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Macroscopic Analysis of a Hydrogen Economy

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(*The author list provided assumes no particular order as every individual contributed to the successful execution of the project.*)

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Glossary

Grey hydrogen	Hydrogen produced using natural gas
Green hydrogen	Hydrogen produced through renewables

(Note: This is primarily through electrolysis using renewable electricity, however in the report biomass gasification is also included in this definition)

Abbreviations

Mt	Million Tonnes
DRI	Direct Reduced Iron
LOHC	Liquid Organic Hydrogen Carriers
PEM	Proton Exchange Membrane
PLI	Production Linked Incentive
RE	Renewable Energy
SMR	Steam Methane Reforming
SOE	Solid Oxide Electrolysis
TRL	Technology Readiness Level

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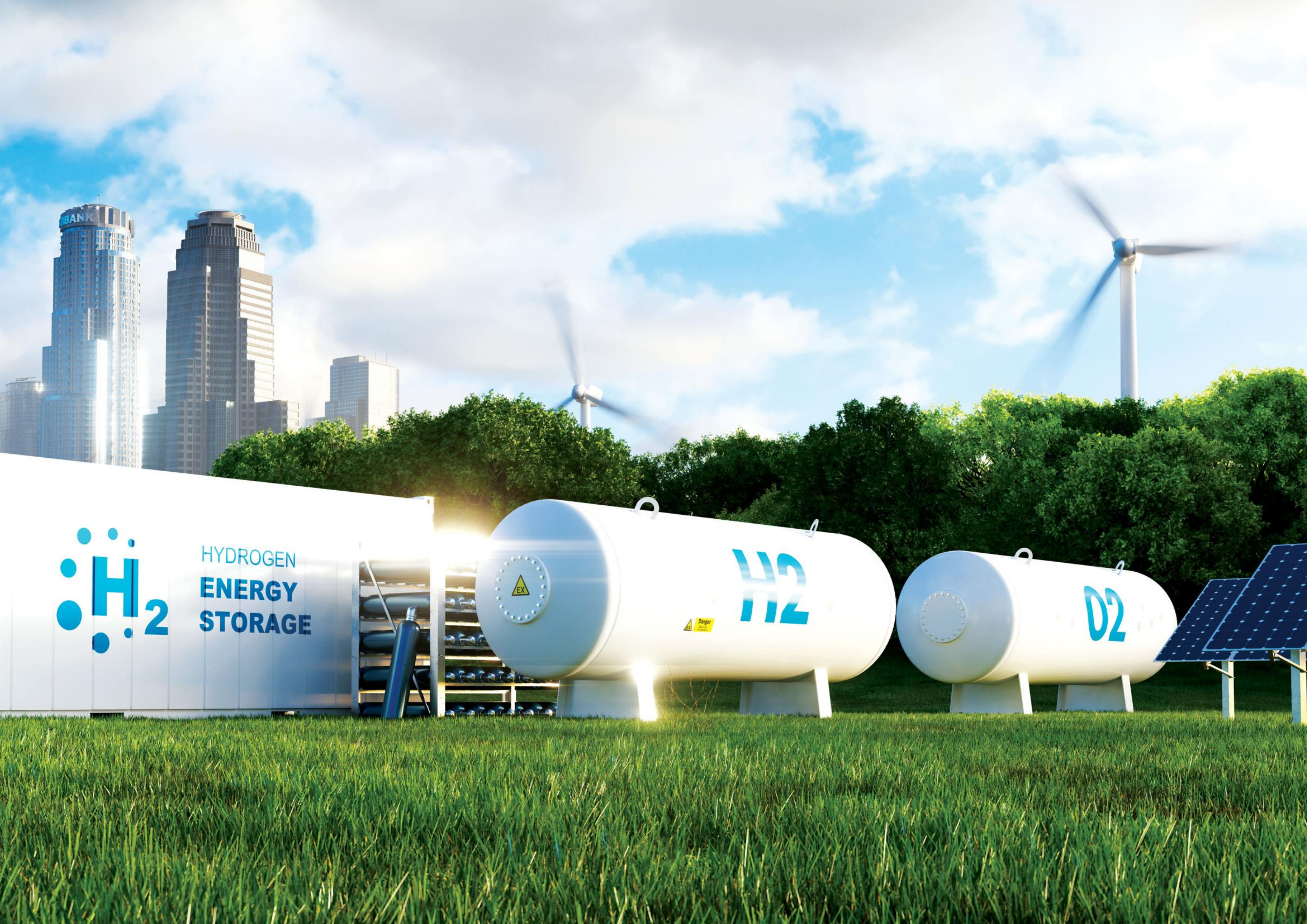
BANK
H2
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H2
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1. Background

India's energy sector will face two key challenges in the future. Firstly, there is the rising energy demand from a developing economy, whose priority remains bringing people out of poverty. For a country heavily dependent on fossil-fuel imports, there are high costs to meeting this demand. Secondly, India has set an ambitious target of becoming a net zero economy by 2070. These are strong climate commitments and requires the entire energy sector to reduce its overall emissions and mitigate the effects of the global climate crisis.

The government has worked on addressing both challenges with increased efforts for building renewable energy (RE) capacity, including an ambitious target of establishing 500 GW of RE capacity by 2030 and becoming a net-zero economy by 2070. However, there remain significant barriers to be overcome in achieving these. Renewables are variable in nature, and without an appropriate buffer, the large-scale addition of renewables can result in both electricity curtailment and shortages. Moreover, large parts of the industrial and transportation sectors have a non-electrical energy demand and face major technical challenges in the electrification of these sectors. These may never be completely decarbonised *directly* through renewables.

A **hydrogen economy** (the potential large-scale use of hydrogen [H_2] as a fuel in future energy systems) has been publicised as an enabler for addressing these challenges. Hydrogen has no emissions during usage and is a familiar fuel in industries. Until now, hydrogen could only be produced economically from fossil fuels. But the sharp reduction in the costs of renewables, such as solar and wind, have created a big opportunity for hydrogen production and use in recent years. Clean production is rapidly becoming more affordable and hydrogen is increasingly being looked at as a low-carbon alternative fuel for the future. This is being reinforced by the commitments of nations to tackle the climate crisis and air pollution.

Hydrogen also provides India an opportunity to enhance the financial strength of its energy sector. Since there is an abundance of renewable energy sources in the country, a higher green hydrogen production will happen, which will eventually lower the import of crude oil and natural gas. This would be a major cost saving for the government. It would also help to realise a greater energy independence and security for the nation. There is also a growing market for the various hydrogen components (e.g. electrolysers), where India can take a leading role (in manufacturing them). While hydrogen-based research is ongoing, in recent times policymakers and industrialists have taken note of the potential benefits of hydrogen. In the 2021 Union Budget, the National Hydrogen Mission was announced by the government. Since then, industrial giants in the oil-refining and steel sectors have announced large investments for the production of green hydrogen, electrolysers, etc.

However, for much of the applications in the global energy sector, hydrogen remains a topic in theory. Despite the advantages, it is still uncertain how a hydrogen economy would look like in India, given the existing research and data gaps.

Thus, the time is ripe to build a comprehensive knowledge base on hydrogen systems, in order to answer the questions of feasibility and help make crucial policy decisions regarding the technology's future.

Objectives

The primary objective of this project was to examine the status of hydrogen technologies and envisage what a hydrogen economy could look like for India in the future. The study aims to answer the following questions:

- What sectors of the economy are expected to drive the future hydrogen demand?
- What technologies are expected to be used for the production and storage/transportation of the amount of hydrogen demanded?
- How much of hydrogen will be produced in-situ or delivered from other production locations?

