GREEN HYDROGEN IN INDIA: STATUS AND THE WAY AHEAD

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ABSTRACT
Due to a self-sustainable and matured Renewable Energy industry especially solar, Green Hydrogen has a great potential in India. With its applications in Steel, Cement, Refining, Chemical and Fertilzers and Fuel Cell based vehicles for transportation, it can be the future fuel to achieve energy security and achieve net zero emission target for India. At least 43 countries have now set up or are setting up strategies or roadmaps for a hydrogen economy and have allocated more than $76 billion of government funding. India has also taken a lead with government announcing green hydrogen policy in February 2022, in addition various private industrial groups like Reliance, Adani and Public Sector undertakings like IOC, GAIL and NTPC have started investing in green hydrogen. Sector faces challenges of high production cost, limited research and development presently, no market demand, storage and transportation, water availability, cost dependency on the tariffs of renewables and safety issues. To achieve mass rollout and economies of scale, India needs to focus on a creating demand based on purchase mandate, a stable regulatory framework with right polices for market creation, reducing import dependency on raw material required in solar and electrolyzer industry along with due focus on research and development on the technology and green hydrogen supply chain.

Keywords
Green Hydrogen economy, Green Hydrogen India, Fuel Cells, Electrolyzer, Renewable Energy India

Highlights
(with each line containing not more than 85 characters) are as under:
1. Identification of the status of green hydrogen in India
2. Identification of challenges in the growth of green hydrogen in India.
3. Recommended of actions required to achieve the growth and development of wind energy in India.
4. Elaboration on the utility of green hydrogen in various sectors in India.

1. INTRODUCTION

India is 5th ranked in world among most polluted countries and regions((IQAir, 2021). The energy sector contributes to 73% of India's greenhouse gas emissions and 43% of the energy sector's contributions come from power generation(GWEC, 2021). Being a developing economy , its electricity demand is projected to grow at 9.9% yearly towards 2025 (GWEC, 2021). Today there is an urgent need for India to decarbonise its energy-intensive sectors such as industry, transport, and power. India has also embarked on the journey towards RE where in COP26 summit at Glasgow India has put a target of installing non-fossil fuel electricity of 500 GW capacity by 2030. In addition it has also committed to achieve net zero emissions (balance between emissions produced and reduced) by 2070. (Subrahmanyam, 2022). The renewable energy sector mainly comprising of wind and solar has come a long way now and the industry is self-sustaining with tariffs getting stabilized. Considering ever increasing energy demand of industry and transport sector, hydrogen complemented with other renewable energy technologies can play a critical role in achieving our national goals. Hydrogen is a non-polluting source of energy and has zero carbon content and has the highest energy content by weight and lowest energy content by volume(Priya, 2021)

Green hydrogen as a source of clean energy and industrial feedstock is now becoming the key focus area across the world. The European Union (EU), Australia, and Japan have already announced their hydrogen roadmap (Biswas et al., 2020)Indian government, with a broad objective of scaling up green hydrogen production and utilisation and to align India's efforts with global best practices in technology, policy and regulation, launched National Green Hydrogen Mission on 15 Aug 2021(Priya, 2021) and continuing in the same momentum government announced India's Green Hydrogen Policy on 17 Feb 2022(MoP, 2022) .

Green hydrogen is at an early stage of entering the energy sector in India, it is presently not affordable for having viable business model and the entire value chain of green hydrogen economy is still evolving. All this necessitates the need to study the green hydrogen in India, to know its current status, scope of future growth as well as the various challenges the sector faces. According to best of the author's knowledge, there is limited literature available on green hydrogen in India and no comprehensive work dedicated to the same is available, which necessitates study of green hydrogen in India, to know its present status as well as the various challenges that the sector is likely to face and this paper is an attempt to bridge gap in the literature related to same.

Research Methodology has been explained in Section 2. Section 3 gives an overview on how hydrogen is used for energy applications, its industrial utility and what is green hydrogen. The status of green hydrogen across the world is given in Section 4. National Green Hydrogen Mission and Green Hydrogen Policy has been elaborated in Section 5. Section 6 describes the value chain and stakeholders in the green hydrogen economy. The impact of green hydrogen in current industries and sectors in India is discussed in Section 7. Section 8 gives the impact green hydrogen will have over various existing industries. Section 9 gives the challenges and way head. Limitations and scope of future research is given in Section 10 and finally the conclusion and policy implications in section 11.

