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India's Green Energy Transition

Navigating Green Hydrogen Energy Transition Challenges through Technology, Critical Minerals, and Strategic Partnerships

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THE ENERGY FORUM

INDIA'S GREEN ENERGY TRANSITION: NAVIGATING GREEN HYDROGEN ENERGY TRANSITION CHALLENGES THROUGH TECHNOLOGY, CRITICAL MINERALS, AND STRATEGIC PARTNERSHIPS

1.0 Introduction

India is the third largest economy in the world, and one of the fastest growing economies, with a population of nearly 1.4 billion, which is almost one-sixth of the global population[1]. To fuel this economy, energy has become an integral part of India's growth plan. In 2024–25, the energy demand reached 1.74 million MU (Million Units).[2] With the rapid urbanisation, infrastructure development, industrial expansion, and growth of the transport sector, we are working towards a reliable source of energy. India is at the crossroads for a sustainable approach to fueling the demand of economic expansion, i.e., to convert our fossil fuel-dependent economy to a clean energy powerhouse. India's planning and development policies have consistently aimed to align with the global climate change agenda.

India's National Green Hydrogen Mission, launched in January 2023, is targeted to produce 5 million metric tons (MMT) of green hydrogen annually by 2030[3], which will place country as a potential global leader for the production, utilisation, and export of green hydrogen and its derivatives. Hydrogen is very unstable in its elemental form, but it is very stable in a molecule we all know, i.e. water (H_2O), which is abundant on the Earth's surface. Deriving hydrogen from this will require an electrolyser. However, this transformation comes with many challenges, from the development in the R&D sector to securing critical rare earth minerals, dealing with global political tensions, and needing strong cooperation between the Government and the private sector.

Sectors like electricity generation, industries and transportation are producing almost 88 per cent of GHGs (Greenhouse Gases).[4] Hence, transition to renewable energy seems to be the most reliable way to meet the clean energy agenda. While India has demonstrated remarkable progress in renewable energy development, ranking fourth globally in renewable energy installed capacity and 3rd in solar power capacity (following China and the US),[5] Figure 1 represents[6] the trend of this growth. The shift to a hydrogen-based economy comes with key challenges like integrating energy storage, ensuring grid stability, fixing supply chain gaps, and building local manufacturing capacity for essential technologies like electrolysers.

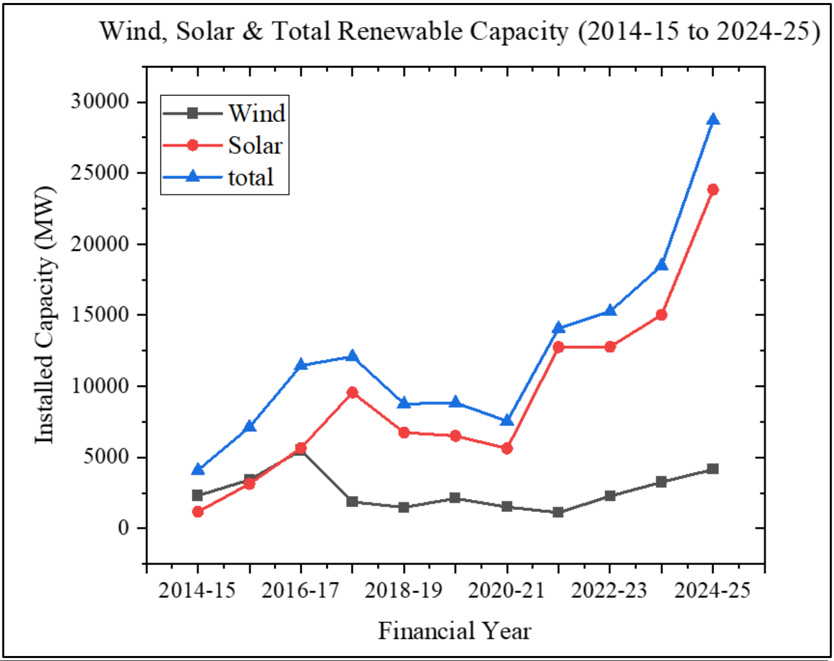

Figure 1: The graph highlights the annual growth in installed capacities of solar and wind power in India from 2014–15 to 2024–25, along with the total renewable capacity. Solar shows the steepest rise, contributing significantly to the overall increase in renewables.