2. Approach

The first step in this macroscopic analysis was to take inputs from various secondary literature sources. A literature review was conducted to examine various journal articles, policy papers, reports, and government roadmaps to gain knowledge about the main aspects of a hydrogen economy and understand the expected growth of hydrogen technologies in worldwide energy systems.

Based on the inputs, a modelling exercise was conducted, calculating the amount of hydrogen in the demand-supply projections for India. The model calculations were made from 2020 until 2047.

2.1 Framework for H2 Projections

The first part of the model involved making long-term projections of hydrogen demand in India. For this, a bottom-up approach was chosen, individually analysing the different sectors of the present and future application of hydrogen.

2.1.1 Sectors of hydrogen demand

Currently, hydrogen use in India is restricted to two sectors: **oil refining** and **fertilisers**. Hydrogen is utilised for refining crude oil into multiple products and in desulphurisation processes. It is also a key input in the manufacture of ammonia, a pre-requisite for the fertiliser industry. Both sectors have a high demand (5 to 6 million tons of H_2 currently), and this hydrogen is currently provided using natural gas as a source (known as grey hydrogen).

In the future, hydrogen demand is also expected from multiple other sectors. Three sectors in particular have been highlighted in this report, given their importance. Hydrogen is expected to play a key role in the steel industry, to be used as a source of energy and as a reducing agent. Hydrogen demand is also expected in the road transportation sector, particularly the freight sector, which is dominated by trucks, buses and other forms of heavy-duty vehicles. As the country's natural gas pipeline infrastructure expands, hydrogen blending in city gas distribution (CGD) grids will emerge as a potential demand sector to reduce the emissions and costs associated with natural gas. More information about the sectors is given in Section 6.3

Growth scenarios

Two scenarios for the overall demand-supply projections have been considered in the exercise. In the medium-growth scenario, a business–as–usual growth rate has been considered for grey hydrogen demand (oil refineries, fertilisers), while a nominal integration of hydrogen expected in the future sectors of demand (steel, freight, CGD hydrogen blending) has been considered based on reactive national policies to global developments in hydrogen technologies. In the high-growth scenario, a proactive approach is taken by policymakers to increase the hydrogen demand by setting aggressive mandates for hydrogen usage, having clarity on the R&D and commercialisation strategy, promoting domestic manufacturing of hydrogen supply chain components, etc.

2.1.2 Technology assessment – Indian context

To meet this hydrogen demand, various technologies in the fields of production, storage, and delivery of hydrogen need to be deployed on a large scale. Assessing the suitability of the various technologies for the local conditions is an important component of the H_2 projections framework.

Technology Readiness Level

Technology readiness levels (TRLs) have been used as a parameter to measure the maturity of the various hydrogen technologies, namely hydrogen production, storage, and transportation.

TRL	Hydrogen Production	Hydrogen Storage and Transportation
High	Steam Methane Reforming (SMR) PEM Electrolysis Alkaline Electrolysis	Geological Storage Ammonia Hydrogen Compression - Tanks Hydrogen Liquefaction
Medium	Solid Oxide Electrolysis Coal Gasification Biomass Gasification	Hydrogen Compression - Pipelines Liquid Hydrogen Organic Carriers (LOHCs)

Table 1: Hydrogen technologies and readiness levels

Technologies with high and medium TRLs have been considered in the macroscopic analysis, while those with low TRLs have been left out. This is due to the lack of research data on the technologies as of today, which makes reliable predictions for the long-term future extremely tough. However, given the potential transformative impact of the low-TRL technologies, a qualitative analysis has been done, which is detailed in Sections 6.1 and 6.2

Key Performance Indicators

With regard to both production and storage/transportation, the hydrogen technologies have different key requirements. A Technology Assessment Framework (TAF) prepared by CSTEP, which evaluates any given technology along the following criteria:

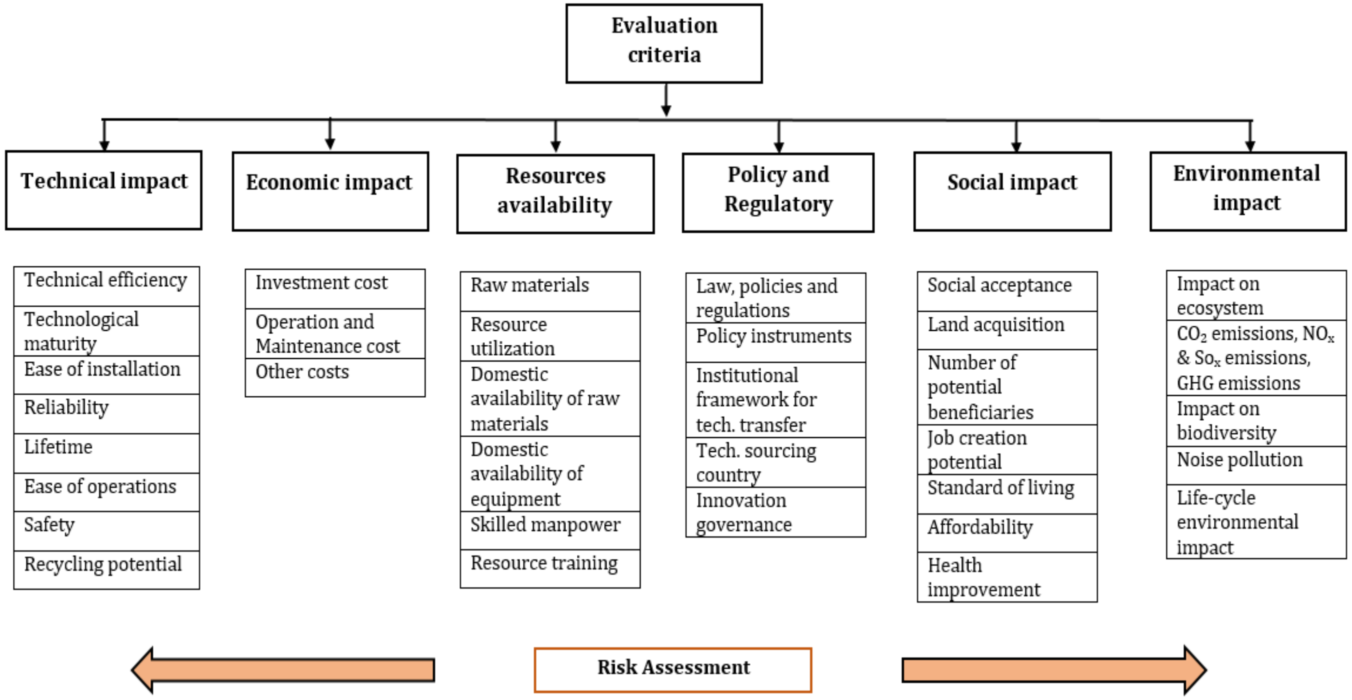

Figure 1: Technology Assessment Framework

Applying this framework for each technology is a critical step. It provides the basis for the assumptions and logic of the supply side of the model. It is also used to understand the wider implications of the model results, which are elucidated in Section 4

2.2 Key Drivers for Projections

Some of the key variables influencing the demand and supply of hydrogen in India include:

Sector parameters

These refer to the macroeconomic parameters of each sector considered for estimating the future demand of energy/ feedstock which could theoretically be replaced by hydrogen. This also requires an understanding of the sector processes and the properties of the hydrogen utilisation technologies; for instance, the status and growth of the direct reduced iron (DRI) pathway of steelmaking, since hydrogen can be integrated into this manufacturing process.

Market adoption rate

The adoption of hydrogen as a fuel/feedstock compared to the current sources in sectors that haven't yet utilised hydrogen. The market adoption rates are influenced by landscape indicators like sectoral climate commitments, mandates and purchase obligations implemented by the government, economic and logistical viability of hydrogen supply, etc.

