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India's Commitment to Hydrogen: Strategic Initiatives and Goals for Climate Change Mitigation

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ABSTRACT
The Government of India (GOI) has acknowledged the significance of hydrogen as a fuel and has implemented targeted policies and missions to encourage its production and utilization within the country. As a part of these endeavours, the GOI has launched the National Hydrogen Energy Mission with the primary goal of creating a comprehensive roadmap for hydrogen production, storage, and utilization. This mission encompasses the establishment of hydrogen hubs and pilot projects to showcase hydrogen-based technologies and their integration with renewable energy sources. In addition to the National Hydrogen Energy Mission, the GOI has also introduced the Green Hydrogen Policy. This policy serves as a catalyst for the production and utilization of green hydrogen through various means, including financial support and research & development activities. These initiatives exemplify India's commitment to harnessing hydrogen as a clean energy source while reducing dependence on fossil fuels. By actively pursuing these initiatives, India aims to develop a comprehensive hydrogen ecosystem that facilitates the efficient production, storage, and utilization of hydrogen.
In this paper, we delve into the strategic initiatives and goals outlined by India to foster a robust Green Hydrogen ecosystem. We will examine how these initiatives align with India's broader climate change mitigation strategies, the infrastructure and technology development required, the potential economic and environmental benefits, and the global implications of India's commitment to Green Hydrogen. By exploring these dimensions, we aim to provide a comprehensive understanding of how Green Hydrogen can drive India's transition to a sustainable and resilient future.

INTRODUCTION
India's deep commitment to aspirational Climate Goals has been widely acknowledged in the comity of nations. Our achievements have matched our ambition. India has the fastest growing Renewable Energy capacity in the world. India has also emerged as one of the most attractive destinations for investments in Renewables. As India has set its sight on becoming energy independent by 2047 and achieving Net Zero

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by 2070, we recognise the critical role of Green Hydrogen. India, with its vast renewable energy resources, also could produce Green Hydrogen for the world. The National Green Hydrogen Mission aims to provide a comprehensive action plan for establishing a Green Hydrogen ecosystem and catalysing a systemic response to the opportunities and challenges of this sunrise sector.

Green Hydrogen, produced using renewable energy, has the potential to play a key role in such low-carbon and self-reliant economic pathways. Green Hydrogen can enable utilization of domestically abundant renewable energy resources across regions, seasons, and sectors, feeding multiple usage streams, either as a fuel or as an industrial feedstock. It can directly replace fossil fuel derived feedstocks in petroleum refining, fertilizer production, steel manufacturing etc. Hydrogen fuelled long-haul automobiles and marine vessels can enable decarbonisation of the mobility sector. Green Hydrogen can be particularly useful as a versatile energy carrier for meeting energy requirements of remote geographies, including islands, in a sustainable manner.

Rapid deployment of Renewable Energy and Electrolysers capacities will be required to achieve economies of scale. Associated infrastructure and regulatory ecosystem will need to be established for delivery of renewable power, and for storage, transportation, and utilization of Green Hydrogen for various applications. Accelerated technology development to improve performance, efficiencies, safety, and reliability would also be crucial. The global value chain for Green Hydrogen is in its nascency and international cooperation and engagements could further bolster the national efforts. There is, therefore, a clear need for coordinated efforts and diverse policy interventions across all domains.

WHY IS GREEN HYDROGEN IMPORTANT?

Green hydrogen offers India a chance to become a leading global producer, shifting from an energy importer to an exporter. To leverage the high international demand, India should support its green hydrogen developers with incentives and streamlined processes, ensuring global competitiveness. Acting quickly is crucial to outpace competitors like the Middle East and Australia. Additionally, India could utilize Article 6.2 of the Paris Agreement to form beneficial bilateral agreements, fostering large-scale project development that not only meets international demand but also strengthens its domestic green hydrogen infrastructure.

To cultivate a robust domestic market for green hydrogen, generating demand is essential. Initiatives such as Green Hydrogen Purchase Obligations could give industries an initial boost, particularly in sectors like crude oil refining and fertilizer production, which are major consumers of green hydrogen. Additionally, there's considerable scope for using green hydrogen as an alternative fuel or feedstock in various sectors including power generation, steel manufacturing, transportation, aviation, glass production, and marine applications.

MEASURES TAKEN IN INDIA TO DATE

India has set its sight on becoming energy independent by 2047 and achieving Net Zero by 2070. To achieve this target, increasing renewable energy use across all economic spheres is central to India's Energy Transition. Green Hydrogen is considered a promising alternative for enabling this transition. Hydrogen can be utilized for long-duration storage of renewable energy, replacement of fossil fuels in industry, clean transportation, and potentially also for decentralized power generation, aviation, and marine transport. The National Green Hydrogen Mission was approved by the Union Cabinet on 4 January 2022, with the intended objectives of

- Making India a leading producer and supplier of Green Hydrogen in the world
- Creation of export opportunities for Green Hydrogen and its derivatives
- Reduction in dependence on imported fossil fuels and feedstock
- Development of indigenous manufacturing capabilities
- Attracting investment and business opportunities for the industry
- Creating opportunities for employment and economic development
- Supporting R&D projects

GREEN HYDROGEN MISSION OUTCOMES

The mission outcomes projected by 2030

- Development of green hydrogen production capacity of at least 5 MMT (Million Metric Tonne) per annum with an associated renewable energy capacity addition of about 125 GW in the country
- Over Rs. Eight lakh crores in total investments
- Creation of over Six lakh jobs
- Cumulative reduction in fossil fuel imports over Rs. One lakh crore
- Abatement of nearly 50 MMT of annual greenhouse gas emissions[3]

TYPES OF HYDROGEN BASED ON EXTRACTION METHODS

Depending on the nature of the method of its extraction, hydrogen is categorised into three categories, namely, Grey, Blue and Green.

- **Grey Hydrogen** It is produced via coal or lignite gasification (black or brown), or via a process called steam methane reformation (SMR) of natural gas or methane (grey). These tend to be mostly carbon-intensive processes.
- **Blue Hydrogen** It is produced via natural gas or coal gasification combined with carbon capture storage (CCS) or carbon capture use (CCU) technologies to reduce carbon emissions.
- **Green Hydrogen** It is produced using electrolysis of water with electricity generated by renewable energy. The carbon intensity ultimately depends on the carbon neutrality of the source of electricity (i.e., the more renewable energy there is in the electricity fuel mix, the "greener" the hydrogen produced).

GREEN HYDROGEN POLICY 2022

Green Hydrogen Policy 2022 defines green H2/ammonia to also include H2 and ammonia produced from the banked renewable energy (RE) and that produced from biomass.

MARKET STRUCTURE OF HYDROGEN

- Current global H2 demand is around 90 MMT/year, which grew at 2% since 1975; demand will increase further as countries set targets.
- Current demand of hydrogen in India is ~6 MTPA; driven by captive consumption of refineries and fertilizer units.
- India’s hydrogen demand could reach anywhere between 15 (conservative) – 25 (optimistic) MTPA by 2040.

[3] Hydrogen market in India, ICF India 15 -Jun -2023 Asia Clean Energy Forum, 2023

- Green hydrogen market is likely to be at $30–35 billion by 2035- 2040 in India (under the optimistic demand case).
- Green vs. grey hydrogen economics will depend on fossil fuel prices, carbon prices, cost reduction and efficiency improvements in electrolysers and Government support for green hydrogen.

This study focuses on the following key study areas

- Hydrogen demand in India
- Green hydrogen production technology trends across globe
- Future cost economics
- Hydrogen storage and transportation
- Identifying imperatives for hydrogen policy and regulatory environment.