2. Research Methodology

Systematic literature review has been used as the research methodology. “use of hydrogen in India, “green hydrogen in India”, “challenges in green hydrogen in India”, “hydrogen as a source of energy” , “ status of green hydrogen in world ” were used as key words for search. Articles were considered with in the domain of policy, utilization, status, technological aspects of green hydrogen in India. There is very limited research articles are available on the subject and the authors had to rely on grey literature which included newspaper and magazine articles, studies and reports of companies as well as data available on government website and Overall 35 articles were identified and studied.

3. Hydrogen as a Source of Energy.

Hydrogen’s energy density is almost three times more than diesel or gasoline (Agarwal et al., 2022). Fuel cells use hydrogen for generating heat and electricity and thus hydrogen is emerging as a key technology in transportation. Petroleum refining and fertilizer production are other major areas of usage of Hydrogen (Satyapal, 2017).

3.1. Production of Hydrogen

Steam methane reforming process in which hydrogen is produced by reaction of steam at a high-temperature with a hydrocarbon fuel is the most common hydrogen producing process. Electrolysis process is also a common technique which separates water it into oxygen and hydrogen. Biological reactions are also used to produce hydrogen gas. In addition ,processes such as photo - biological, photo-electrochemical, photovoltaic-driven electrolysis and solar thermochemical use sunlight to produce hydrogen (Satyapal, 2017).As a global practice, hydrogen has been colour coded, based on its production source or process . The colour coding along with method of production is elaborated in Table 1 below.

Table 1: **Colour coding and various processes to produce Hydrogen**
Source :(Agarwal et al., 2022)

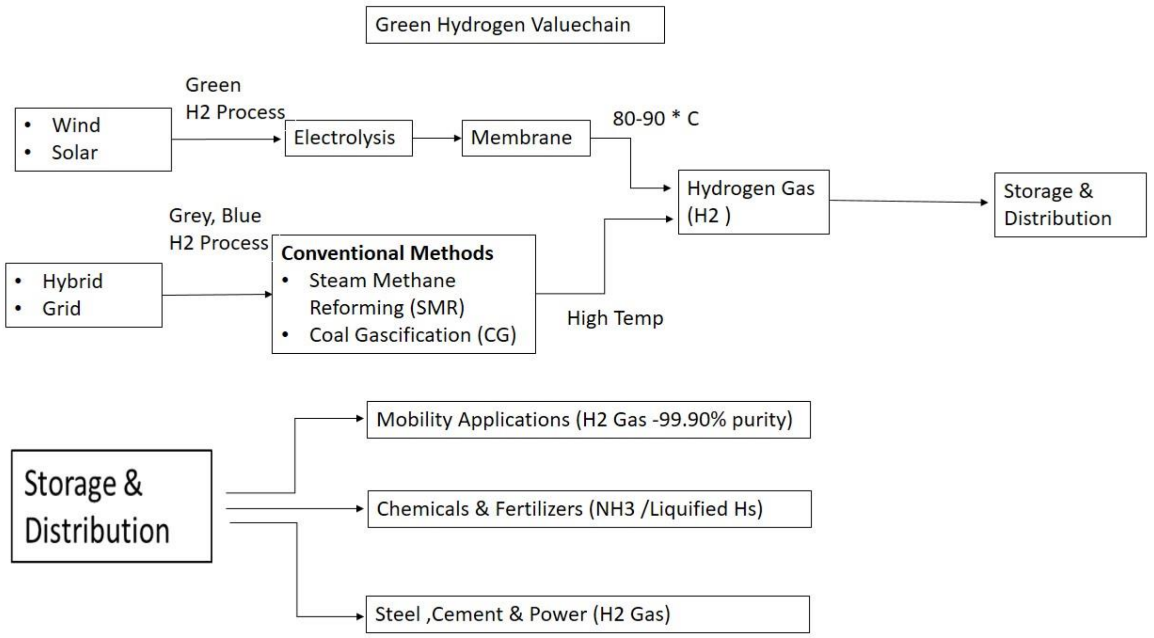
Colour Code	Technology Used/Process	Remarks
Grey	Thermochemical Process of natural gas reforming without Carbon capture, utilisation and storage (CCUS)	
Brown	Thermochemical Process using brown coal (lignite)	
Blue	Thermochemical Process of natural gas reforming with CCUS	
Green	Electrolysis (Splitting of water using electricity) using renewable electricity	
Pink	Electrolysis using nuclear energy	