Technology adoption rate

Within hydrogen usage, the breakup of technologies used for supplying hydrogen (production, storage, and transportation) was also estimated. The adoption rates are based on the results of technology assessments; therefore they estimate the future associated costs of the hydrogen economy.

3. Results

Here we highlight the results of the analysis and the modelling exercise conducted.

3.1 Hydrogen Demand Projections (2030 and 2047)

The first half of the model focusses on the quantum and breakup of future hydrogen demand from 2030 to 2047. Accordingly, the following results emerge:

Grey Hydrogen (Refineries and Fertilisers)

The refineries and fertilisers (urea) sectors are expected to have a steady growth in the long-term future. This results in an increase in the demand of grey hydrogen from 2020 to 2047. In the high-growth scenario, an assumption is made that the final hydrogen requirements of the refineries and fertiliser sectors remains unchanged. However, a larger part of the demand is met by green hydrogen, thereby reducing grey hydrogen production. In 2030, 10%

of grey hydrogen demand is assumed to be replaced by green hydrogen, which rises to 25% (refineries) and 30% (ammonia) in 2047. The grey hydrogen demand in 2030 is 6.8, which rises to 9.3 Mt in 2047 (Please see Figure 2 & Figure 3). In the medium-growth scenario, with a business-as-usual approach, only 5% of grey hydrogen demand in 2030 is expected to be replaced by green hydrogen. This rises to 15% (refineries) and 20% (fertilisers) in 2047. The grey hydrogen demand in 2030 is 7.1 Mt, which rises to 10.4 Mt in 2047.

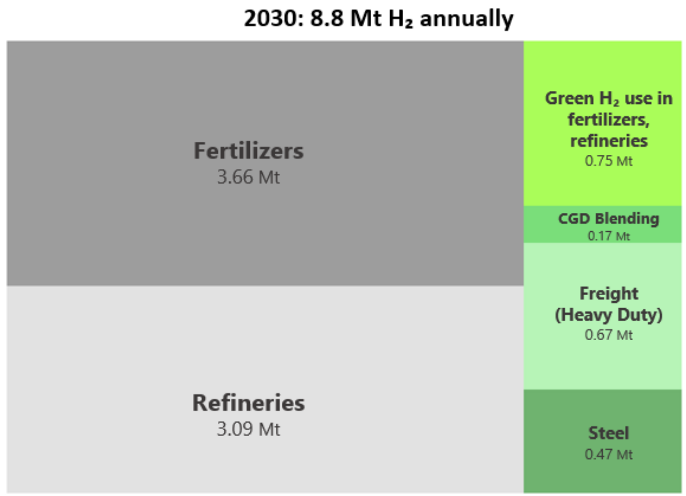

Figure 2: Hydrogen demand breakup: High-growth scenario (2030)

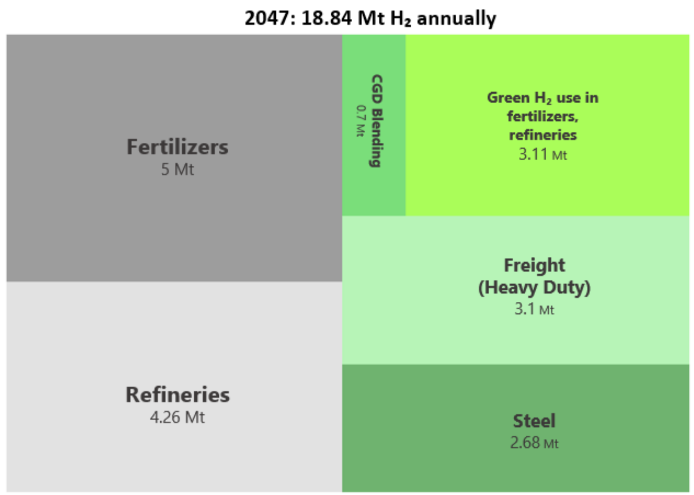

Figure 3: Hydrogen demand breakup: High-growth scenario (2047)

The cost of green hydrogen is expected to steadily drop in the future and become competitive (or cheaper) with the grey hydrogen produced via natural gas. Nevertheless, in both scenarios, **grey hydrogen requirements will rise steadily to 9 – 10 Mt** in the long-term future (2047), with only a partial replacement by green hydrogen. This is due to the nature of hydrogen use in the refineries and fertilisers sectors. India being the third-highest importer of crude oil, has already several oil refineries, with grey hydrogen being produced on-site as a by-product of other processes or steam methane reforming (SMR). The production of fertilisers like urea also requires an input of carbon dioxide. This carbon dioxide is produced as a by-product in grey hydrogen production and is recycled for fertilisers. The use of green hydrogen in the fertiliser industry would also necessitate finding another carbon source and supply chain to provide carbon dioxide.

Green Hydrogen (Freight, Steel, Natural Gas)

Currently the green hydrogen demand in the country is negligible, with hydrogen use limited to the fertilisers and refineries sectors, as mentioned above. But green hydrogen demand is expected to rise with the introduction of hydrogen in the steel, heavy-duty freight and CGD-blending sectors. Some green hydrogen demand is also expected from the fertilisers and refineries sectors as they transition away from fossil fuels.

In the high-growth scenario, green hydrogen demand grows from 2 Mt in 2030 to 9.6 Mt in 2047, thereby accounting for almost 50% of the total hydrogen demand in 2047 (please see Figure 2 & Figure 3). In the medium-growth scenario, green hydrogen demand grows from 0.9 Mt in 2030 to 4.4 Mt in 2047 (see Figure 5).

There are significant barriers in the adoption of hydrogen in the aforementioned sectors. Hesitation from the steel, freight, and CGD-blending sectors will continue in the short term until more demonstration/pilot projects are implemented. An assumption is made that the final market adoption rates of hydrogen will begin small and grow gradually until the 2047 timeline.

Nevertheless, in both scenarios, there is scope for an exponential rise in the demand of green hydrogen (from the current levels). This stems from the energy-intensive nature of these sectors and their expected growth rates.

3.2 Hydrogen Supply

The second half of the analysis focusses on how this hydrogen demand is to be met, detailing the various production and storage/transportation technologies.

3.2.1 Hydrogen production

Presently, almost 6 Mt of hydrogen is produced in India. However, to meet the present and future demand of a hydrogen economy, a variety of sources of production are required. In the high-growth scenario, the total hydrogen demand rises annually at the rate of 5% to reach 8.8 Mt in 2030 and 18.9 Mt in 2047. Here, green hydrogen production rises from a negligible share today to an over 50% share in 2047. In the medium-growth scenario, the total demand for hydrogen rises annually at a rate of 4% to reach 8 Mt in 2030 and 14.9 Mt in 2047. While green hydrogen production rises, the slower uptake in the newer sectors (steel, freight, CGD-blending, etc.) results in a relatively lower 30% market share in 2047.

