	• Nodal agency as assigned by the Indian government	• Realigning with global requirement	• There is a push in the EU to move to greener shipping. Green hydrogen / green ammonia is being considered as a possible green fuel for the future. India may look to provide green hydrogen / green ammonia refuelling facilities to the global shipping industry.
	• Medium Term	• Nodal agency as assigned by the Indian government	• Development of export hub for green hydrogen/ green ammonia	• Proactive engagements through bilateral agreements and MoUs with other countries (with potential future hydrogen demand) to establish the market for green hydrogen exports. • Providing appropriate land and infrastructure support to create these port facilities for hydrogen export • Providing special status (e.g., SEZ status) and concessions to these hubs to ensure their cost competitiveness
	• Short Term	• Nodal agency as assigned by the Indian government	• Promote blending of hydrogen with natural gas	• Hydrogen blending in natural gas pipeline can be considered as a relatively easier way to achieve a significant scale of hydrogen demand with limited cost implications
COST OF GREEN H_2 PRODUCTION	• Short/ Medium Term	• Nodal agency as assigned by the Indian government	• Providing key raw material at subsidised rates	• The Indian government should ensure accessibility to affordable water resources by prioritising water allocation to green hydrogen production facilities over other industries.

KEY AREAS	TIMEFRAME	KEY DECISION-MAKERS/ STAKEHOLDERS	ACTION PLAN	POLICY RECOMMENDATIONS
		• Ministry of Power (MoP)/ Central electricity regulatory commission (CERC) • Department of Water Resources, River Development and Ganga Rejuvenation, Ministry of Jal Shakti • Financial Institutions • Donor Agencies	• Financial support for production • Increasing domestic manufacturing of key equipment	• Procuring bulk renewable energy power through the Solar Energy Corporation of India Limited (SECI) bidding process • Waiver of open access charges • Annual banking provision • Mechanism to implement inter-state transmission system transmission charge waiver and banking. • Introduction of VGF / subsidy scheme for hydrogen production plants • Extending the PLI scheme for balance of plant for green hydrogen • The Indian government should move towards creating a carbon taxation and carbon pricing policy. Pilots for hard-to-abate sectors should be followed by pilots for all sectors • Creation of 'green hydrogen certificates' to meet sustainability goals. The initial focus should be on heavy industries and fertilisers to help them achieve their green hydrogen targets
TRANSPORTATION AND STORAGE	• Medium Term	• Nodal Agency • Implementing agency: Gail India/ Oil India and other major natural gas distribution company	• Development of dedicated hydrogen pipeline and associated infrastructure • Retrofitting of existing pipelines • Development of pipeline for blended hydrogen • Development of storage facilities • Development of refuelling stations	• Nodal Agency • Government support in right of way acquisitions • Defining the norms and standards for hydrogen pipeline construction • Defining norms and standards for hydrogen transport safety • Certification for standardising the usage of equipment in hydrogen plants • Implementing agency • Technical studies to test the viability of green hydrogen, and test the same through pilot projects • Assessing the impact of hydrogen usage across the consumer group
SPOT MARKET FOR HYDROGEN	• Medium Term	• Nodal Agency • Indian Gas Exchange (IGX)	• Push for creation of centralised merchant market for hydrogen	• Trading of green hydrogen under day-ahead market • Introduction of green hydrogen certificates

The report was prepared at the beginning of the year 2023. Since then, the government has been actively demonstrating a proactive stance in advancing hydrogen adoption across diverse sectors. Several initiatives which were a part of the original recommendations within the report, have already been initiated by the government, showcasing their proactive approach. A few of these initiatives by the govt. are highlighted in the table below:

Table 29: Recent Initiatives of Government of India

<table>
<tr><th>Key Area</th><th>Initiatives taken by the govt. of India</th></tr>
<tr><td>Promoting Research and Development</td><td>MNRE has unveiled a R&D Roadmap for the National Green Hydrogen Mission (NGHM) with a budget of Rs. 400 crores.
Focus areas of the roadmap –
Development of new materials, technologies, and infrastructure to improve efficiency, reliability, and cost-effectiveness of green hydrogen production, storage, and transportation.
Prioritize safety and address technical barriers and challenges in developing a hydrogen economy.
An R&D scheme is under finalization by MNRE.</td></tr>
<tr><td>Development of Institutional Structure</td><td>MNRE to be the nodal coordinating ministry for the NGHM and will undertake overarching policy formulation and programme implementation.
An Empowered Group (EG) chaired by the Cabinet Secretary and comprising Secretaries of Government of India and experts from industry will guide the NGHM; an Advisory Group chaired by the PSA and comprising experts will advise the EG on scientific and technology matters.
After the central government announced the national green hydrogen policy, several states, including Maharashtra, Andhra Pradesh, Uttar Pradesh, Rajasthan, etc., have notified their own green hydrogen policies.
The govt. of India has provided a detailed definition of green hydrogen in the MNRE notification dated 18.08.2023.
BEE has been appointed as the nodal authority for accreditation of agencies for the monitoring, verification and certification for green hydrogen production projects.</td></tr>
<tr><td>Demand Creation</td><td>Outlay of ₹400 crore up to 2025-26 has been provided for Hubs and other projects.
Government of India has come out with guidelines for undertaking pilot projects for using green hydrogen in the shipping sector. Areas identified for as thrust areas of pilot project:
Retrofitting of existing ships so as to enable them to run on GH2 or its derivatives
Development of bunkering and refuelling facilities in ports on international shipping lanes for fuels based on GH2.
MNRE has launched pilot projects to use green hydrogen in long haul transportation sector. The program supports deployment of green hydrogen through FCEVs and hydrogen ICE based trucks in a phased manner.
Outlay of ₹455 crore up to 2029-30 has been provided for low carbon steel projects.
PNGRB has issued permission to three CGD entities for trial blending projects in their respective authorized GAs and Hydrogen injection up to 5% vol in Natural gas has been achieved in low pressure MDPE network.</td></tr>
<tr><td>Cost reduction of Green H2 Production</td><td>MNRE has issued detailed guidelines for the PLI schemes for Green Hydrogen production electrolyser manufacturing under the flagship SIGHT program of National green hydrogen mission. A budget allocation of ~17500 Crore has been done for the same.
CSS and additional surcharge have been waived if green energy is utilized for production of green hydrogen and green ammonia.
Government has decided to grant waiver of ISTS charges to Green Hydrogen/Green Ammonia.
MNRE has proposed an exemption on duties and taxes up till 2035 on equipment imports for setting up export oriented GH2 projects.</td></tr>
</table>

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