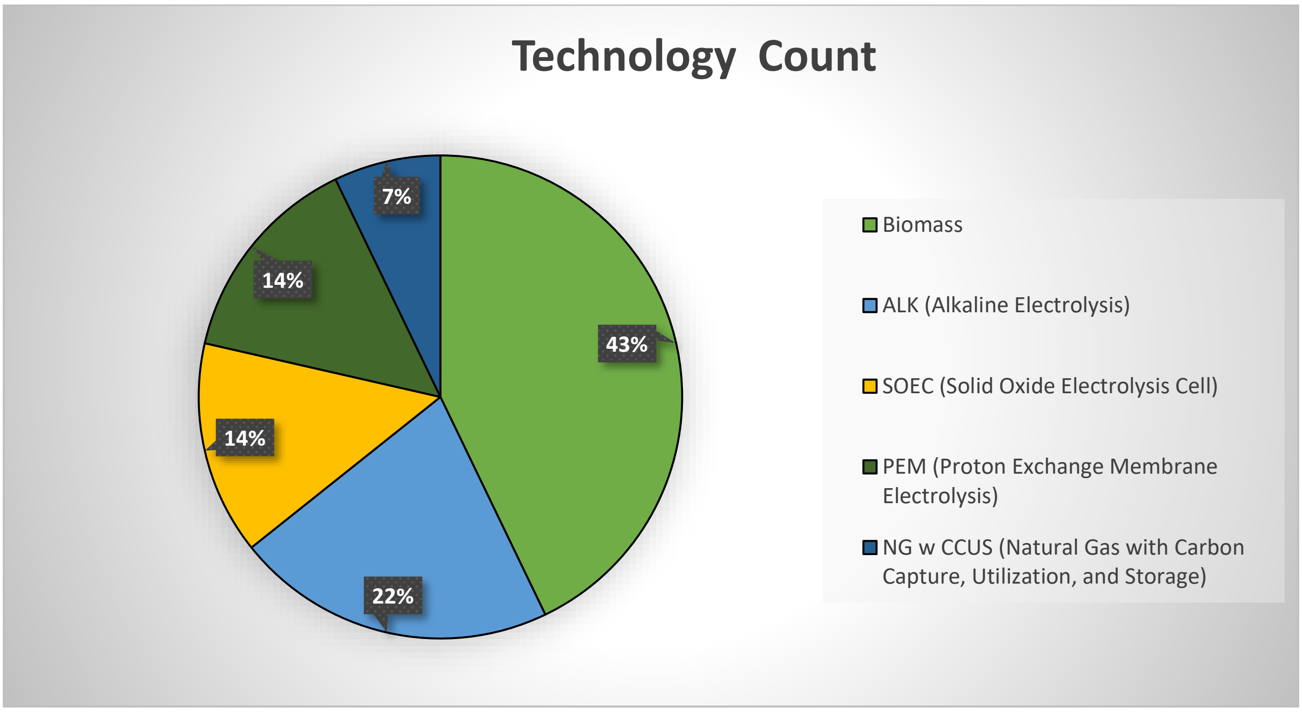
KEY FINDINGS

- India is the third largest consumer & producer of hydrogen today in the World after China & USA.
- Hydrogen demand In India is expected to increase significantly (by 2.5 - 3.5 times) by 2040.
- However, given the large growth in energy requirements, hydrogen may still only form less than 5% of total primary energy consumption of India by 2040
- Since, the cost of Hydrogen transportation is high therefore supply needs to come near demand centres & hydrogen hubs/valleys needs to be created.
- This presents a great opportunity for clean hydrogen suppliers to build a business with a market size of ~$27 B/yr (2030) & ~$40 B/Yr (2040).

However, there are challenges.

- As per MNRE, 125 GW of additional renewable energy capacity addition would be required to meet the GOI's 2030 target of green hydrogen production capacity - 5 million tonnes per annum. Further, India has committed at COP26 that it would have 500 MW Non-fossil fuel capacity by 2030; majority of which is expected to replace existing conventional power.
- Difficult to drive Green Hydrogen demand purely on economics, might need fiscal incentives to support consumption. Assuming $9 per MMBTU flat delivered gas prices, green hydrogen is likely to achieve parity by 2035 (~$2/kg by 2035)
- Key benefit (1) CO2 reduction (2) Import Bill Savings of $14 - 22 billion per annum can be achieved by replacement of current fuels with locally produced Hydrogen in end use sectors.
- US, EU, Korea and Japan leading initiatives to drive Hydrogen consumption e.g. US IRA provides up to $3 per kg production subsidy to green H2 projects.

Figure 1-Percentage use of H2 production techniques from 2005-2024- India



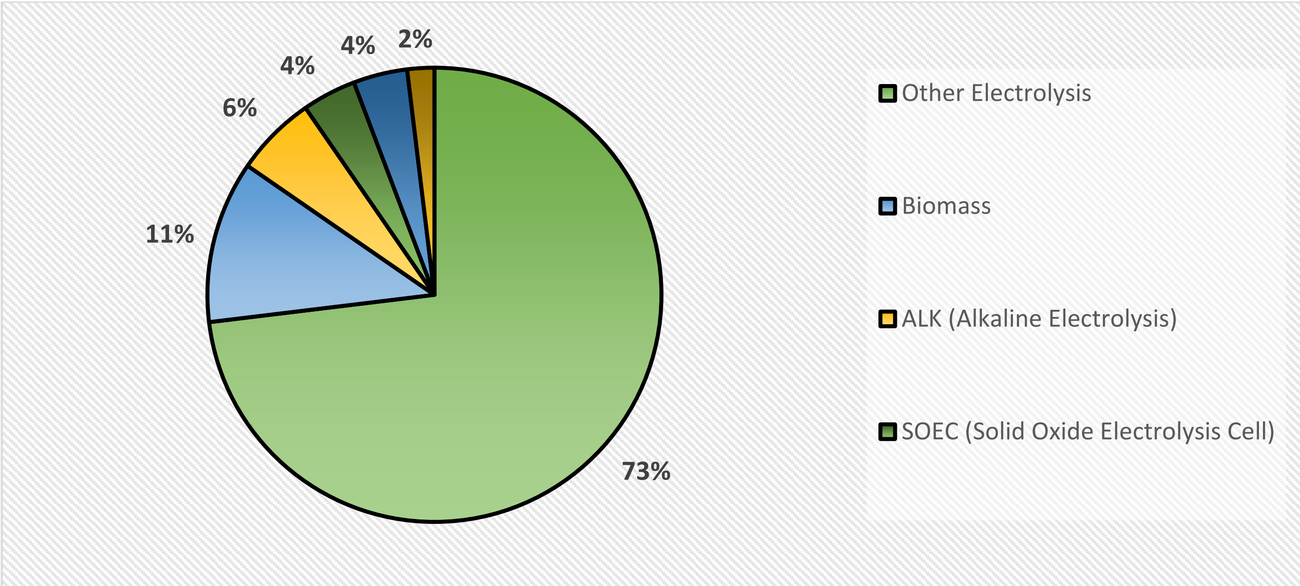
Source of data IEA
Graph Authors calculation

This diagram titled "Technology Count" displays the distribution of different technologies used for hydrogen production projects in India from 2024 to 2040. Here is the breakdown:

- **ALK (Alkaline Electrolysis)** This is the most widely used technology, constituting 43% of the projects. Alkaline electrolysis is a mature technology that uses an electrolyte solution, typically potassium or sodium hydroxide, with two electrodes to split water into hydrogen and oxygen.
- **PEM (Proton Exchange Membrane Electrolysis)** The second most common technology, making up 22% of the projects. PEM electrolysis involves a solid polymer electrolyte and operates at relatively low temperatures, producing high-purity hydrogen.
- **NG w CCUS (Natural Gas with Carbon Capture, Utilization, and Storage)** Accounts for 14% of the projects. This technology produces hydrogen from natural gas and captures the CO2 emissions resulting from the process to reduce the environmental impact.
- **SOEC (Solid Oxide Electrolysis Cell)** Also representing 14% of the distribution. SOEC is a high-temperature electrolysis technology that is more energy-efficient compared to traditional methods, as it uses solid ceramic material as the electrolyte.
- **Biomass** The least utilized among the listed technologies, at 7%. Biomass conversion to hydrogen involves the gasification or pyrolysis of organic materials such as plant or animal matter.

The chart indicates a preference for electrolysis-based hydrogen production methods, with a significant focus on ALK technology, followed by PEM and SOEC. The use of natural gas with CCUS reflects an intermediate approach to leverage existing natural gas resources while managing carbon emissions. The smaller share of biomass suggests it is a less favoured option, which might be due to its scalability, efficiency, or other technological challenges.

Figure 2 -The distribution of technologies used in the projects listed in your data for the years 2024 to 2040 is as follows



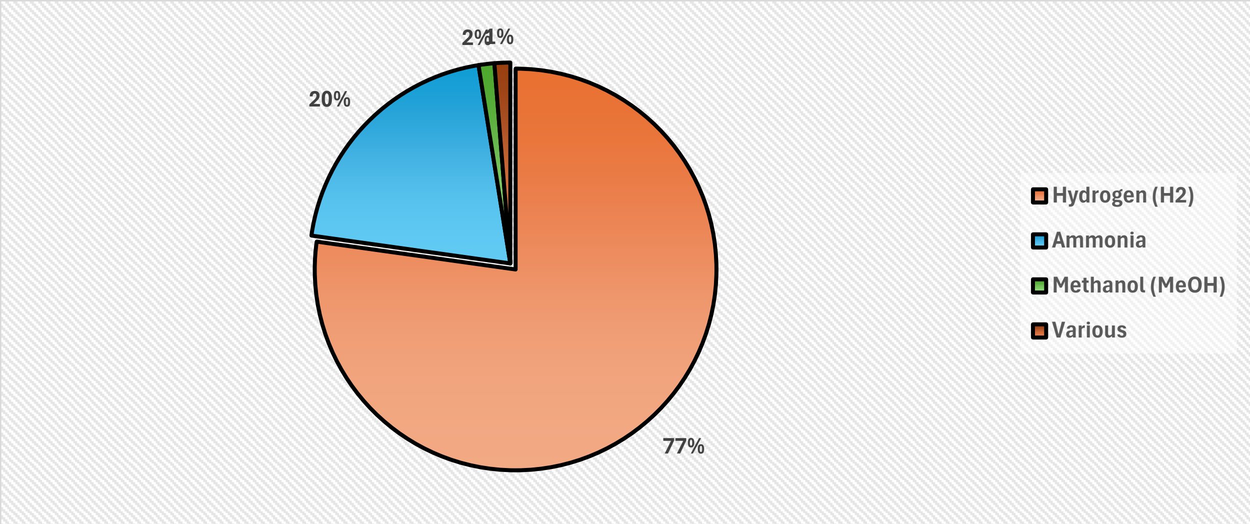
Source of data IEA
Graph Authors calculation

The diagram displays the proportion of hydrogen production technologies in Indian projects between the years 2024 and 2040

- **SOEC (Solid Oxide Electrolysis Cell)** This technology dominates the chart with a significant majority of 73%. SOEC is a high-temperature electrolysis method that is known for its efficiency in converting electricity to hydrogen, typically used for large-scale hydrogen production.
- **ALK (Alkaline Electrolysis)** The second most utilized technology, it accounts for 11% of the projects. Alkaline electrolysis is one of the older methods of producing hydrogen and involves passing an electric current through water to split it into hydrogen and oxygen.
- **Biomass** Making up 6% of the projects, biomass refers to the use of organic materials, such as agricultural waste or wood, to produce hydrogen, often through processes like gasification.
- **Other Electrolysis** This category, comprising 4% of the projects, likely includes various other forms of electrolysis that are not specified in the chart, possibly including newer or less common technologies.
- The remaining 6% of the chart is split between two categories, each making up 2% and 4% respectively. These could represent emerging technologies or less commonly used methods for hydrogen production.