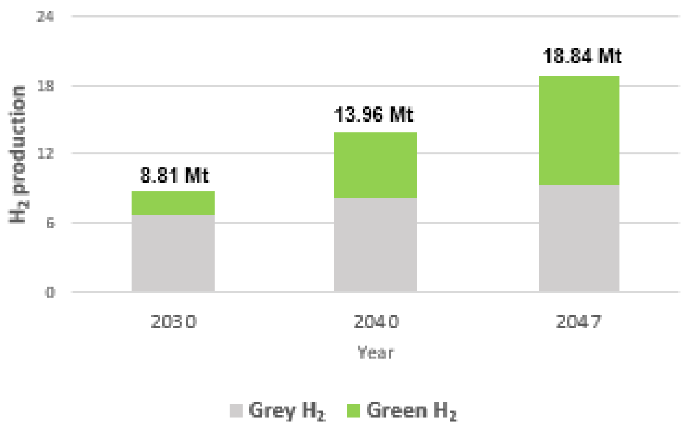

Figure 4: Hydrogen production: High-growth scenario

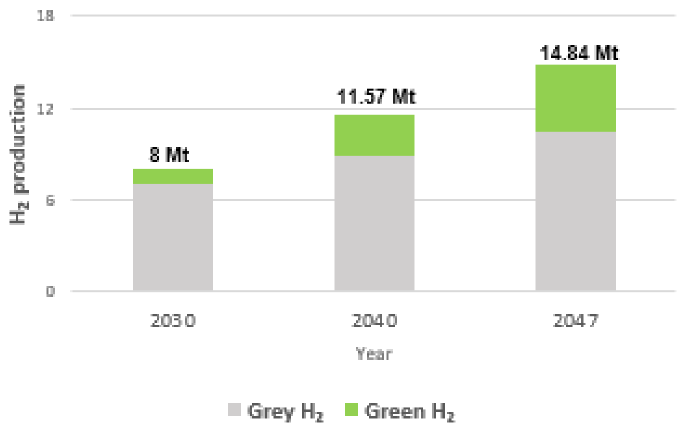

Figure 5: Hydrogen production: Medium-growth scenario

Technology breakup

Fossil-fuel-based hydrogen production today consists of SMR technologies. The future green hydrogen production is expected from two major sources: electrolysis of water, and biomass gasification. Electrolysis has been further categorised into three distinct technologies, which are expected to play a major role in the future. These are: proton exchange membrane (PEM) electrolysis, alkaline electrolysis, and solid oxide electrolysis.

In both scenarios, electrolysis technologies are widely expected to dominate green hydrogen production, having an 80%-90% technology share. Within electrolysis, alkaline and PEM electrolysis are expected to be the dominant technologies adopted in the long term (Figure 6).

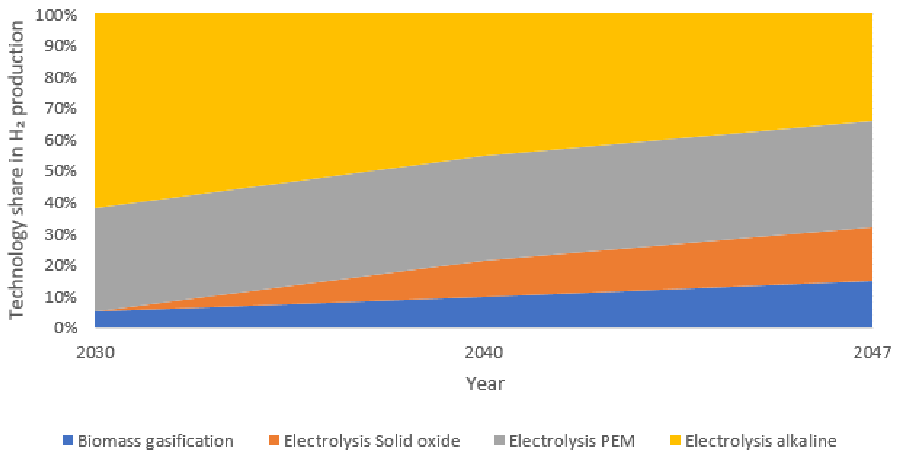

Figure 6: Green hydrogen (H_2) production by technology

Coal gasification was *not considered* amongst the final technologies for hydrogen production. Given India's vast coal reserves, the technology has often been considered as a means towards reducing energy imports. However, coal gasification has a lower technology maturity, higher costs, and no existing production in India compared to SMR. It also has high carbon emission (2 times the specific emissions of SMR) and a water footprint 2-3 times higher than the other technologies considered, rendering it incompatible with India's climate goals. It is not expected to be a part of India's long-term future, as hydrogen production from renewables and biomass become more cost effective in meeting the hydrogen demand.

Associated costs

There are significant costs associated with the functioning of a hydrogen economy. Green and grey hydrogen have high initial costs and operating costs (which include the cost of fuels like natural gas, biomass, and/or electricity). To produce the 15-19 Mt of hydrogen by 2047, the annual production costs were calculated. As these production technologies grow in capacity, cost reductions (per unit of hydrogen produced) is expected owing to factors such as economies of scale and learning curves (depending on technology maturity).

These cost reductions were factored in for individual technologies, with electrolyser technologies in particular expected to have significant cost reductions by 2030 itself. These costs per kg of hydrogen, for a given technology, have been highlighted in Figure 7. In both high-growth and medium-growth scenarios, major cost reductions are expected in the PEM and alkaline electrolyser technologies, while the more mature gasification technology pathways have a lower scope for further cost reductions.

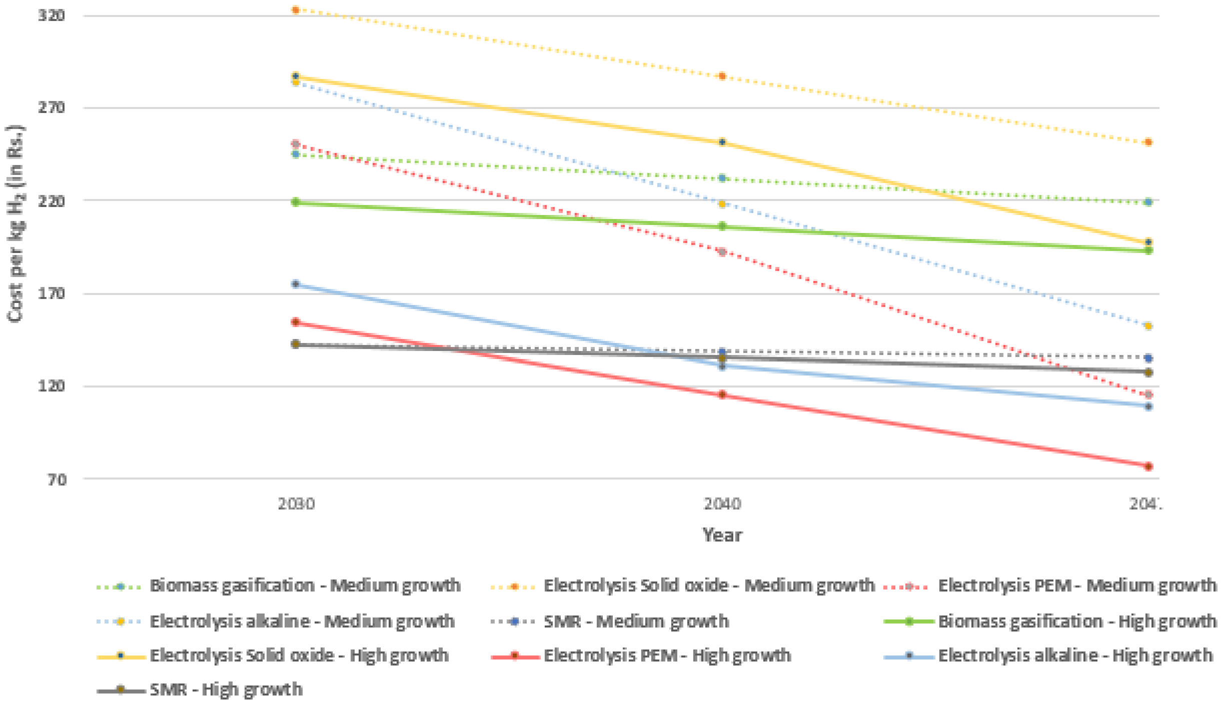

Figure 7: Hydrogen production costs (by technology)

3.2.2 Hydrogen storage/transportation

Currently, the consumers of hydrogen have the capacity to produce it according to their own requirement. But this will change in the future, as a larger number of diverse consumers will utilise hydrogen in a more decentralised manner. Therefore, as the hydrogen economy develops, there would be an increased requirement for a diverse range of storage and transportation technologies.