3.2 Production of Green Hydrogen

Green hydrogen is the hydrogen produced using renewable electricity. The device where this splitting takes place are hydrogen electrolysers which receive electricity input from renewable sources like wind and solar. Figure 1 describes the Green Hydrogen Value Chain. Key feature of green hydrogen is that no polluting gases are emitted either during combustion or production. It can be mixed with natural gas in proportion of 20 % presently and can use same transmission infrastructure of gas pipelines. Any further increase in this percentage or to transmit it separately would require changes in the existing gas networks for compatibility. Hydrogen can be stored physically as a gas under very high-pressure tanks (350–700 bar tank pressure) or as a liquid at cryogenic temperatures. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption)(energy.gov, 2021).

Figure 1: Green Hydrogen Value Chain

(Source : Agarwal, Mulukutla and Malladi (2022))



3.3. Applications of Green Hydrogen

Green hydrogen can be used both as feedstock for industries as well as fuel for transportation and power. The various applications of green hydrogen are elaborated below.

3.3.1. Steel

Steel production requires direct reduced iron (DRI) as reductant green hydrogen can be used as the reducing agent in DRI which will ensure nearly emission-free steel production.

3.3.2. Refineries

Hydrogen is critical for the operation of a refinery as it is used in the de-sulfurisation of crude oil to make petrol and diesel and other chemicals. Presently it is generally made at the refineries via steam methane reformation (SMR) using natural gas for the feedstock. As this process results in a high CO_2 output per tonne of hydrogen, refineries are intending to shift to green to reduce the same.

3.3.3. Chemicals and Fertilizers

Ammonia is one of the prime materials which is used in the production of synthetic nitrogen fertilizers such as urea, ammonium sulphate, ammonium sulphate nitrate, and ammonium chloride. Conventionally, ammonia is produced by mixing hydrogen (presently produced from fossil fuels) with atmospheric nitrogen. This process is also highly CO2 intensive. Usage of green hydrogen in will lead to emission free ammonia production. In addition, ammonia is easy to transport, hydrogen can be converted to ammonia for transportation and then reconverted to hydrogen at the destination.

3.3.4. Cement

The cement industry across the world is a major emitter of carbon dioxide. It is a highly energy-intensive and requires temperature of 1500 degree Celsius. Green Hydrogen can be utilized in Cement industry by replacing natural gas with green hydrogen for such high temperatures.

3.3.5. Fuel for Transportation

Fuel Cells can be powered by Hydrogen. The polymer electrolyte membrane (PEM) fuel cell is the most common type of fuel cell which uses, a thin surface called a membrane to separate oxygen and hydrogen. The hydrogen molecules in the fuel cell is further broken into protons and electrons by an electro-chemical reaction. These electrons through an external circuit provide power to the battery and which further propels the vehicle. Only by-product of the system is water that is emitted from the exhaust. Similar to petrol or diesel hydrogen is stored in a tank, in compressed form. Refuelling hydrogen cells is much faster than charging battery cells and can be similar to existing diesel cars and is especially suited for long distance trucking (Ralston, 2022).

3.3.6. Fuel for Power

Hydrogen power projects presently use grey hydrogen but new gas turbines based on green hydrogen are also being developed which will reduce the dependence on natural gas. In addition certain niche applications like replacing diesel generators with replenishable hydrogen fuel cells which can act as a short-term source of energy.