The chart highlights a strong inclination towards SOEC, suggesting a strategic focus on the efficiency and scalability of this technology for India's hydrogen production. The presence of "Other Electrolysis" also suggests diversification in the research and development of electrolysis technologies.
From the analysis of the data, it is observed that between the years 2005 and 2024, solar energy, specifically Solar Photovoltaics (PV), accounted for approximately 47% of the renewable energy sources utilized to produce hydrogen.

Figure 3 -The overall distribution of products



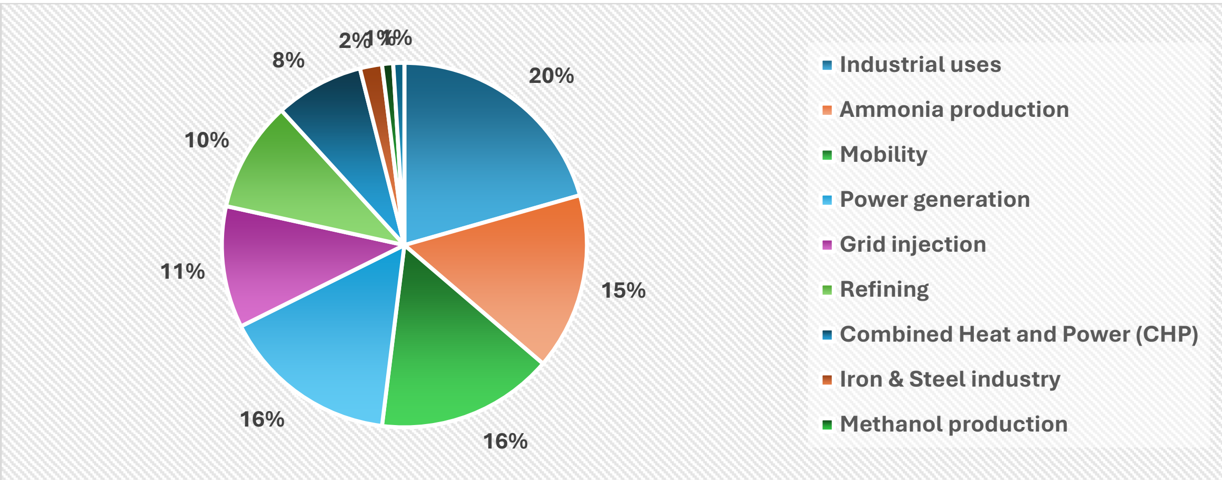
Source of data IEA
Graph Authors calculation

The diagram illustrates the distribution of different products, presumably from a chemical or energy sector, based on their percentage share.

- Hydrogen (H2) The largest share at 77%, indicating that hydrogen is the primary product, reflecting its importance or demand in the market or production portfolio.
- Ammonia Holding the second-largest share at 20%, which suggests that ammonia is also a significant product, possibly for use as a fertilizer, in industrial processes, or as a potential hydrogen carrier.
- Methanol (MeOH) A smaller share at 2%, showing methanol's presence in the product mix, likely for uses in fuel applications, solvents, or as a feedstock in the production of other chemicals.
- Various The smallest slice at 1%, this category may include a variety of other chemicals or products produced in smaller quantities compared to the main products listed.

This distribution indicates a strong focus on hydrogen production, with ammonia also playing a substantial role, while methanol and other products occupy much smaller niches in the portfolio.
END USE SECTORS

Figure 4a-Hydrogen Utilization Across Various Sectors

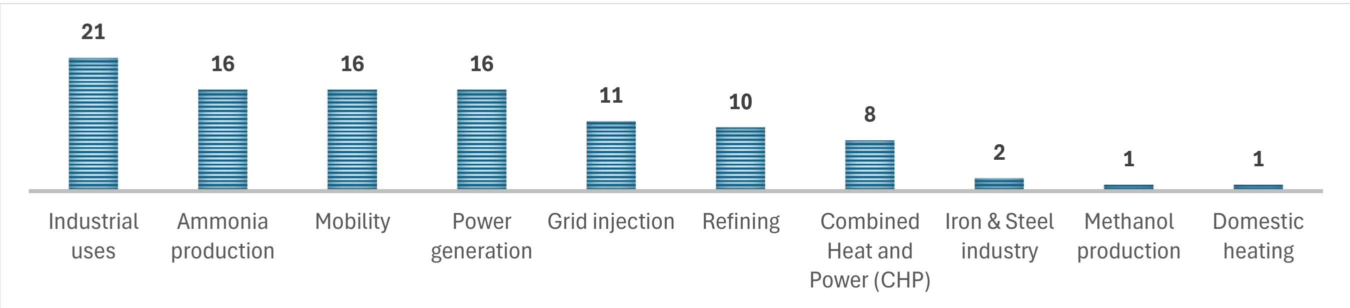


The diagram represents the utilization of hydrogen across various end-use sectors

- **Industrial Uses** take the highest share, with over 20% of hydrogen going towards various manufacturing processes and applications that may not be classified under other specific categories in the data.
- **Ammonia Production** consumes approximately 15.69% of hydrogen, underscoring its critical role in synthesizing ammonia. This is primarily for fertilizer production in the agricultural sector, which is crucial for meeting the global food supply.
- **Mobility** also accounts for 15.69% of hydrogen use, reflecting the growing interest in hydrogen fuel cell vehicles. These vehicles convert hydrogen into electricity to power an electric motor, offering a promising zero-emission transportation solution.
- **Power Generation** matches mobility in terms of hydrogen usage, at 15.69%. Here, hydrogen is used to generate electricity, potentially through turbines or fuel cells, which can provide clean power to grids or standalone systems.
- **Grid Injection** represents 10.78%, a significant proportion indicating hydrogen's role in energy storage and grid stabilization. Injecting hydrogen into the natural gas grid can also help decarbonize energy systems.
- **Refining** uses about 9.80% of hydrogen, which is essential in refining processes, particularly to remove sulphur and impurities from crude oil, thus producing cleaner fuels.
- **Combined Heat and Power (CHP)** systems account for 7.84% of hydrogen usage. These systems utilize hydrogen to generate both heat and electricity in an efficient and localized manner, which can significantly reduce energy wastage.
- **Iron & Steel Industry** sees a smaller slice at 1.96%. In this sector, hydrogen serves as a reducing agent to process iron ore into iron, offering a pathway to reduce carbon emissions from traditional coke-based steel production.
- **Methanol Production** involves a modest 0.98% of the hydrogen utilization, where hydrogen is used to produce methanol, an important chemical feedstock and potential fuel.
- **Domestic Heating** has the smallest share at 0.98%, signalling an emerging application of hydrogen in residential settings, where it may be used in fuel cells or hydrogen-ready boilers to provide heating without carbon emissions.

The chart gives an overview of the diverse applications of hydrogen, from heavy industry to residential use, highlighting the versatility of hydrogen as an energy carrier and its potential for decarbonizing various sectors.

Figure 4b-Hydrogen Utilization Across Various Sector



Source of data IEA
Graph Authors calculation

HYDROGEN DEMAND SCENARIO IN INDIA

- Current H2 demand in India is 6.5 MTPA, driven by captive consumption of refineries (3.1 MTPA), fertilizer & ammonia (2.1 MTPA); concentrated in western region.
- Declining prices of hydrogen and growing urgency for decarbonization means that the demand for hydrogen in India could grow by almost 2.4 times by 2040, led by industry and transportation.
- Hydrogen demand as a feedstock is in the following sectors Refineries, Ammonia, Steel, Glass & Chemicals and as a fuel in transport, large industries and CGD blending.
- Total unconstrained H2 demand in 2030 is projected at ~11 MTPA and total H2 demand in 2040 at ~24 MTPA.
- Constrained Demand for Hydrogen reaches 16-23 MTPA across the scenarios.
- Grey Hydrogen will continue to take up significant share of Hydrogen Mix in 2040 in cases without govt. intervention / obligation.