In both the scenarios modelled, the share of hydrogen that requires transportation to the site of application will rise.

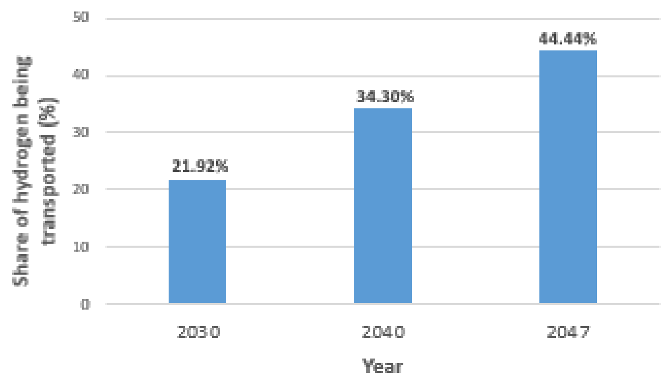

Figure 8: Share of hydrogen being transported: High-growth scenario

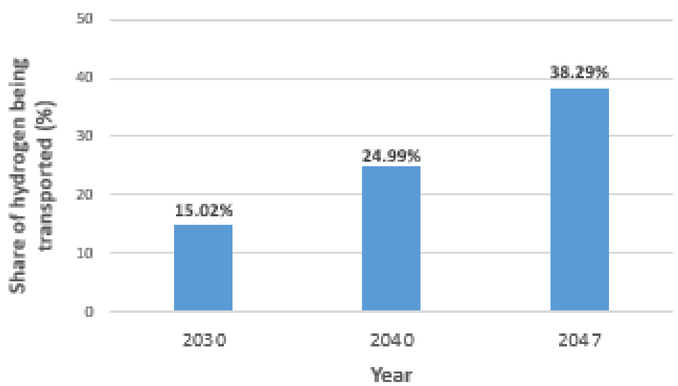

Figure 9: Share of hydrogen being transported: Medium-growth scenario

In the high-growth (Figure 8) scenario, the share of hydrogen being transported rises from 22% in 2030 to 44% in 2047. In the medium-growth (Figure 9) scenario a higher proportion of grey hydrogen usage in the fertiliser and refineries sectors explains a lower but nevertheless significant 38% share of hydrogen with additional storage and transportation requirements in 2047.

Technology breakup

The technology assessment was conducted, considering the suitability of the various technologies in the Indian landscape. While geological storage is rated highly on several parameters, there is a lack of information on suitable locations (e.g. salt caverns, depleted oil fields) in India. Until a proper assessment of the geographic potential is made, no reasonable analysis can be made. Hence the study assumes the hydrogen economy functioning in 2047 will not use geological storage options.

Hydrogen compression is an effective way of storing hydrogen to provide energy storage solutions with sufficiently high energy densities. To transport this over short distances or for lower volumes, **compressed hydrogen** is transported in trucks containing pressurised tanks. **Liquefied hydrogen,** as well as chemical intermediary carriers such as **ammonia** and **liquid organic hydrogen carriers (LOHCs),** have also been considered as storage media. An additional pathway, **pipelines,** has been created in the analysis to account for higher-volume, long-distance transportation of this compressed hydrogen.

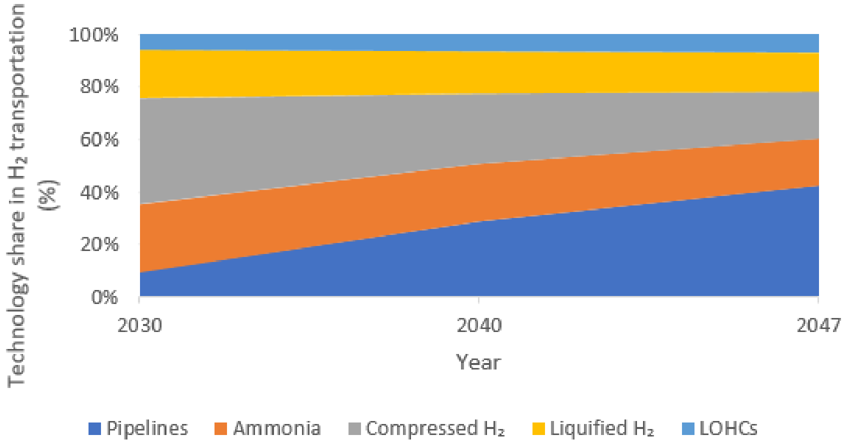

Figure 10: Technology share of H_2 storage/transportation

Overall, there is an expected rise in the use of pipelines for the transportation of hydrogen in the long-term future, given the centralised nature of hydrogen demand in certain sectors and the lower costs of delivery. By 2047, pipelines will account for 45% of transported hydrogen (by mass) in the high-growth scenarios (Figure 10). However, pipelines have high initial costs and thus more research is required before entire networks can be created. In the short term, simpler and proven systems such as pressurised tanks, ammonia, and liquefied hydrogen will play the biggest roles.

Associated costs

Costs are incurred in setting up the requisite infrastructure for delivering hydrogen from the production site to the site of application. This involves costs of storage, transportation, and processing (chemical conversion and reconversion for intermediary compounds), as well as an uncertainty range. The delivery costs (per kg of hydrogen) for multiple pathways are noted below (Figure 11):

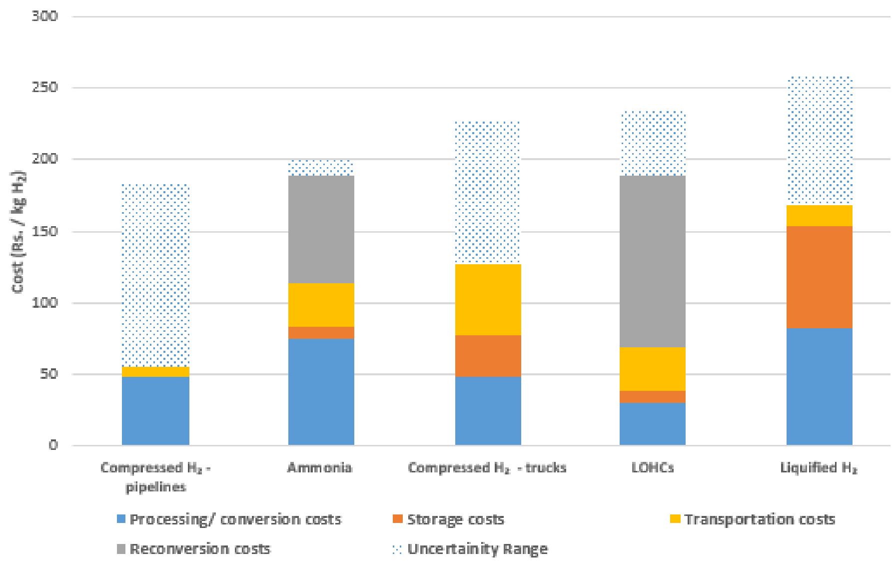

Figure 11: Cost of transporting H_2 (by technology)

On the basis of the above associated costs, the annual costs of transporting the amount of hydrogen demanded have been calculated for both scenarios. An assumption was made to consider the entire additional costs within the uncertainty range.