2.0 The Complex Landscape of Energy Transition Challenges

2.1 *Technological and Infrastructure Barriers*

These challenges go far beyond simply replacing fossil fuels with renewable energy. One of the most pressing issues is the intermittent nature of renewable energy sources. Wind and solar power are not always available, i.e., 24x7, which means they are unreliable during peak demand, creating challenges for grid stability.

For this transition, there is a need for grid modernisation and transmission infrastructure development. India's power grids were originally built for coal, which is a steady, predictable energy source. Integrating variable renewable energy like wind and solar into the power grid requires major upgrades in grid flexibility, efficient consumption, and wider adoption of distributed energy resources (DER). Achieving this will need faster grid connection processes and strong, ongoing policy support, such as renewable energy tax credits and State-level renewable portfolio standards.

These upgrades are very important to reduce the wastage of energy. Tamil Nadu faces significant renewable energy output reductions due to grid constraints, with 70 million units of renewable power wasted in just one week in May 2025.[7]

2.2 *Economic and Financial Challenges*

Developing an immense grid infrastructure faces an urgent financial challenge that needs to be addressed. In India, solar and wind energy are cheaper than coal in many cases, but there is a concern that without the technological development and financial investment in the power grids, storage systems and the factories to make electrolysers, this means little. For example, India's plan to spend US$109 billion (₹9.5 lakh crore) by 2030 to double its grid capacity shows how critical and expensive this backbone infrastructure is.[8] Green hydrogen costs US$3.5–$5/kg, while grey hydrogen is US$1.5–$1.8/kg in India. For industries to switch to green hydrogen, it needs to fall below US$2.[9]

The economics behind this is also a little tricky to bear. Banks and investors do not see green hydrogen as trust- worthy, as it is new. High interest rates – 8-10 per cent in India versus 3-5 per cent in Europe – make loans costlier, adding ₹30-40 per kg to hydrogen's price.[5] Besides, around 70 per cent of the funding [5] would need to come from private investors, many of whom are reluctant to commit without assured buyers or consistent policy support. The Government's ₹19,744 crore National Green Hydrogen Mission tries to bridge this gap by paying producers ₹30-50/kg for three years.[10]

Green hydrogen's success depends on three things: cheaper electrolysers, i.e., technological advancement, market adoption of green hydrogen, investors willing to wait 7-10 years for returns, and infrastructure development. Without all three, the move to green energy could be slow.

2.3 *Geopolitical and Social Complexities*

Historically, countries like India had a very small contribution to harmful emissions, but due to geopolitical and environmental pressures of the current era, the Global South is now being forced to adopt renewable methods of energy production. Countries like India, which rely heavily on coal for energy security and employment, argue that a sudden shift to renewables could destabilise economies that are dependent on fossil fuels. For instance, India's NITI Aayog has emphasised the need for a phased transition framework to protect 13 million workers in coal-related sectors.[11] Similar are the cases with China, South Africa, Brazil and Mexico.

2.4 *Job Displacement and Reskilling Imperatives*

The risk of job losses in the fossil fuel sectors requires the need for a reskilling programme. Skill Council for Green Jobs (SCGJ) India, recommends roles in solar energy (e.g., solar PV technicians) as a reliable pathway for coal workers, which can create 3.26 million jobs in solar by 2050.[11] Still, it is very challenging to train informal workers; for every formal worker, there are four informal workers. According to a study done by the IEA, by 2030, 5 million workers will shift away from fossil fuel sectors, but the renewable sector can create 14 million new roles, on condition that workers acquire skills like grid management or green manufacturing.[12]

2.5 *Energy Justice and Equitable Pathways*

Along with reskilling, energy justice highlights the issue that the transition process burden is not shared equally. Most of the countries of the Global South are developing nations, and they lack the financial, technical ability to scale the renewable system rapidly, which ultimately risks dependency on foreign countries for critical minerals or renewable infrastructure. A way suggested for this transition can be international collaboration of the transfer of technology, infrastructure, and developed countries can also help developing countries via funding under some agreements.