MOBILIZING SUPPORT

Financing is key to reducing green hydrogen production costs. Exploring low-cost funding options from institutions like the World Bank and ADB is crucial. Additionally, generating extra revenue through carbon credit sales can be facilitated by a structured framework. The government could reduce hedging costs for domestic developers by creating special provisions for dollar-denominated debt through the RBI. Implementing credit enhancement mechanisms to boost project credit ratings can also lower borrowing costs, making projects more appealing to investors. Moreover, ramping up R&D efforts to improve electrolyser efficiencies, materials, and local manufacturing is vital for cost reduction. This can significantly impact the overall affordability and sustainability of green hydrogen. The certification process for green hydrogen is another crucial aspect, especially since requirements differ across regions like the EU, Japan, and Korea. The government should appoint agencies to certify hydrogen as green and develop guidelines in collaboration with other nations.

With its immense potential for cost-competitive green hydrogen production, India is poised to become a global leader in this field. By working cohesively, the country can excel in green hydrogen technology, manufacturing, and production.

BUILDING CONDUCIVE ENVIRONMENT FOR LONG-TERM CAPITAL INVESTMENTS

Interventions to encourage industry investment in green processes can be summarized as follows

1. Reducing Cost of Capital

- Offer incentives to industrial players for investing in new plants.
- Incentives could include accelerated depreciation, discounted land, and tax rebates throughout the plant’s lifecycle.

2. Making More Funds Available

- Ensure easy access to investment funds.
- Consider including green hydrogen in the Priority Sector Lending List to expedite fund availability.

3. Adopting a Long-Term Vision

- Implement a 25-year investment vision for green hydrogen, similar to the existing 20-year power-purchase agreements for renewable energy in India.
- This long-term approach can minimize investment risks by ensuring the sustainability of the technology.

4. **Customer/Demand-Side Mandates**

- Establish industry-specific demand-side mandates.
- For example, mandates for a certain percentage of green steel in vehicle manufacturing can create a stable long-term demand.

Additionally, globally, around 43 countries are developing hydrogen economy plans, including financial incentives. In India, aligning with the hydrogen transition is vital for economic growth, energy security, and a low-carbon economy.

As per NITI Aayog

- The government should ensure the availability of long-term, low-interest financing.
- Initiate a working carbon market.
- Implement investment facilitation strategies like demand aggregation for early adopters.

NITI Aayog estimates that India's green hydrogen market could be worth US$8 billion by 2030 and US$340 billion by 2050.

KEY TAKEAWAYS

- H2 demand In India is expected to increase by 2.5-3.5 times by 2040; it is still not expected to meet more than 5% of total primary energy consumption of India by 2040.
- The H2 market in India is likely to reach ~$30n-35 bn/yr by 2035 - 2040.
- RE power requirement for green hydrogen will be significant at 400 GW.
- Cost parity between green hydrogen and grey hydrogen will depend on factors such as fossil fuel prices, carbon market prices, cost reduction and efficiency improvements in in electrolysers, and, importantly, government support/ incentives for green hydrogen.
- India can achieve savings of $15-20 billion per year in fossil fuel imports by replacing fossil fuels with locally produced hydrogen in end use sectors.

Green Hydrogen is likely to play a critical role in India's energy transition, particularly in decarbonization of hard to abate sectors. The National Green Hydrogen Mission is a step in this direction. The Mission is expected to facilitate deployment of Green Hydrogen ecosystem and create opportunities for innovation and investments across the Green Hydrogen value chain, translating into investments, jobs, and economic growth. The Government of India interventions will ignite the process and provide required impetus for unlocking the market potential in various sectors through cost reduction and economies of scale.

GREEN HYDROGEN APPLICATIONS, CHALLENGES, AND EMERGING MARKETS IN INDIA

Use Case	Challenges and Drivers	Emerging Market Description
Industrial Feedstock	• Price parity between green and grey hydrogen production will determine the speed and scale of transition. • H2 DRI production will result in 0% CDRI increasing the cost of EAF steel production	• Ammonia production in fertilizer industry • Desulphurization in crude oil refineries • Hydrogen based Direct Reduced Iron (DRI) - Electric Arc Furnace (EAF) steelmaking.

Use Case	Challenges and Drivers	Emerging Market Description
		• Methanol production
Process Heating	• Direct electrification will be competitive wherever feasible. • Significant investment in H2 transportation and distribution infrastructure required. • Hydrogen embrittlement is a major technical challenge for the durability of blending in existing pipelines. • Technical and regulatory barriers need to be addressed with the adoption of robust standards	• Blending in piped natural gas grids (~15%) • Industrial boilers, furnaces and heating applications, domestic cooking and other commercial end uses
Transportation	• Significant investment in H2 storage, handling and bunkering / refuelling infrastructure required. • Competition with battery electric vehicles will determine speed and scale of transition	• Long-haul heavy-duty trucking • Maritime shipping for freight transportation • High speed passenger ferries, boats, and cruising for tourism industry
Power Generation and Energy Storage	• Significant capital expenditure and low round-trip efficiency (~30-40%) lowers the cost-competitiveness storage applications. • Batteries are already competitive for short duration storage applications	• Long-duration (>20 hours) energy storage applications for high shares of renewable energy integration in power grids • Power generation for peak demand supply

Source Ministry of Power, Government of India, 2022

THE GLOBAL SCENARIO- THE HYDROGEN INITIATIVE

- The Hydrogen Initiative (H2I) operates under the Clean Energy Ministerial framework to promote hydrogen and fuel cell technologies in the global economy.
- H2I is a collaborative effort by multiple governments and intergovernmental entities, including Australia, Brazil, Canada, China, the European Commission, and the United States, among others.
- The initiative is co-led by Canada, the European Commission, Japan, the Netherlands, and the United States, with China and Italy as observers.
- The International Energy Agency (IEA) coordinates the H2I, assisting member countries in aligning their activities with the initiative's goals.
- H2I functions as a platform for cooperation between governments, international organizations, and the industry sector.

- The initiative maintains active partnerships with entities like the Hydrogen Council, IRENA, and the World Economic Forum.

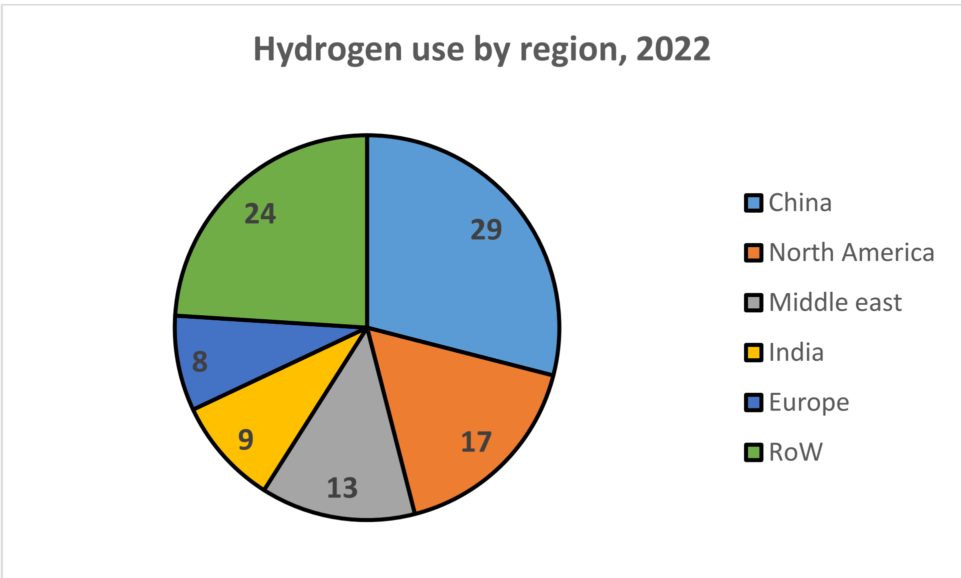
THE CURRENT SITUATION OF HYDROGEN MARKET

Right now, almost all hydrogen produced worldwide is “grey,” which means it is produced from natural gas. Without a price on carbon emissions, grey hydrogen is inexpensive (€1 to €2 per kilogram), but it compounds the challenge of improving environmental sustainability. Green hydrogen, in contrast, uses renewable electricity to power electrolysis that splits water molecules into hydrogen and oxygen. Because green hydrogen doesn’t require fossil fuels, it is a better long-term solution to help decarbonize economies. Yet green hydrogen—currently costing €3 to €8/kg in some regions—is more expensive than grey.
The most attractive production markets for green hydrogen are those with abundant, low-cost renewable resources. In parts of the Middle East, Africa, Russia, the US, and Australia, for example, green hydrogen could be produced for €3 to €5/kg today. In Europe, production costs vary from €3 to €8/kg. The low end of these ranges can be achieved most easily in locations with access to low-cost renewable energies plants. Yet production costs will decrease over time, due to continuously falling renewable energy production costs, economies of scale, lessons from projects underway and technological advances. As a result, green hydrogen will become more economical. The challenge is anticipating those trends and acting in time.