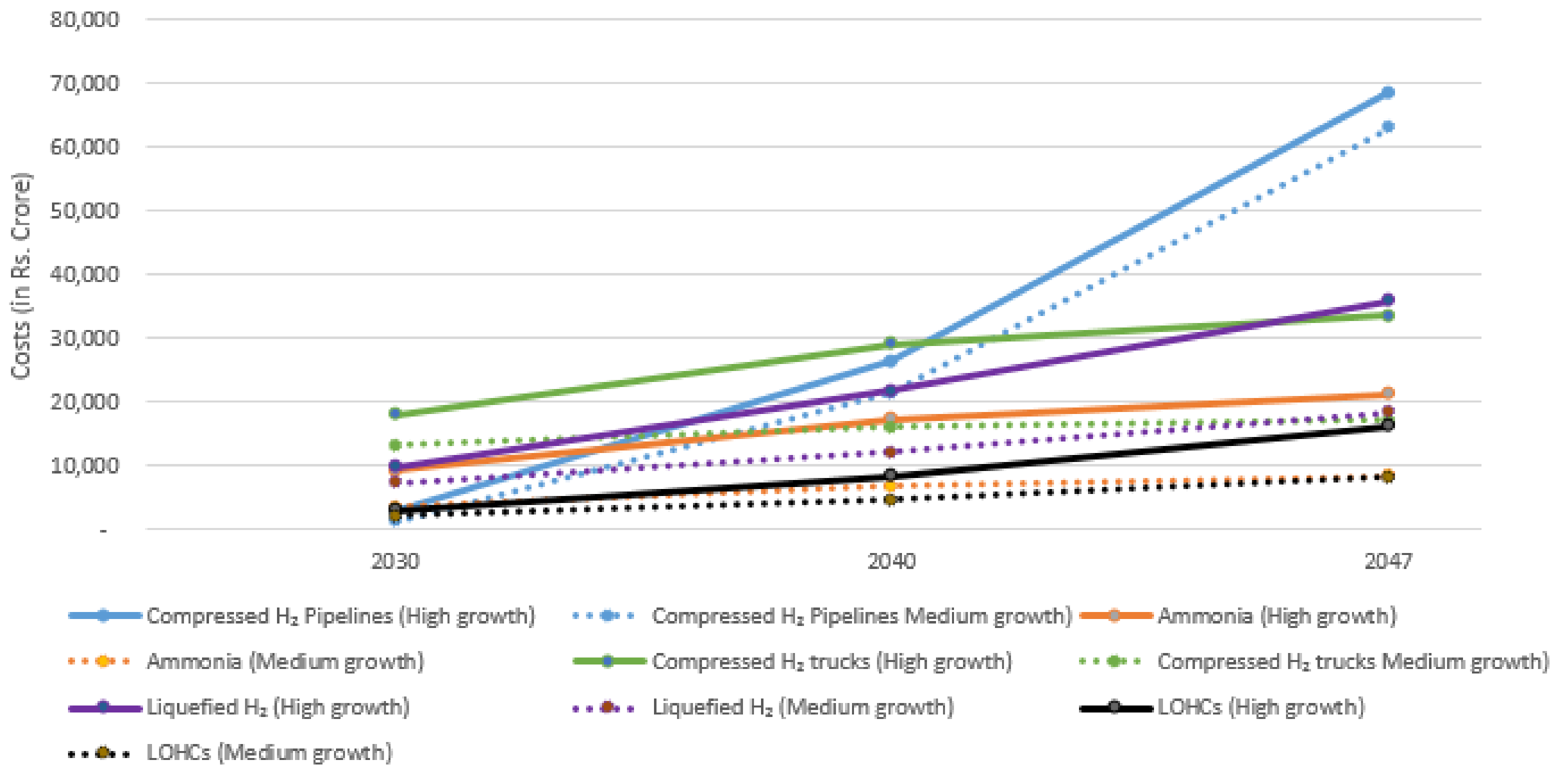

Figure 12: Annual cost of transporting H_2 (by technology)

The total annual costs of hydrogen storage and transportation have been calculated for both scenarios. In the high-growth scenario, the total annual costs rise from INR 0.43 lakh crore in 2030 to INR 1, 75 lakh crore in 2047. In the medium-growth scenario, the annual costs rises from INR 0.27 lakh crore in 2030 to INR 1.15 lakh crore in 2047.

4. Discussion

Through the macroscopic analysis conducted, a better outlook on the potential hydrogen economy has been made.

An estimated **8 to 8.8 million tons** of hydrogen demand is expected by 2030, rising to ≈ **15 to 19 million tons** by 2047, from an approximate 6 million tons required presently.

Though the demand from refineries, fertiliser sectors, etc. will continue to exist, hydrogen demand will be primarily driven by the growth of green hydrogen use in new sectors like steel, heavy-duty freight, and blending in city-gas-distribution grids.

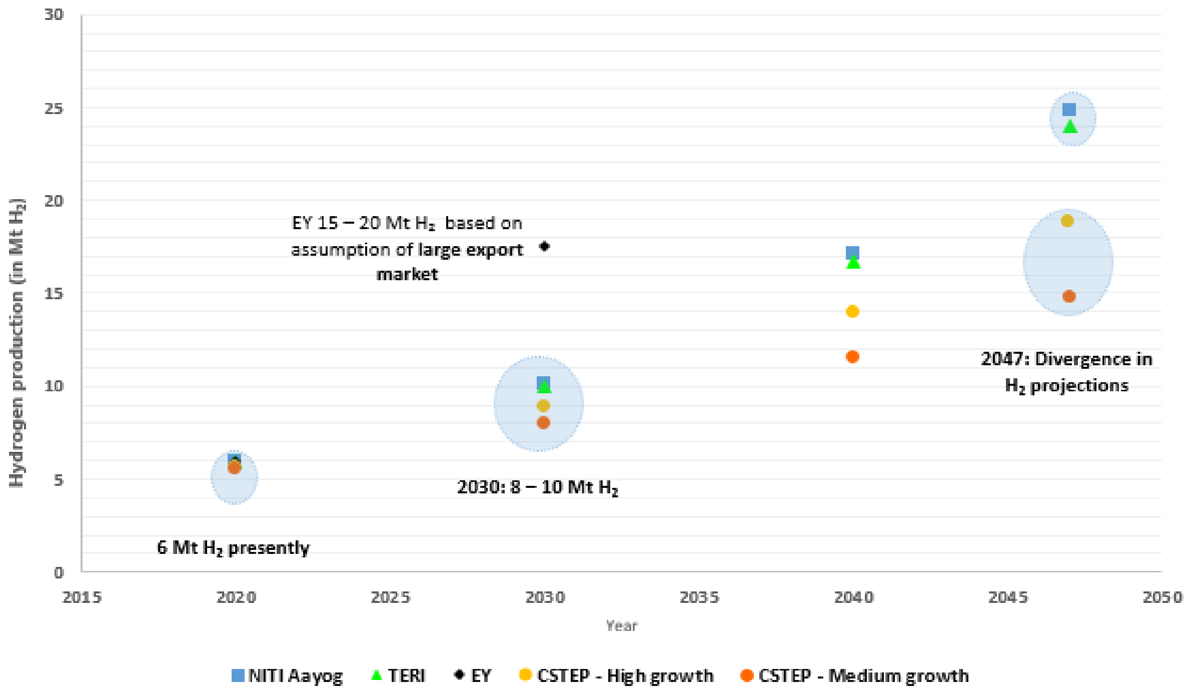

Figure 13: Hydrogen demand projections comparison (existing literature)

From a negligible production presently, green hydrogen production is expected to rise 0.9 to 2 million tons in 2030, and potentially 9.5 million tons in 2047, more than 50% of the total hydrogen demand.

Figure 13 with other relevant studies in the field (Hall et al., 2020; Moda, 2022; Raj et al., 2022). It is interesting to note that in the longer term (2047), there is a divergence in the expected demand. CSTEP expects a hydrogen demand of 15–19 Mt H_2, as compared to the projections by other studies, which are higher than 24 Mt H_2 in the long term.