The Global South needs to make a transition to clean energy in a way that secures jobs, ensures fairness, and keeps control in local hands, focusing on homegrown solutions instead of rules pushed by others.

3.0 India's Technological Readiness for Green Energy Transition

3.1 *Renewable Energy Infrastructure and Grid Capabilities*

In recent years, India has undergone a substantial transformation in power grids, aiming towards its agenda to support green energy. The 'One Nation-One Grid-One Frequency'[13] policy, enforced in 2013, provides a platform for uniting all regional grids into a single network. In other words, it is like merging different highways into one seamless expressway to increase the connectivity between all the cities. For example, if there is surplus production of electricity via solar panels which can be transferred to Karnataka. The current inter-regional transfer capacity (118.74 GW) still lags the total installed renewable capacity (220.1 GW), highlighting the need for further grid upgrades.[14]

To support the development of renewable energy, the Government of India has waived the Inter-State Transmission System (ISTS)[15] charges for offshore wind (until December 2032), and for green hydrogen, and ammonia plants until December 2030. This means making a wind farm in Gujarat and selling power to Tamil Nadu's hydrogen plant will not need extra fees for using the national grid, saving developers ~₹1-2 crore/MW annually. The result of these strategies can be seen as India's renewable capacity has skyrocketed from 75.52 GW in 2014 to 220.1 GW by March 2025, where solar capacity increased from 2.82 GW to 119 GW[16] as compared to the period 2014 to July 2025, and has aimed for an overall 500GW capacity by 2030.[17]

3.2 *Electrolyser Manufacturing and Innovation*

Electrolysers are the devices used for splitting water into hydrogen and oxygen; these are the heart of green hydrogen production. Under the Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme, ₹4,440 crores have been allocated to eight companies to enable annual production of 1,500 MW electrolysers by 2026.[18] Table 1 depicts the companies under this scheme. For perspective, 1 MW of electrolysers can produce about 500 kg of hydrogen daily.

Table 1: List of companies manufacturing electrolysers under the SIGHT Scheme – Bucket 1 and Bucket 2[19].

SIGHT Scheme - Bucket 1: Open to any electrolyser technology (including international/imported stacks) with a capacity range of 100-300 MW per bidder, allocated 1,200 MW total capacity

S. No.	Name of Bidder	Capacity (MW)	Type of Electrolyser
1	Reliance Electrolyser Manufacturing Limited	300	Alkaline
2	Ohmium Operations Private Limited	137	PEM

3	John Cockerill Greenko Hydrogen Solutions Private Limited	300	Alkaline
4	Advait Infratech Limited (consortium with Rajesh Power Service Private Limited)	100	Alkaline
5	L&T Electrolyser Limited	300	Alkaline
6	Matrix Gas and Renewables Limited	63	Alkaline
Total		1200	

SIGHT Scheme - Bucket 2: Reserved exclusively for fully indigenous/domestically developed electrolyser stack technologies with a maximum 300 MW per bidder, allocated 300 MW total capacity.

S. No.	Name of Bidder	Capacity (MW)	Type of Electrolyser
1	Homi Hydrogen Private Limited	101.5	AMSE/Solid Oxide
2	Adani New Industries Limited	198.5	Alkaline
Total		300	

3.3 *Standards and Regulations: Keeping It Green*

When we say ‘green’, it should not be just the final product; the manufacturing process should also be green, and its production must meet strict emission standards. According to India's Ministry of New and Renewable Energy (MNRE), green hydrogen should emit no more than 2 kg of CO_2 per kg of hydrogen, measured from the energy source to the factory gate. For comparison, conventional hydrogen from coal emits 18-20 kg CO_2/kg H_2.[20]

The Bureau of Energy Efficiency (BEE) keeps a close watch, supervises and approves agencies that meet the emission standards, verify and certify their green energy projects. Factories must submit their yearly report of emissions per kg of hydrogen produced, and third-party auditors check if they are using only solar or wind power and not electricity based on fossil fuels. Violators of the above norms risk losing subsidies or certifications, ensuring accountability.