GLOBAL HYDROGEN DEMAND SCENARIO

- Demand for hydrogen is on a constant rise. Current global demand is approximately 90 MT/year as opposed to 18 MT/year in 1975.
- 78% of hydrogen produced comes from Natural gas and coal, and over 80% H2 demand comes from the refining and ammonia sector alone.

Figure 5-Hydrogen use by region, 2022.



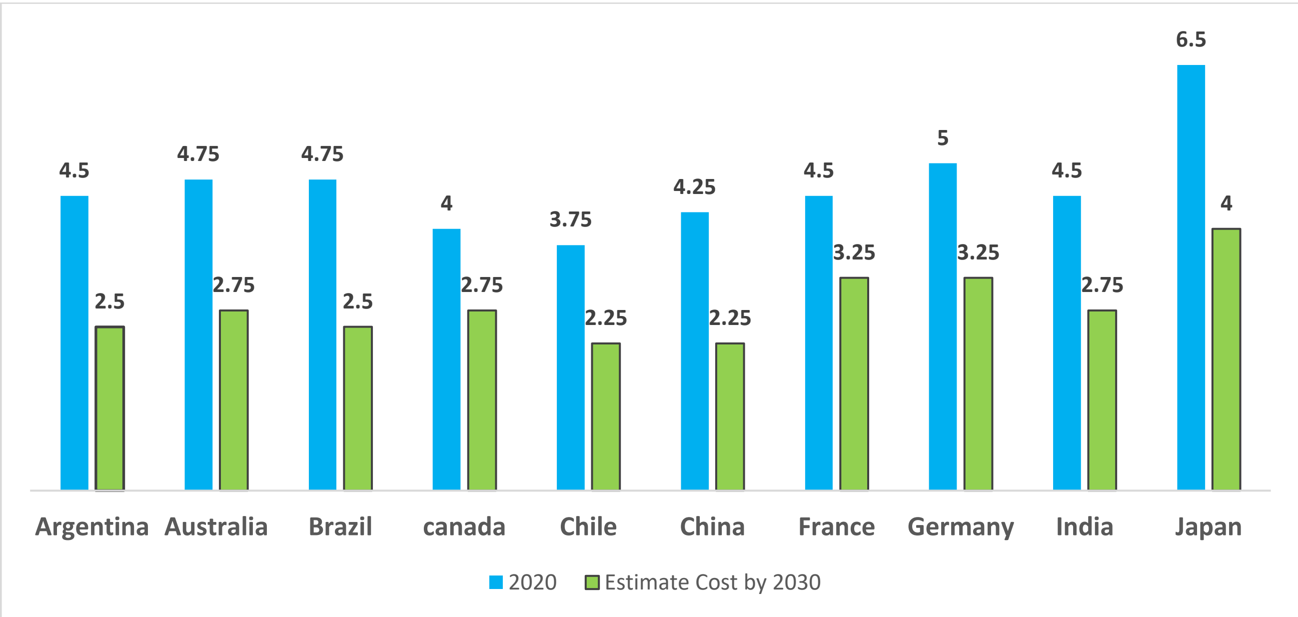
Data Source IEA
Diagram Authors Calculation
The diagram illustrates the distribution of hydrogen use by region for the year 2022. Each segment of the diagram represents a different region and the size of each segment corresponds to the percentage of total

hydrogen use attributed to that region. Here's a breakdown of the hydrogen use by region as depicted in the chart

- **China** With the largest segment at 29%, China is the leading consumer of hydrogen, indicating its significant role in the hydrogen market.
- **North America** Accounts for 24% of hydrogen use, making it the second-largest regional consumer.
- **Europe** Represents 17% of hydrogen use, highlighting its substantial consumption of hydrogen.
- **India** At 13%, India's share indicates its growing importance in the global hydrogen economy.
- **Middle East** Holds 9% of the hydrogen use, suggesting the region's active involvement in the hydrogen sector.
- **Rest of the World (RoW)** Comprises 8% of global hydrogen use, which includes all regions not individually listed.

The chart shows that hydrogen use is most significant in China and North America, followed by Europe and India, with the Middle East and the rest of the world consuming smaller fractions. This distribution is indicative of the current focus and development of hydrogen technologies and infrastructure within these regions as of 2022.

Figure 6- PRODUCTION COST OF GREEN HYDROGEN WORLDWIDE (IN EUROS PER KG)



Source of data IEA
Graph Authors calculation

The bar graph presents the production costs of green hydrogen in euros per kilogram for various countries, comparing the costs in the year 2020 with the estimated costs for the year 2030. Here is an explanation of the data shown

- **Argentina** The cost reduced from €4.5/kg in 2020 to an estimated €2.5/kg in 2030.
- **Australia** There's a decrease from €4.75/kg to an estimated €2.75/kg.
- **Brazil** A similar pattern to Australia, dropping from €4.75/kg to €2.5/kg.
- **Canada** The cost is projected to go down from €4/kg to €2.75/kg.

- **Chile** A decline from €3.75/kg to €2.25/kg is observed.
- **China** The cost is expected to decrease from €4.25/kg to €2.25/kg.
- **France** There is a reduction from €4.5/kg to €3.25/kg.
- **Germany** The cost is estimated to lower from €5/kg to €3.25/kg.
- **India** The production cost is anticipated to drop from €4.5/kg to €2.75/kg.
- **Japan** The highest cost in 2020 at €6.5/kg is projected to reduce to €4/kg by 2030.

The graph indicates a trend of decreasing production costs for green hydrogen across all listed countries, reflecting anticipated improvements in technology and economies of scale that could make green hydrogen more competitive with traditional hydrogen sources over the next decade.

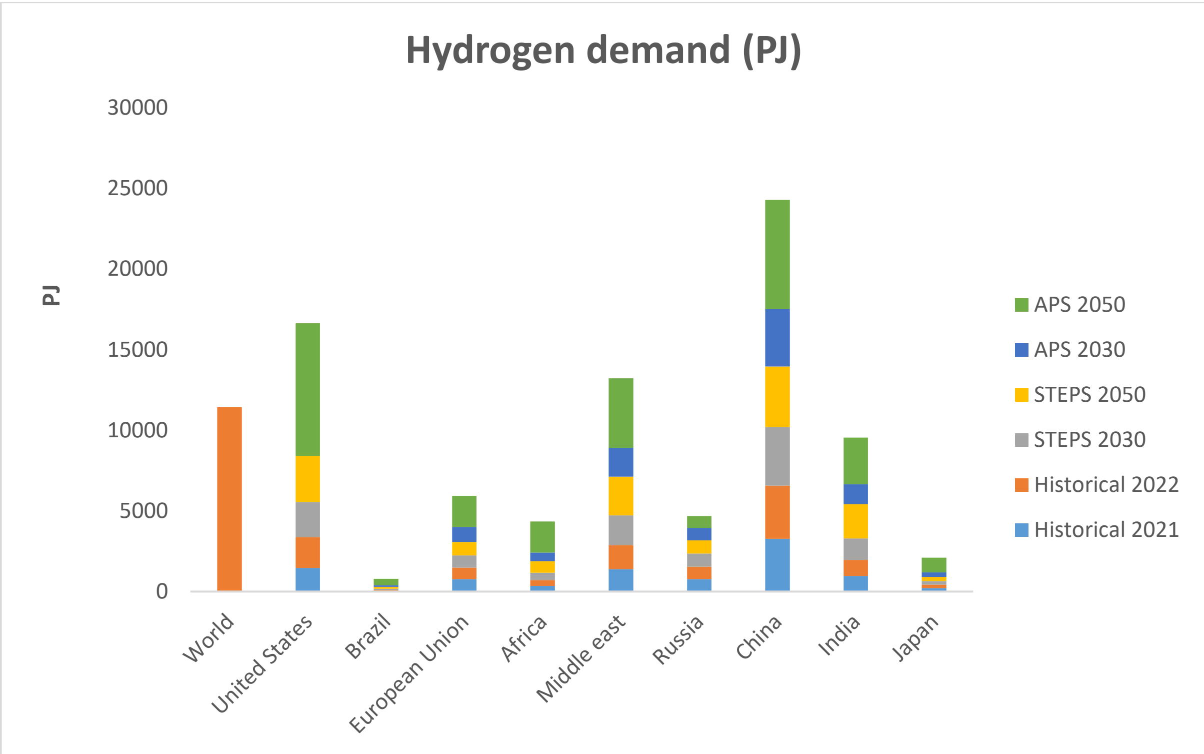


Figure 7-Hydrogen use

- Global hydrogen consumption increased to 95 Mt in 2022, marking a nearly 3% rise from the previous year, continuing an upward trend disrupted only in 2020 due to the Covid-19 pandemic.
- Hydrogen use expanded significantly in all major regions except Europe, where it declined by about 6% due to the energy crisis following Russia's invasion of Ukraine.
- North America and the Middle East each saw approximately 7% growth in hydrogen usage, offsetting the decline in Europe.

The above figure represents the demand for hydrogen in petajoules (PJ) across different regions and projects this demand into the future based on two scenarios APS (Advanced Policy Scenario) and STEPS (Stated Policies Scenario), for the years 2030 and 2050, as well as showing historical data for 2021 and 2022.