Bridging this gap requires concerted efforts from the government, which includes aggressively expanding *renewables, electrolyser manufacturing capacity,* etc. *Hydrogen export* is another measure (not yet considered in this study) to increase the market demand of hydrogen. This would require *upgrading port/freight infrastructure* across several regions of the country, having a cogent *trade strategy* and proactively *building partnerships* with other countries.

On the supply side, multiple technological pathways are expected to be used for hydrogen production, storage, and transportation. SMR use is expected to continue till 2047 in the refineries and fertiliser sectors.

In Figure 7, the production costs have also been explored for the future. An important conclusion here is that in the high-growth scenario, PEM and alkaline electrolysis have the potential become *cheaper than SMR* in the 2030s. While costs are not being considered

This would also translate to a potential electrolyser capacity requirement of up to 61 GW in 2030, 290 GW in 2047 to be powered by solar.

These demand projections have been compared in

as the sole factor driving the choice of hydrogen technologies, electrolyser technologies (particularly PEM and alkaline) are expected to account for 80%-90% of green hydrogen production. Scope for biomass gasification technologies exists in the Indian context (Figure 6).

As the hydrogen economy develops, it would be difficult to produce all the hydrogen demanded on-site. Thus, storing and transporting hydrogen in greater quantities, over longer distances and in a cost-effective manner will be needed. While only *15% - 20%* of hydrogen is expected to require transportation by 2030, this ratio could rise to *38% - 44%* by 2047.

In the short term, modular, mature systems like compressed or liquefied hydrogen, and ammonia are expected to be used extensively. In the long-term future, hydrogen pipelines are also expected to be a key component of a hydrogen economy, potentially transporting over 45% of the hydrogen demand by 2047.

4.1 Recommendations

Two topics of interest emerge from the macroscopic analysis, given their relative importance for a future hydrogen economy and the large scale of efforts required.

1. The role of biomass gasification is of unique interest in the Indian context. Hydrogen generation from biomass residue is a cleaner alternative and can potentially be cost-competitive with SMR, electrolysis technologies, etc. Importantly, there is an "abundance" of this resource in India, with estimates of over 200 Mt of surplus biomass residue produced annually (Trivedi,2020). With the present technologies, this amount of residue can be used to produce over 14 Mt of hydrogen annually, more than the entire green hydrogen demand projected for 2047. However, the biomass resource will have competing demand from the power and transportation sectors. Moreover, gasifier technologies have not yet been widely implemented in the country while a supply chain needs to be built to transport the biomass in a reliable and cost effective manner. These challenges need to be addressed before any significant fraction of this biomass potential can be utilised for hydrogen production.

The initial focus area for support can be agricultural land in the vicinity of existing refineries and ammonia/fertiliser manufacturing. These sectors are widely expected to have green hydrogen purchase obligations in the future, which can be met locally, thereby creating a nearby hydrogen market for gasifiers. This synergy between the industries and the gasifiers can be mutually beneficial to both and can help promote the overall growth of biomass gasification technologies in the country.

A GIS-oriented framework which isolates potential demand centres near an agrarian setup would benefit various stakeholders across different governance structure. Governments can benefit from building a hydrogen supply chain in these areas to understand this technological pathway better, while also inspiring more confidence in potential investors.

2. *RE-powered electrolysis* is at the forefront of all global visions of a hydrogen future, more so in India, where an abundance of RE resources and proactive government policies create long-term conducive conditions for the supply of clean electricity at low prices. However, electrolysis technologies are still a challenge that has not been addressed in the country. India has the opportunity to develop a domestic manufacturing market which could have the scale to drive down electrolyser costs, similar to the case of solar-PV panels. But while there is extensive research ongoing in the country, more efforts are required for bringing about commercialisation and scale up. While the global market is still growing, China and Europe are investing heavily in the expansion of the PEM and alkaline electrolyser manufacturing. For these electrolysers, India would also have to import critical raw materials such as nickel, platinum, iridium etc.

A clear domestic manufacturing strategy (including instruments like the PLI scheme) is thus required to consider these factors and enact a long-term vision— to grow India's market share, while maximising self-reliance of the domestic supply chain.

4.2 Limitations

The following can be considered as the limitations of this analysis:

1. During the hydrogen supply modelling, the focus remained on meeting the national demand. As such, India's green hydrogen export potential was not considered a topic of research. For India to become a leader in this segment, a detailed examination of export-driven indicators should be undertaken in subsequent iterations of the National Hydrogen Policy.
2. Given the scope and rationale of this exercise, discount rates, future value of money, etc. were not considered while calculating monetary values.
3. Since the conclusion of this research study, global developments have caused a marked increase in exchange rates, natural gas prices, etc., which could affect the outcomes of the final modelling exercise (e.g. cost of hydrogen produced through SMR). Therefore, prices predicated on the basis of geopolitical factors have not been modelled.

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6. Appendix

6.1 Selected Technologies and Their Readiness Levels

Technology readiness level (TRL) is a metric developed initially by National Aeronautics and Space Administration (NASA), and used to define the maturity of any given technology and chart the journey of its progress. TRLs are widely used in institutions worldwide to create a more uniform understanding of technologies for various actions (research priorities, degree of funding etc.). There are typically nine levels. Low-TRL technologies (TRL 1–4) consist of technologies where the scientific principles and possible applications are still being established. Medium-TRL technologies (TRL 5–7) have basic validation of their applicability but require further testing in the environment and at greater scales, based upon which further alterations can be made to the technology. High-TRL technologies (TRL 8–9) have reached a mature state, validating their expected functioning and being deployed commercially. It must be noted that while high-TRL technologies have been approved for use, the potential for their further commercial deployment may still be there, which could lead to further development and cost reductions etc.

For the various hydrogen production, storage and transportation technologies, the TRLs have been decided on the basis of the ETP Clean Energy Technology Guide, developed by the International Energy Agency (IEA).

TRL	Hydrogen Production	Hydrogen Storage and Transportation
High	Steam Methane Reforming (SMR) PEM Electrolysis Alkaline Electrolysis	Geological Storage Ammonia Hydrogen compression - tanks Hydrogen liquefaction
Medium	Solid Oxide Electrolysis Coal Gasification Biomass Gasification	Hydrogen compression - pipelines Liquid Hydrogen Organic Carriers (LOHCs)

The high- and medium-TRL technologies have been considered in the long-term scenarios of India's energy future.

6.2 Low-TRL Technologies

Low-TRL technologies have not been considered in the long-term scenarios of India's energy future due to the high degree of uncertainty involved in how these technologies would evolve. However, given their potential for transformative impact, some of these technologies have been listed below for consideration in future research:

- Anion exchange membrane (AEM) electrolysis (hydrogen production)
- Metal hydrides (hydrogen storage and transportation)
- Methane pyrolysis (hydrogen production)

- Algae action on biomass (hydrogen production)

6.3 Sectorial Narratives of Hydrogen Demand

On the demand side of a hydrogen economy, the study focussed on five sectors: **fertilisers, oil refining, steel, heavy-duty freight, and CGD blending**. After conducting a literature review, these sectors were chosen on the basis of factors such as their relative impact on future hydrogen demand, present energy/feedstock costs, sector-specific hydrogen utilisation technologies presently available etc. Calculated assumptions were also made on their relative ease towards market integration, as compared to alternatives like electricity.