3.4 *Energy Storage: Solving the Intermittency Puzzle*

As discussed earlier, solar and wind power are intermittent in nature. The sun cannot shine at night, and wind speeds also vary. To provide 24x7 clean energy for hydrogen plants, India is investing in two key storage solutions:

1. Pumped Hydro Storage (PHS):

   These are the giant 'Water Batteries'. During a sunny day, the excess solar energy is used to pump water uphill to a reservoir. At night, water flows down freely, and its path is made to go through turbines, which generate electricity. For example, Maharashtra's Koyna Hydroelectric Project is

India’s largest hydro power station, with a total installed capacity of 1,960 MW, generated across four stages.[21]

2. Battery Energy Storage Systems (BESS):

   In Chhattisgarh, SECI (Solar Energy Corporation of India) has developed India’s largest BESS, which is a 152 MWh facility connected with a 100 MW solar farm[22]. India is aiming to install 74GW of battery storage capacity by 2030, which will support renewable energy growth and grid stability, as stated by Union Power Minister Manohar Lal Khattar in 2025.[23]

3.5 *Dealing with Challenges*

India is constantly making efforts to bring about changes in its policies to use more clean energy and produce green hydrogen. The Government is assisting companies to use the grid by waiving taxes, helping more renewables grow.

India is constantly investing and promoting domestic production of the electrolyser to reduce its dependency on other countries. There are strict rules that ensure that hydrogen production does not harm the environment above a certain level., India is addressing the problem of intermittency of solar and wind energy by adding big batteries and water storage systems. All these steps mean that India can make clean and green hydrogen in a reliable and affordable way, helping the country move towards a greener future through exports.

The transportation of H_2 is also a big challenge due to its small size, low density, and high reactivity. Current methods include compressed gas storage (the most widely used method), liquid hydrogen storage, which requires cryogenic cylinders at -253°C, and liquid organic hydrogen carriers (LOHCs), that allow using organic compounds like toluene and benzyl toluene for storage.[24]

4.0 Critical Mineral Security and Geopolitical Navigation

4.1 *Strategic Importance and Supply Chain Vulnerabilities*

Minerals such as lithium, cobalt, copper, nickel, and rare earth elements (REEs), referred to as critical minerals, are important due to their chemistry; they serve as essential components in electrolysers, batteries, wind turbines, solar panels and other green energy-based technology. The global trade of the supply chain is very delicate, as most of the production occurs in just a few countries. China leads the production of rare earth elements which comprise 70 per cent of the total production,[25] also dominating the refining of lithium, cobalt and graphite, as can be seen in Figure 2[26] for the rare earth metals.

Due to almost 100 per cent import dependency for critical minerals like Lithium, Cobalt and Nickel, India's supply chain is at risk and could be easily disrupted. This dependence is ironic, especially since the country has good reserves of minerals like Cobalt Ore, which means securing these resources should be our top priority. Until we secure a steady supply of these resources, there will always be a risk in the supply chain, which could potentially result in slow progress towards energy security. One suggested way to tackle this problem of shortage is to go through a waste-to-wealth solution like urban mining, i.e., extracting and recycling the spent battery materials, solar panels, spent magnets, etc.