Here's a breakdown of what the chart indicates

Historical Data The bars in the lightest colors represent the actual recorded hydrogen demand for the years 2021 and 2022. It provides a baseline for comparison with future projections.

STEPS Scenarios The mid-tone colors (orange and blue) show the projected demand according to the STEPS scenario, which assumes that current policy frameworks will not change. These figures are given for both 2030 and 2050, showing an expected increase in demand over time.

APS Scenarios The darkest colors (dark blue and green) depict a more aggressive projection based on the APS, which assumes the implementation of more ambitious policies to stimulate hydrogen use. These are also provided for 2030 and 2050, indicating a significantly higher demand compared to the STEPS scenario.

Regional Data The chart breaks down the data by region, including the World aggregate, the United States, Brazil, the European Union, Africa, the Middle East, Russia, China, India, and Japan. This allows for a comparison of hydrogen demand across different areas.

Growth Over Time It's evident from the chart that hydrogen demand is expected to grow significantly in all regions, especially in China and India, according to the APS 2050 projections.

Comparison of Scenarios The APS scenario predicts a higher demand for hydrogen than the STEPS scenario, suggesting that with more aggressive policies, hydrogen could play a larger role in the energy mix of these regions.

Notable Trends The chart indicates that the World's total hydrogen demand is expected to grow substantially, particularly under the APS, and that regions like China and the European Union could see major increases in demand by 2050 under both scenarios.

- China's hydrogen use grew by around 0.5%, maintaining its position as the world's largest consumer, accounting for nearly 30% of global usage.
- The increase in global hydrogen use is attributed to global energy trends rather than specific hydrogen policies, primarily in refining and chemical sectors.
- Most of the increased demand was met by production from unabated fossil fuels, thus not contributing to climate change mitigation.
- The use of hydrogen in new applications like heavy industry, transport, and electricity generation remains minimal, representing less than 0.1% of global demand.
- The IEA's 2023 Net Zero Emissions Scenario projects a 6% annual increase in hydrogen use until 2030, potentially reaching over 150 Mt, with nearly 40% from new applications.

COMPARITIVE ANALYSIS OF INDIA AND THE REST OF THE WORLD

Figure 8 Product based percentage of projects from 2005 – 2024, India

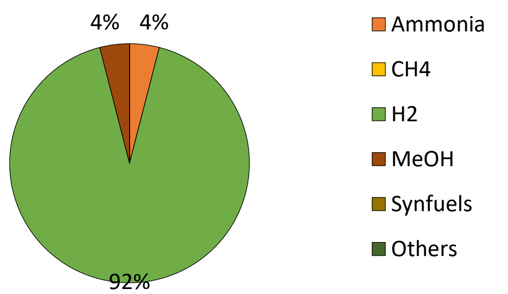
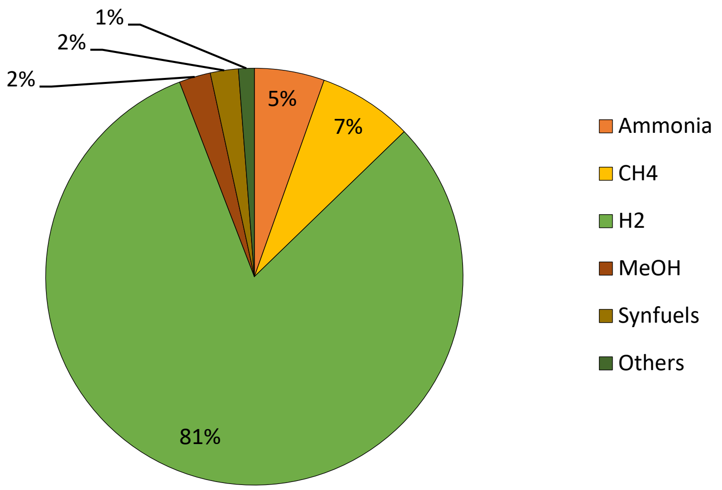


Figure 9 Product based percentage of projects from 2005 – 2024, Rest of the world



Source of data IEA
Graph Authors calculation

The provided image appears to be a set of two diagrams depicting the comparative analysis of product-based project percentages between India and the rest of the world from 2005 to 2024.

Indian Scenario

- Most projects, 92%, are categorized as "Others," which suggests a diverse range of products that do not fall into the specified categories.
- Both "Ammonia" and "CH4" (methane) projects account for 4% each. This indicates a relatively small but equal focus on ammonia and methane-based projects within the timeframe.

Global Scenario

- "Others" still represents the largest category at 81%, but it's a smaller proportion compared to India, implying a more diversified approach to product-based projects globally.
- "Ammonia" makes up 7% of the projects, which is higher than India's 4%, indicating a greater emphasis on ammonia-related projects worldwide.
- "CH4" constitutes 5% of projects, again higher than India's 4%.
- "H2" (hydrogen) projects have a 2% share, and "MeOH" (methanol) projects also have a 2% share, showing some investment in these areas.
- "Synfuels" are the least represented with only 1%, which indicates limited focus on synthetic fuels relative to other categories.

From this comparison, we can infer that India has a predominant focus on a wide array of other projects not specified in the chart, while the rest of the world has a more balanced distribution across different product-based projects, with slightly more emphasis on ammonia and methane.

CREATING DEMAND FOR LOW EMISSION HYDROGEN

Challenge of Uncertainty in Demand Market players identify uncertainty in future demand for low-emission hydrogen as a major obstacle, compounded by higher production costs compared to hydrogen from unabated fossil fuels, lack of infrastructure, and unclear regulations and certification.

- Need for Coordinated Approach Addressing these challenges requires a coordinated approach. For instance, reducing the cost gap in production won't be effective if regulatory frameworks are unclear or if there's no demand from end-users.
- Global Initiatives for Low-Emission Hydrogen Efforts include the European Union's IPCEI, the UK's Low Carbon Hydrogen Business Model, and the US's Clean Hydrogen Production Tax Credit. Regulations and infrastructure development, especially in Europe with the European Hydrogen Backbone initiative, are gaining attention.
- Demand Creation Initiatives Policies to stimulate hydrogen demand are recent. Without strong demand, the viability of low-emission hydrogen industry is at risk. Project developers need secured off-takers to attract investors.
- Current Outlook and Demand Creation Strategies Exploring options to create demand in existing and new applications, assessing government and private sector efforts, and presenting options to stimulate low-emission hydrogen demand.

Two-Pronged Approach for Demand Creation

- Switching Existing Applications Replacing current industry and refining demand from unabated fossil-based hydrogen to low-emission hydrogen. This involves large-scale deployment of electrolysis capacity and retrofitting with CCUS.
- Creating Demand in New Applications Expanding low-emission hydrogen demand in new areas where other low-emission alternatives are limited, requiring adoption of new technologies, infrastructure adaptation, and robust regulations.

Regulatory and Financial Strategies

- Carbon Pricing and Public Policies Implementing carbon pricing and supporting low-emission hydrogen production through financial incentives.
- Voluntary Carbon Credit Markets Utilizing carbon credits to support low-emission hydrogen initiatives.
- Regulatory Measures Enforcing quotas or mandates for the use of low-emission hydrogen in existing applications.

Hydrogen momentum continues to accelerate, but investment decisions are lagging

- Overall Goal The aim is to close the cost gap between existing efforts and those needed to align with the Net Zero Emissions Scenario, ensuring the use of low-emission hydrogen in both existing and new applications.
- Growing Momentum There's a notable acceleration in the momentum of hydrogen projects, indicating increased interest and potential in hydrogen as an energy source.
- Investment Lag Despite this growing interest, investment decisions seem to be falling behind. This could be due to various factors such as economic uncertainties, technological challenges, or regulatory environments.
- Large Number of Projects There are 1,418 hydrogen projects announced globally, which is a significant number and reflects the growing interest in hydrogen energy.
- Deployment Plans Out of these, 1,011 projects are planning full or partial deployment by 2030. This indicates a strong future focus on hydrogen energy within this decade.

- Substantial Investment USD 570 billion in direct investments in hydrogen projects have been announced through 2030, showing a 30% increase. This is a substantial amount, signifying that hydrogen is seen as a key area for future energy development.
- Final Investment Decisions (FID) USD 39 billion, representing a 26% increase, have passed the Final Investment Decision stage. FID is a crucial step in project development, indicating a commitment to proceed.
- Clean Hydrogen Supply By 2030, there's an expectation of 45 million tonnes per annum (Mt p.a.) of clean hydrogen supply. Importantly, 70% of this is projected to come from renewable sources, and 30% from low-carbon sources. This split underscores the focus on sustainability in hydrogen production.

Hydrogen momentum is strong 1,418 projects have been announced globally

- USD 570 billion investments announced Global hydrogen industry 1,418 clean hydrogen projects announced as of October 2023.
- 372 new projects added since the last publication.
- Over 1,000 projects aimed for full or partial commissioning by 2030.
- Total investment in hydrogen value chains about USD 570 billion (up from USD 435 billion).
- Giga-scale projects over USD 330 billion investment.
- Regional growth
- Europe Most projects (540) and highest investments (USD 193 billion).
- North America 248 projects, 20% investment growth (USD 12 billion).
- Latin America Less projects (120) but high investment (USD 85 billion), focus on larger, giga-scale projects.
- High investment growth also in India, the Middle East, and China.