4. Status of Green Hydrogen across the World

Hydrogen can be a key enabler act as a critical enabler to achieving the global targets to limit the increase in temperature to 1.5-degree Celsius . Realizing the importance of same , numerous global initiatives towards hydrogen economy have been taken. Expected global investments until 2050 are likely to be US $10.2t, government support to transition to hydrogen is likely to be US 70b and estimated annual sales by 2050 will be US$2.5t (Moda, 2022).Currently annual hydrogen production in the world is approximately 75 million tonnes, however 98% of the same is from fossil fuels ("Green Hydrogen Catapult," 2021).. Governments and industry across the world today consider that green hydrogen, with its diverse applications across the industries, is key to achieve a net carbon zero economy. Though many countries have launched programmes for green hydrogen development, usage and growth, however, the technology and its different industrial applications is still in nascent stage based with deployment based on

pilot projects . Very limited commercialisation at scale and mass deployment has been carried out (Ghosh and Chhabra, 2021). Around 30 countries around the world have made strategies for green hydrogen development and have allocated $76 billion funds (Gupta, 2021).
With an aim to bring down the cost of green hydrogen, green hydrogen leaders around the world with the support of the UN High Level Champions for Climate Action have made a coalition known as Green Hydrogen Catapult. It has also committed through secured financing for development and commissioning of 45 GW of electrolyzers by 2027. Britain has made a Ten Point Plan for a Green Industrial Revolution and it also is committed to create 5 GW of low carbon hydrogen by 2030("The Ten Point Plan for a Green Industrial Revolution," 2021). China is global leader with annual Hydrogen production of about 33 million tonnes. (Collins, 2022). Sinopec ,China's state-controlled energy company, aims to set up plants which will for produce 500,000 tonnes of green hydrogen a year by 2025 from renewable energy sources (Reuters, 2021). One of the world's largest hydrogen electrolyzer of 20 megawatt capacity to produce green hydrogen for fuel cell vehicles during the Winter Olympics began operations in Zhangjiakou, China in January 2022 (Frangoul, 2022). China adopted a new fuel cell vehicle subsidy policy in 2020, with an aim to enhance the manufacturing capacities of China's FCEV industry and focus on using fuel cells in medium- and heavy-duty commercial vehicles(IEA, 2021). China aims to have 50,000 hydrogen-fuelled vehicles by 2025 as significant increase from about 7,500 which are there currently(Collins, 2022).
In USA approximately 10 million metric tons of hydrogen is produced annually which is equivalent to 1 percent of U.S. energy consumption but out of which over 95 percent of grey hydrogen is only produced . Nearly all hydrogen produced in the USA is used for petroleum refining, treating metals and fertilizers production. However, some applications and usage of Green Hydrogen are also coming up. Currently, more than 40 hydrogen vehicle fuelling stations have been set up. In addition , operating fuel cells at approximately 110 industrial facilities with a total capacity of about 250 MW are also functional. The current estimated average cost of green hydrogen in USA is $5 per kilogram Considering the importance of green hydrogen, US Government has also launched "Hydrogen Shot," a "1-1-1" goal which aims to cut the cost of clean hydrogen to $1 per 1 kilogram in 1 decade. ("HYDROGEN'S PRESENT AND FUTURE IN THE US ENERGY SECTOR," 2020).
The strategies adopted by various other countries have been elaborated in Table 2 below.

Table : 2 Green Hydrogen Strategies of various countries
Source: (Patel, 2021)

Country	**Year Hydrogen Strategy/ Roadmap Issued**	**Key Points of Emphasis**
Japan	2017	Aims of achieving cost parity with liquefied natural gas and other competing fuels Target of having electrolyzer costs of $475/kW, with 70% efficiency and cost of production of $3.30/kg by 2030.