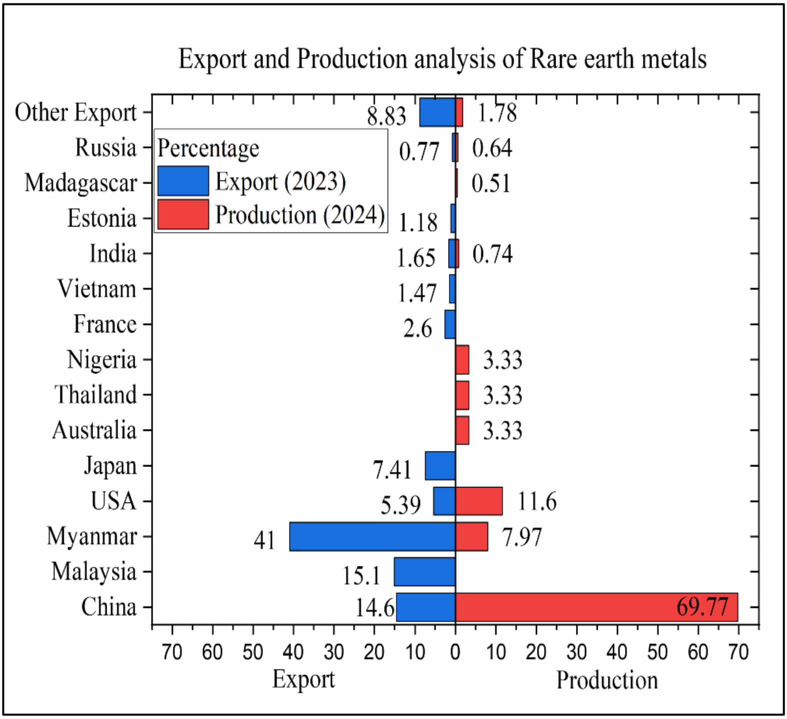

Figure 2: Sankey diagram illustrating the production and export shares of different countries in rare earth metals.

4.2 *National Critical Mineral Mission and Domestic Capabilities*

In response to these shortcomings, the Government of India launched the 'National Critical Mineral Mission' in January 2025, with a budget of ₹34,300 crores (US$4 billion) over seven years to reduce the overdependency and diversify our ways to fulfil the need of critical minerals, from exploration and mining to processing and recovery from end-of-life products.[27] These initiatives result in the speeding up of mining approvals, help India secure overseas resources, and focus on key strategies like building up reserves, setting up processing hubs, improving recycling, and creating a Centre of Excellence for R&D to ensure a reliable supply of critical minerals.

The Geological Survey of India has increased exploration efforts with 368 projects completed, 195 ongoing, and 227 planned.[28] For promoting domestic production, India is introducing regulatory and structural reforms such as allowing private players to invest, and allowing the auctioning of critical mineral blocks. To boost domestic production, India is implementing regulatory and structural reforms, including increased private investment opportunities and auctioning of critical mineral blocks. However, funding and advanced technology would be needed to make these initiatives effective.

4.3 *International Partnerships and Diplomatic Strategies*

India is aiming to secure the supply chain by diversifying the sources of critical minerals. The country has signed Memoranda of Understanding with Australia, Argentina, and the Democratic Republic of the Congo to collaborate on exploration, share technology, and invest in mineral supply chains.[29] In January 2025, Khanij Bidesh India Limited secured 15,703 hectares of land in Argentina for lithium mining, securing a long-term, steady supply of essential resources.[30]

India's geopolitical strategy is dictated by the global dynamic and its strategic rivalry with China, which results in cooperation with the United States, Australia, the European Union, Argentina, Chile, the Quad, the G20 and other players, in order to secure a reliable and steady supply of resources. So far, out of the total imports, most came from China. This diplomatic approach by India, of changing its geopolitical landscape, makes adaptability and collaboration essential for having a sustainable supply chain of critical mineral resources.

4.4 *Technology Innovation for Material Constraints*

To be in the race to produce green hydrogen, there is a need to build efficient electrolysers. As discussed earlier, hydrogen is very unstable in its elemental state. Also, in air, it is 0.00005 per cent by mol. Hence, for a reliable source of hydrogen, H_2O is used, which is most abundant on the Earth's surface (71 per cent of the Earth's surface), for which we need electrolysers and hence rare earths. These materials are expensive and hard to find, as they are controlled by a handful of countries.