Clean hydrogen deployment steadily continues.

- GW of electrolysis capacity deployed globally by October 2023, an increase of 400 MW.
- Approximately 12 GW of electrolysis capacity has passed Final Investment Decision (FID) globally, marking an additional 3 GW.
- 860 kilotons per annum (kt p.a.) of operational clean hydrogen supply capacity deployed, which constitutes about 1% of the current grey hydrogen market.
- Over 1,100 hydrogen refuelling stations deployed globally, with a growth of more than 60% in the last two years.

Clean hydrogen production costs have increased.

- 30–65% increase in the Levelized Cost of Hydrogen (LCOH) due to factors such as capital expenditure, financing, and the cost of renewable power.
- Estimated cost for LCOH by 2030 is between 2.5–4.0 USD/kg, a decrease from the current costs of approximately 4.5–6.5 USD/kg.
- 30–45% reduction in capital expenditure expected by 2030 compared to current levels.

Electrolyser plant capital expenditure costs could decline by about 45%

- Through 2030Near-term renewable hydrogen capital expenditures (capex) are higher than previously estimated by public consensus. In-depth analysis of Electrolyser, material components, and installation costs indicates potential cost reductions of 35% to 45% by 2030.
- Factors contributing to increased near-term capex include inflation rates on materials, equipment, and labor, as well as a more sophisticated understanding of developer costs.

- Balance of plant and indirect costs, such as contractor fees and owner's costs, make up the largest difference compared to prior estimates.
- Lower Electrolyser system costs are anticipated to be the main focus for cost reduction efforts through 2030. This cost reduction depends on ramping up Electrolyser manufacturing capacity to meet the expected giga-scale demand in the mid to late decade.
- Cost reductions in Electrolyser systems could arise from designing-to-cost strategies, including minimizing precious metal content in core components and streamlining system designs.
- Increases in Electrolyser power density and efficiency are expected to reduce the overall system footprint and decrease the nominal capacity needed for equivalent hydrogen output.
- Technological advancements in Electrolyser systems could lead to reduced balance of plant and indirect costs. More efficient and compact plant designs would require fewer materials, less construction labor, and marginally lower shipping costs.
- Indirect costs like overhead, contractor fees, and owner's costs, which are proportionate to direct costs, are expected to decrease along with the total direct capex[4].

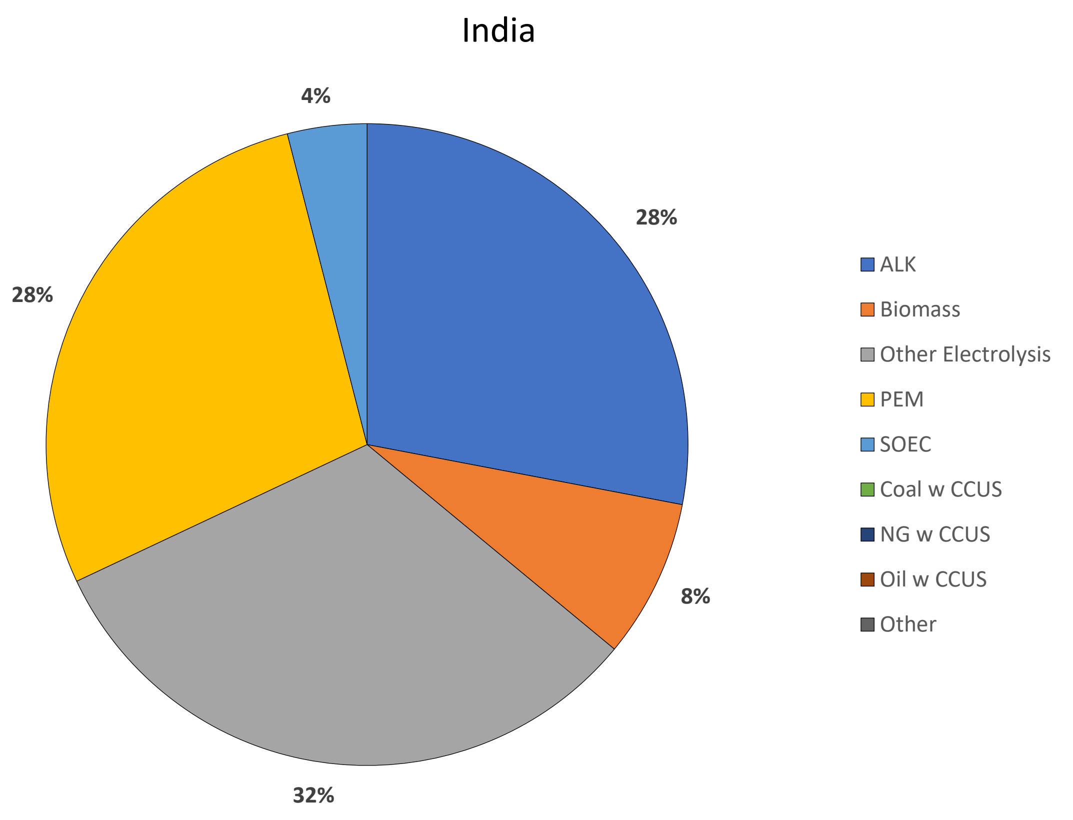
UNIQUE LEVERS OF HYDROGEN STRATEGIES ADOPTED IN DEVELOPED COUNTRIES

Country	**Hydrogen Plan and Targets**	**Unique Features of Hydrogen Strategy**
Germany	• ~GBP8 billion allocated to hydrogen economy development; - ~GBP6 billion to domestic hydrogen capabilities and ~GBP2 billion overseas investments. • Target of 5GW wind-based generation capacity by 2030 and an additional 5GW latest by 2040;- 90-110TWh of hydrogen targeted by 2030	• Emphasis on green hydrogen from the start. • Dedicated governance for hydrogen. • Direct investment in developing overseas supply centres. • Repurposing the extensive gas network. • Preferential status for green hydrogen
Norway	• ~GBP8 billion allocated to hydrogen economy development. • ~GBP6 billion to domestic hydrogen capabilities and ~GBP2 billion overseas investments. • - Target of 5GW wind-based generation capacity by 2030 and an additional 5GW latest by 2040. • - 90-110TWh of hydrogen targeted by 2030	• EV like privileges for FCEVs; • Leveraging strong maritime capabilities. • End-user engagement through information dissemination on refuelling and costs
Japan	• Y70 billion allocated to hydrogen in financial year ending March 2021.	• Strong focus on mobility applications

[4] Hydrogen Insights 2023, McKinsey and Company

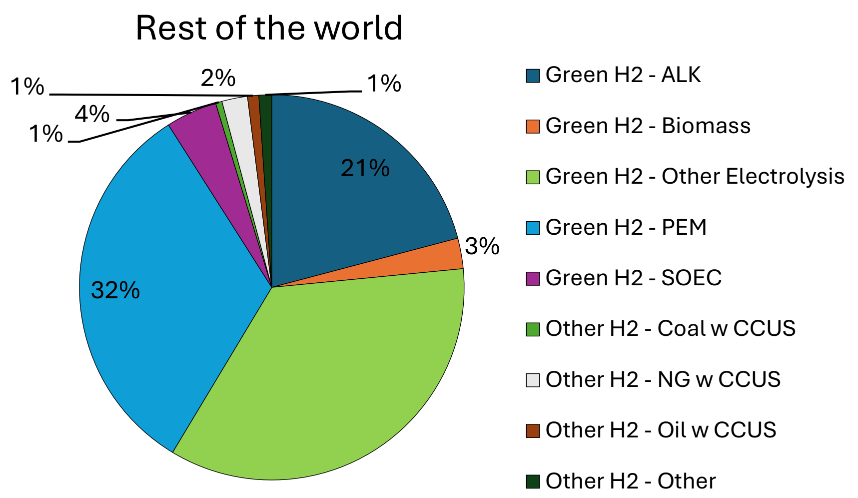
Country	Hydrogen Plan and Targets	Unique Features of Hydrogen Strategy
	• Target of 800,000 FCEVs by 2030 and 900 refuelling stations by 2030. • Commercial hydrogen-based power generation by 2030 targeted. • 300,000 tonnes/year hydrogen production by 2030[5]	• Point-to-point supply chain development plans. • Focus on the residential fuel cell market. • Specific cost targets across the supply chain
Australia	• Target of 500-1,000MW or equivalent clean hydrogen production • - Aim to become one of the top three exporters of hydrogen globally	• Strong focus on export capability development. • State-specific hydrogen strategies. • Dedicated fund for hydrogen

Figure 10 Percentage of hydrogen supply technology from 2005 – 2024, India



5 Accelerating Green Hydrogen Economy, Prepared for Green New Energy for a Net Zero India, June 2022, E&Y

Figure 11 Percentage of hydrogen supply technology from 2005 – 2024, Rest of the world



Source of data IEA
Graph Authors calculation

Indian Scenario

- The largest segment, colored in green, represents **PEM (Proton Exchange Membrane) electrolysis**, accounting for 32% of hydrogen supply technology.
- Two segments, both colored in purple, indicate a tie at 28% each for **ALK (Alkaline Electrolysis)** and **Other Electrolysis** methods.
- The red segment shows **SOEC (Solid Oxide Electrolysis Cell)** technology at 8%.
- Two small segments at 4% each represent **Biomass** and **Other** technologies.