South Korea	January 2019	Emphasis on Fuel Cell Electric Vehicles
Australia	November 2019	Target of “H2 under 2” i.e. production cost of green hydrogen below AU$2/kg.
Netherlands	April 2020	Completely sustainable energy supply in 2050 With 30% to 50% of final energy consumption through biogas and hydrogen.
Norway	June 2020	Expand the use of hydrogen in the maritime sector as energy carrier Government funding for innovation for subsea storage of hydrogen from offshore wind energy
Germany	June 2020	Increase in electrolyzer capacity up to 5 GW by 2030 14 TWh of green hydrogen production by 2030
European Union	July 2020	Electrolyzer capacity targets of 6 GW by 2024 and 40 GW by 2030, Production targets of 1 million by 2024 and 10 million tonnes by 2030 of renewable hydrogen per year .
France	September 2020	An investment of €7.2 billion by 2030 incl €1.5 billion for construction of electrolysis plants. A hydrogen production capacity target of 6.5 GW by 2030.
Spain	October 2020	Installations of 4 GW of electrolyzer capacity by 2030 Goal of Green Hydrogen production of at least 300 MW to 600 MW by 2024 .
Chile	November 2020	Aims to be World’s cheapest green hydrogen producer and a leading exporter by the 2030s. A target of 25 GW by 2030 with hydrogen production cost of less than $1.50/kg
Canada	December 2020	Aim to deliver up to 30% of Canada’s end-use energy by Green Hydrogen by 2050. Aim to achieve delivered hydrogen costs of CA$1.50–3.50/kg

5. Status of Green Hydrogen in India

India is the third-largest consumer as well as producer of grey Hydrogen. It is mainly as an industrial feedstock in the creation of ammonia-based fertilisers. Mostly grey hydrogen is used in India. One of the first large scale alkaline electrolyser facilities in the world to produce hydrogen from electricity was at the Nangal Facility from 1962(Hall, 2019). At present in Green Hydrogen is at a nascent stage in India. All agencies primarily engaged in pilot projects and research & development related to its production, storage, power generation and for transport applications and is far away from commercialization and mass deployment in India. .However considering India's very high renewable energy potential and related low renewable energy cost, it is estimated that Green Hydrogen’s cost will fall to less than $1 per Kilogram in future and thus making India , one of the lowest-cost producer in the world of Green Hydrogen. Currently research in India is focussed on improving the water-splitting reaction's efficiency during the electrolysis process. Fuel cell technology is also a major research area with more than 100 research groups working on the same. There are also a number of Indian and foreign companies that are involved in hydrogen production, storage or delivery in India.(ET, 2022; Priya, 2021).

The India has huge potential of use of green hydrogen and it intends to increase between 3 and 10 times by 2050. National Hydrogen Mission which was launched on 15th August 2021 which aims to make India a global hub for green hydrogen production and export. .India plans to manufacture ,by 2030 ,five million tonnes of green hydrogen per annum . There are also plans to set up separate manufacturing zones, waive inter-state power transmission charges for 25 years. In addition to incentivise production, provide green hydrogen and ammonia producers priority connectivity to electric grids (Varadhan, 2022).

To bring further clarity, create a favourable and enabling environment to encourage investments in the sector, Indian government on February 17, 2022 brought out Green Hydrogen and ammonia policy. The policy grants open access to procure electricity within 15 days of application and waiver of inter-state transmission charges. Green hydrogen/ammonia manufacturers will be allowed to purchase renewable power from the power exchange or set up renewable energy capacity themselves or through any other developer. The manufacturer are allowed to bank renewable power for 30 days with distribution companies and take it back when required. The distribution licensees can procure and supply renewable energy to the manufacturers of green hydrogen green ammonia in their states at concessional prices. Green Hydrogen will also form part of Renewable Purchase Obligation. There are provisions to set up bunkers near ports for the export of green ammonia. Renewable energy plants to be given connectivity to the grid on a priority basis to avoid any procedural delays. This policy is first concrete step by Indian government towards creating a green hydrogen economy and majorly benefits all states where renewable energy is require to be wheeled in from other states(Kumar, 2022).

6. Recent developments in green hydrogen in India

Currently hydrogen use in transport in India is limited to bus pilot project , which runs on hythane, a blend of 18% hydrogen and CNG ,in New Delhi in 2020 (Kelly and Zhou, 2022). Oil India Limited has launched India's first Green hydrogen pilot plant in Assam with an installed capacity of 10 kgs per day. In addition, commercial production plants with a combined capacity of 200 tonne per annum (TPA) of green hydrogen are operational in Hazira, Jorhat and Bikaner. Two retrofitted diesel-electric commuter hydrogen powered will g0 into service in 2024. Fuel cell technology company Ballard Power Systems will develop the fuel cell module. Investments in the project will likely to have a payback off less than two years. Also it will reduce annual carbon dioxide emissions by over 11 metric tons and eliminate nearly a metric ton of particulate matter per year (Sridhar, 2022) .