PEM and Alkaline Electrolysers

- **The Iridium Problem**

  The Proton Exchange Membrane (PEM) uses a semi-permeable membrane for hydrogen production, known for its higher efficiency; they need Iridium as a catalyst for the water splitting on the cathode side, particularly for the Oxygen Evolution Reaction (OER), but Iridium is rare and hence expensive. (Table 2). It is 40 times rarer than gold, and most of it is mined in South Africa.

- **Nickel and Steel Demands**

  Alkaline Electrolysers use mostly KOH as electrolyte, and for water splitting and HER, OER, nickel is used as a cost-effective mesh electrode. In addition, stainless-steel parts are used for its construction. But though they are cheaper, India still lacks domestic reserves of both. They use nickel mesh electrodes and stainless-steel parts. Even the quality of steel matters; low-grade steel corrodes faster in the alkaline environment, forcing imports of specialised alloy steel.

Solid Oxide Electrolysers

- **Oxide Ion conducting Solid Oxide Electrolysers (O-SOEs)**

  O-SOEs work at high temperatures, around 700–850 °C, and use a solid ceramic electrolyte, often scandia or yttriastabilised zirconia, that carries oxide ions (O^{2-}). This enables highly efficient water splitting. SOEs do not need precious metals, can handle lower-purity water, and are ideal for continuous, large-scale industrial operations. There are some challenges though: high operating temperature and long start-up times, making them less compatible with many renewable energy sources. Their manufacturing depends on imported minerals such as nickel, zirconium, and rare earths, which makes full indigenisation in India, challenging.

- **Protonic ceramic Electrolysers (PCEs)**

PCEs are solid oxide fuel cells in which H^+ ion goes through the electrolyte. Due to low activation energy for H^+ ion conduction as compared to the oxide ion conduction, these can be operated at a low temperature range (400-600 °C). The H^+ on the cathode side forms H_2. One of the most developed electrolytes is BaZrCeYYb (1711); it offers high proton conductivity. One of the advantages of using PCEs is that we do not require highly pure fuel, i.e., it can perform even in the presence of some CO_2 and H_2S, hence the improved chemical stability. Also, the supply chains for key rare earths (Y, Yb) are still nascent in India. PCEs are in the developing stage as compared to the SOEs; most projects are in the testing stage.

In summary, both O-SOEs and H-SOEs, i.e. PCEs, are a promising solution to green hydrogen production, as they do not require precious metals. SOEs, being more mature, are not as flexible as PCEs, which provide lower operating temperatures. But they mainly rely on rare earth metals, which are under research for the development to the scale of commercialisation. Table 2 represents the quantity required per MW of the material for SOEs & PECs.

Table 2: Mineral Requirements per MW for PEM, Alkaline, SOE and PECs Electrolysers[31]

Critical Mineral	Quantity per MW (kg/MW)			
	PEM Electrolysers	Alkaline Electrolysers	SOEs	PECs
Platinum	0.075-0.5	0	0	0
Iridium	0.076-0.7	0	0	0
Titanium	414-528	0	0	0
Gold	0.71	0	0	0
Yttrium	0	0	1	5
Ytterbium	0	0	0.5	1-2
Barium	0	0	0	50-80
Nickel	0	800-3167	9.1	5-10
Zirconium	0	94-100	54	50-60
Molybdenum	0	0.15	0	0.15
Lanthanum	0	0	7.3-20	10-30
Cerium	0	0	30.3	25.5
Gadolinium	0	0	6.62	6.5
Scandium	0	0	1.7	1.5
Strontium	0	0	2.06	5-10

AEM Electrolysers: The Middle Path

- Anion Exchange Membrane (AEM) is more feasible than PEM and alkaline electrolysers though its efficiency is lower than both. However, its manufacturing cost is slightly lower. AEM is an electrolyser that splits water by reducing H_2O at the cathode to H_2 and OH^-, which then migrates through the hydroxide conducting polymer membrane, where it gets oxidised to O_2 and H_2O. This setup requires a low-cost hydrocarbon membrane and non-noble-metal catalyst (Ni, Fe, Co). AEM systems combine the low material costs of alkaline electrolysers with the modular design and high purity control of PEM stacks, resulting in stacks that cost about 30 per cent less than PEM and take up 10–20 per cent less space than alkaline units take. High purity of water is not needed for operating them, which further reduces the cost of purification.[32]