Global Scenario

- The largest segment, coloured in purple, indicates **Green H2 - SOEC** at 32%.
- The dark blue segment represents **Green H2 - ALK** at 21%.
- A notable portion coloured in red signifies **Green H2 - Biomass** at 4%.
- The green segment shows **Green H2 - PEM** electrolysis at 3%.
- Small portions represented by other colours show **Other H2** technologies, including **Coal w/ CCUS (Carbon Capture, Utilization, and Storage)** and **Oil w/ CCUS**, each at 2% or less.

These charts illustrate a diversified approach to hydrogen production technologies, with a notable emphasis on electrolysis-based methods. India shows a strong preference for PEM and ALK methods, whereas the rest of the world has a significant leaning towards SOEC, along with a mix of other green hydrogen production technologies. The presence of CCUS technologies in the global context suggests a focus on reducing carbon emissions associated with hydrogen production from fossil fuels.

Figure 12 Product based percentage of projects from 2005 - 2024

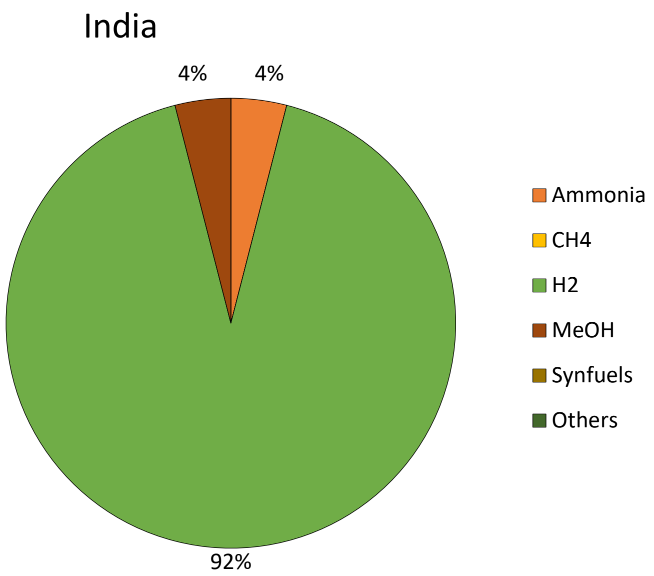
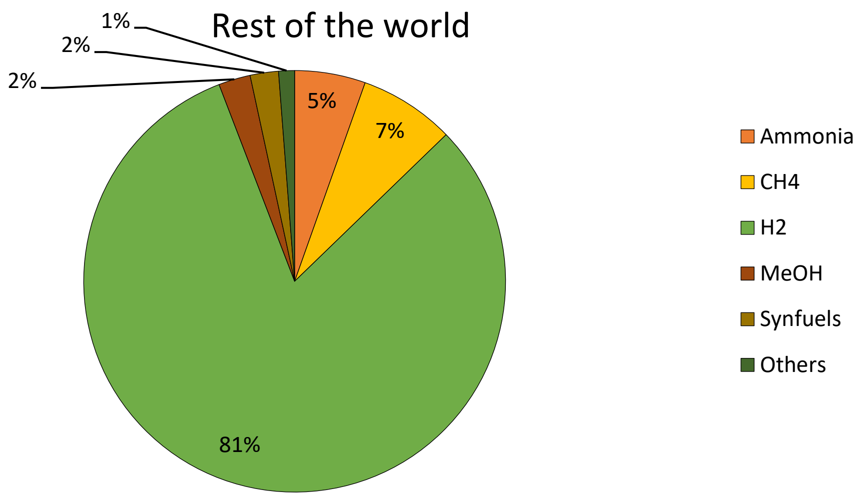


Figure 13 Product based percentage of projects from 2005 – 2024, Rest of the world



Source of data IEA
Graph Authors calculation

Indian Scenario

- **PEM (Proton Exchange Membrane) Electrolysis** Shows consistent growth from around 20% in 2005 to approximately 30% in 2024.
- **ALK (Alkaline Electrolysis)** Starts around 30% in 2005, dips slightly in the middle years, and then rises again to around 30% by 2024.
- **Other Electrolysis** Remains relatively stable at around 20-25% throughout the period.
- **SOEC (Solid Oxide Electrolysis Cell)** Begins at approximately 20% in 2005, declines steadily, and ends at around 5% in 2024.
- **Biomass** Maintains a small but consistent presence, hovering around 5-10% throughout the years.

Global Scenario

- **Green H2 - SOEC (Solid Oxide Electrolysis Cell)** Starts at about 5% in 2005, rises significantly to over 30% by 2024.
- **Green H2 - ALK (Alkaline Electrolysis)** Begins around 10% in 2005, dips slightly, and then steadily climbs to nearly 20% by 2024.
- **Green H2 - Biomass** Remains relatively stable at around 5% throughout the period.
- **Green H2 - PEM (Proton Exchange Membrane) Electrolysis** Starts around 5% in 2005, experiences fluctuations, and ends around 10% in 2024.
- **Other H2 Technologies** Maintains a small presence, fluctuating between 5-10% over the years.

This graph provides insights into the shifting trends in hydrogen supply technology over the past two decades, highlighting the increasing prominence of green hydrogen production methods such as SOEC and ALK electrolysis, particularly in the global context.

GAPS IN HYDROGEN PRODUCTION STANDARDS

- **Lack of Standards for Alternative Hydrogen Production**
- No existing standards for hydrogen production from natural gas or biomass pyrolysis.
- These methods could bridge the gap between grey and green hydrogen.
- **Incomplete Coverage in Electrolyser Technology Standards**
- Indian standard based on ISO 227342019.
- Covers PEM, AEM, and alkaline water electrolysers.
- Excludes Solid Oxide Electrolyser Cells (SOECs).
- **Deficiencies in Feedstock-Based Production Standards**
- Current standards don't specify efficient resource use and effluent management.
- Could lead to inefficient and environmentally harmful practices.

Gaps in standards for hydrogen storage

- **Uncertainty About IS 81982004 Origin**
- It's unclear if IS 81982004 is original or derived from an ISO standard.
- As India aims to be a hydrogen hub, aligning storage standards with global requirements is crucial.
- **Adopting Features from Other Standards**
- India could consider incorporating aspects of standards from bodies like ASME and NFPA.
- **Strengthening Indian Standards**
- Conducting an adequacy assessment of current standards.
- Comparing them with international standards like EIGA Doc 06/19 and NFPA 55 could help enhance stringency.

Improving these aspects of hydrogen storage standards is essential for ensuring safety, efficiency, and global compliance, especially as India positions itself as a key player in the hydrogen market.

Gaps in standards for hydrogen transportation

- **IS 81982004 for Gaseous Hydrogen Storage and Transport**
- This standard applies to the storage and transport of gaseous hydrogen.
- It is unclear whether IS 81982004 is based on or a derivative of ISO 198812018.
- **Lack of Standards for Hydrogen Pipelines**
- India currently does not have specific standards for hydrogen pipelines.
- This is also the case for countries like Germany, South Korea, Australia, and Japan.

- **Absence of Standards for Metal Hydride Storage**
- India lacks standards for the metal hydride storage of hydrogen.
- In contrast, countries such as Australia, Canada, Germany, Japan, Korea, the UK, and the US follow the prescribed ISO standard in this area.

Gaps in standards for hydrogen applications

- **Thermally Activated Pressure Relief Devices for Compressed Hydrogen**
- India currently lacks standards.
- Contrastingly, Australia, Canada, Germany, Korea, the UK, and the US have adopted ISO 198822018.
- **Fuel Cell Installations for Industrial Trucks**
- Absent in Indian standards.
- Australia, Germany, Japan, the UK, and the US follow the IEC 62282-4-1022017 standard, either identically or with modifications.
- **Hydrogen-Fuelled Internal Combustion Engines (ICEs)**
- No existing standards in India.
- Suggests an opportunity for India to develop and lead in this area.
- **Hydrogen-Based Aviation and Railway Locomotives**
- No Indian standards for hydrogen-based aviation or railway locomotives.
- The US follows the SAE AIR 6464 for hydrogen aviation.
- The UK has adopted the BS EN IEC 63341 standard for railway locomotives.
- **Safety Aspects of Portable, Stationary, and Micro Fuel Cells**
- India lacks standards in these areas.
- Other countries like Australia, Canada, Germany, Japan, the UK, and the US follow relevant IEC standards (IEC 62282-5-1002018 for portable, IEC 62282-3-1002019 for stationary, and IEC 62282-6-1002010 for micro fuel cells).
- **Operational Parameters and Design Specifications for Hydrogen Combustion Equipment**
- No standards in India defining safe operational parameters and design for equipment used in hydrogen combustion for process heat.

Addressing these gaps is crucial for India to ensure safety, efficiency, and international compatibility in its burgeoning hydrogen economy. Developing comprehensive standards could also position India as a leader in certain aspects of hydrogen technology, particularly where such standards are currently lacking globally.

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