Fertilisers and *oil refining* are the two existing sectors primarily making up hydrogen demand, and this demand is expected to rise. While alternative farming techniques (with lower urea requirements) or the use of other complex fertilisers can become popular in the coming years, the overall demand for urea-based fertilisers is still expected to rise in the agricultural sector up to 2047, according to NITI Aayog. India also currently imports urea. Reducing these imports, as per the *Atmanirbhar* vision, necessitates producing more fertilisers locally. This implies a stable demand of hydrogen for the fertilisers sector. The case for hydrogen demand in the oil refining sector is built on the assumption that as a country develops, there are high requirements for gasoline in the passenger and freight transportation sector. This gasoline is produced through the refining of crude oil, for which hydrogen is a key element. While decarbonisation efforts are increasing in the transportation sector (in the form of expanding public transportation, use of cleaner fuels, etc.), the demand for gasoline-powered vehicles is expected to be present until the 2047 timeline.

As per the 2017 National Steel Policy, India's *steel* sector is expected to triple in capacity (from the current production level), while also increasing the production capacity of DRI-based steel. Hydrogen can be effectively used as a reductant in this form of steelmaking and help reduce the steel sector's considerable carbon footprint. The government has already provided signals about introducing the use of green hydrogen in the industry. As the steel sector expands, there will be an increase in green hydrogen demand by 2047. The *freight* sector in India is also expected to have a rising and high energy demand in the long-term future. This sector will be dominated by *heavy-duty* vehicles on the road (e.g. trucks). Decarbonising the freight sector using hydrogen-powered fuel cell electric vehicles (FCEVs) has received serious attention in recent years. The fuel storage of FCEVs has a lower weight compared to batteries, thereby allowing for a higher loading capacity—a factor more significant in freight transport over passenger transport. FCEVs also have a mileage that is appropriate for long distance travel. As the vehicle and fuel costs drop, the market share of FCEVs is expected to grow within the freight sector. Lastly, natural gas usage is also growing in the country, with the government actively promoting its use. However, with domestic production of natural gas remaining low, hydrogen blending in city-gas-distribution grids can provide the twin benefits of offsetting the energy imports while also making the gas grid cleaner.

Sectors which were not part of this research study include:

Power sector: India has set a 500 GW target for renewables capacity by 2030 and this capacity is only expected to rise in the long term. Integrating such a high volume of renewables brings multiple challenges for the electricity grid. Hydrogen is being considered as a storage medium, with electricity from renewables used to produce hydrogen in times of excess electricity. This hydrogen can be converted back to electricity during periods of low-RE generation, thereby enhancing the integration of RE in to the grid.

Hydrogen has a high energy density and can be used for large, long-term storage of electricity. Hydrogen-based electricity generation has short response times and can be used for flexible electricity generation. Hydrogen can also be used for off-grid or backup power systems (diesel abatement). However, other electricity storage technologies such as pumped-hydro storage and electrochemical storage (batteries) that are growing exponentially in scale, have lower conversion losses and currently have greater integration in the power sector. It remains to be seen what role hydrogen will play in India's power sector, by 2047 and beyond.

Process heat: One of the biggest sources of energy consumption in the industrial sector is process heat, in the form of furnaces, boilers etc., which have high-heat requirements (up to 2000° C). Currently this segment's energy demand is met by fossil-fuel sources such as coal, furnace oil, pet coke etc.

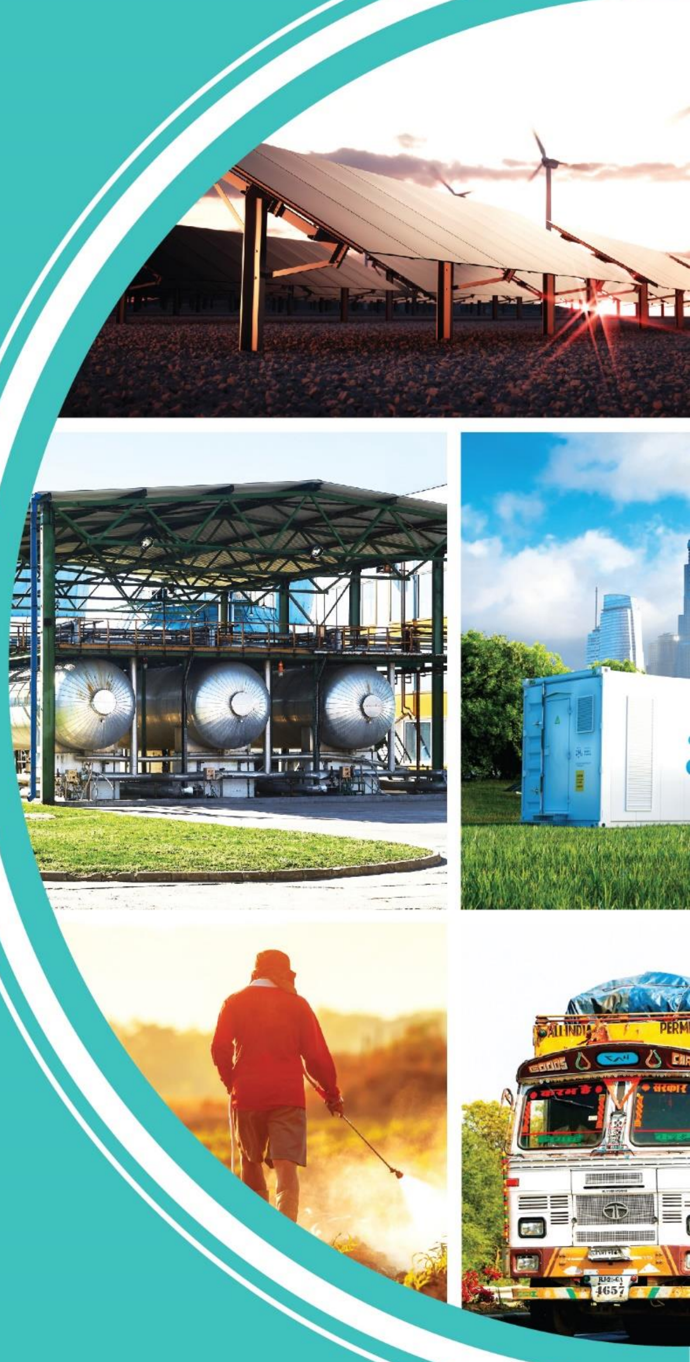
As a fuel for process heating, hydrogen is a far more expensive option currently, but it is being considered as a decarbonisation option, due to the technical limits in electrifying all heating processes within the industry. Further research and demonstrations are required in determining the viability of switching to hydrogen without compromising on the various process heating requirements. Measures are also required to address the economic gaps in hydrogen-based heating.

Methanol: Methanol is an important precursor in India's chemicals industry, used for the production of formaldehyde, acetic acid, solvents etc. While India has a low demand of 2 Mt presently, this is expected to rise in the future as methanol blending in gasoline is increased for the transportation sector. Currently most demand is met through imports, while gasification of coal is being considered for domestic production.

Green hydrogen can be used for the production of methanol, thereby reducing energy imports with a lower environmental impact. However for this, economic support is required in order to compete with existing methanol pricing. Moreover, methanol production requires an additional carbon dioxide stream if produced through green hydrogen, which presents an additional logistical challenge.

Passenger Vehicles: While the heavy-duty vehicles and the freight sectors have been covered in the analysis, there is also a case for hydrogen to be used in the area of passenger vehicles. There are concerted efforts to phase out conventional gasoline-powered vehicles in the future, given the extreme dependence of fossil fuel imports and pressures to reduce emissions in the Transportation sector. Hydrogen-powered fuel cell electric vehicles (FCEVs) are one alternative seen, with zero tailpipe emissions and high mileage capabilities.

However, battery-powered electric vehicles (EVs) are already dominating sales in the two wheeler segment, and in the future are expected to have a large share in sales of all passenger vehicle segments. The long-term growth of hydrogen in the passenger vehicle segment depends on how the total cost of ownership (TCO) of FCEVs changes, and how they can leverage features such as charging infrastructure, higher mileages, lower refuelling times, etc. in order to become more attractive for customers.



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