- There are some disadvantages related to membrane durability, which means it has a lower operational lifetime as compared to the PEM; AEM membranes degrade faster than PEM's 10-year lifespan. Another main issue is the conductivity of OH^- ion via the membrane, which is lower compared to the PEM's H^+ conduction via the Nafion membrane. The efficiency is also low; AEM electrolysers operate at efficiencies slightly lower as compared to 60–65 per cent for alkaline systems and 70–80 per cent for PEM systems, while SOECs can achieve up to 84 per cent.[33]

- Research and development is ongoing on AEM electrolysers that will close the gaps in disadvantages and make them increasingly efficient. Critical mineral scarcity does not mean that it is a dead end; it is an opportunity to break innovation barriers. Using smart policies, upgradation in technology in recycling and recovery, India can rewrite the rules of the clean energy game.

5.0 Public-Private Collaboration in Accelerating Green Energy Transition

5.1 *State-Level Policy Support and Incentives*

A recent study conducted by CEEW shows that State policies are playing a crucial role in attracting major investment in India's green hydrogen. Twelve states have stated their measures that complement the National Green Hydrogen Mission (NGHM), out of which just seven – Odisha, Maharashtra, Tamil Nadu, Uttar Pradesh, Rajasthan, Andhra Pradesh, and Gujarat – account for most of the support.[34] Most of these incentives focus on affordable renewable power, which makes up nearly two-thirds of the total benefits. This shows that the success of the Mission lies in ensuring low cost and reliability on renewable electricity.

Public-Private collaboration is emerging as a driving force for green hydrogen production. The NGHM explains it thus: Government funding, smart incentives and a strong governance framework are providing a pathway, and confidence to the companies to invest in it.

5.2 *Can India Lead the Green Hydrogen Revolution?*

India’s green hydrogen aims to place India as a major exporter at the global level. The NGHM has targeted key markets in Asia and Europe. The Government has directed its efforts at Japan, Korea, and Singapore as suitable markets in Asia, and the European Union,[29] taking advantage of India’s strategic location along abundant renewable energy resources. While the US offers major incentives under the Inflation Reduction Act bringing costs down to about US$3 per kilogram[35], its limited grid capacity and renewable energy supply may restrict its ability to meet global demand. This opens the door for countries like India to step in. By 2030, India aims to capture around 10 per cent of the global green hydrogen import market.[36]

6.0 Conclusion

India has one of the world’s greatest opportunities when it comes to green hydrogen. Even today, India could make 40 million tonnes at a competitive cost of below US$3.5/ kg if we invest in renewables and electrolysers smartly.[3731] India, due to its abundant sunlight, wind, and sufficient land area, can not only become self-sufficient but also become a global hub for exporting green hydrogen and ammonia. The challenge lies in how quickly we can turn this natural advantage into large-scale projects on the ground. It is never just about cleaner air, but economically, it will also create jobs, attract investments, and build energy security for the future.

India has already progressed with renewable energy, modernising its power grid, and building electrolyser manufacturing capacities. The National Green Hydrogen Mission, alongside increasing private investment, will boost this further. The Mission shows how Government and industry can work together to make India a global leader in green hydrogen.

To completely understand the potential, India must overcome some key challenges like securing a reliable critical mineral supply chain, enhancing market adoption, and expanding the infrastructure for electrolysers. The Government's policies, along with global partnerships for mineral security and strong State-level policies, are building a strong foundation for sustainable growth. With these, India is well placed to emerge as a global leader in producing and exporting green hydrogen.

India's success in green hydrogen will largely depend on sustaining this momentum. If we succeed in managing these well, green hydrogen will not only drive decarbonization, but it will also make us energy-independent, create large-scale jobs, and position India at the centre of global clean energy transition.

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