Indian Oil has also set a target of converting at least 10% of its hydrogen consumption at refineries to green hydrogen. Indian Oil Corporation has also announced its plans to build a green hydrogen plant with a capacity of around 160,000 barrels per day at its Mathura refinery

in Uttar Pradesh. IOC also will setup a stand-alone green hydrogen manufacturing unit in Kochi that will draw energy from the solar power facility of the Kochi International Airport (Equitymaster, 2021). GAIL India also plans to build India's largest green hydrogen plant with a capacity of 10 MW. Similarly, NTPC plans to produce green hydrogen by establishing 5 MW plant at Rann of Kutch. NTPC is also running a pilot project in its Vindhyanchal unit. NTPC also plans to set up its first green hydrogen fuelling station in Leh, Ladakh with plan to run hydrogen buses initially(Equitymaster, 2021).
India is emerging as a key base for hydrogen electrolyser production and is likely to have 8GW capacity by 2025 through joint ventures and private investments. Greenko is building a 2GW factory in partnership with Belgium's John Cockerill and Nevada-based Ohmium. Korean steelmaker POSCO has signed an agreement with renewable Greenko ZeroC to make green hydrogen. (Sarkar, 2022)

Reliance Industries Ltd (RIL), plans to become a net carbon-zero firm by 2035. It aims to replace transportation fuels with clean electricity and hydrogen. It will invest Rs 750 bn over the next three years in renewable energy. RIL intends to build a 2.5-gigawatt (GW) electrolyser manufacturing unit and has partnered with Danish company Stiesdal A/S to develop and manufacture hydrogen electrolysers. The company aims to produce hydrogen at 'under US$1/kg within a decade'. (Equitymaster, 2021)..L&T has also commissioned a 45-kg per day green hydrogen plant at Hazira in Gujarat (Kurup, 2022). An electrolyser plant in Pune is being set up by h2e power systems ,a clean technology start-up (Cardoz, 2022).
Adani Group has also announced plan to produce three million tonnes of hydrogen by 2030, which would require 16GW of electrolyser capacity(Baruah, 2022; Prasad, 2021; Sarkar, 2022)
In march 2022, Mirai, one of the few green hydrogen-based advanced Fuel Cell Electric Vehicles (FCEVs) in the world by Toyota , was launched as part of the Toyota Kirloskar Motor (TKM) pilot project with the International Center for Automotive Technology (ICAT).The vehicle is powered by a hydrogen fuel cell battery pack and is capable of providing a range up to 650 km in a single charge, with a refuelling time of five minutes. If successful on Indian roads and climatic conditions ,it could bring down the cost of travel to just Rs 2 per km. (Business Today Desk, 2022)

7. Challenges

With right mix of support policies, fiscal incentives and private sector investments, India has a chance to become a world leader in the production, usage and export of Green Hydrogen. However Green Hydrogen in India is at nascent stage. It is evolving both commercially and technologically and the sector overall faces numerous challenges. Some of these challenges have been discussed in succeeding paragraphs.

7.1 Production Cost

At present in India , Hydrogen costs between Rs 340 to 400 per kg.(USD 4.5 to 5.3 per kg). When green hydrogen production costs comes down to Rs 150 per kg (USD 2 per kg), then only cost parity will be achieved (Upadhyay and Joshi, 2021). The greatest challenge for green hydrogen production is to make it affordable and economically viable. Green Hydrogen should ideally be $1 per kilogram, Currently grey hydrogen is 4 times that levels and green hydrogen costs about $5 per kilogram to produce , which is primarily due to the cost of renewable power equipment, electrolyzers and hydrogen compressors . In addition, the biggest cost is of electricity which is as much as 70-80% of the cost of hydrogen. India has huge renewable energy potential and the cost of renewables especially solar is now competitive, however still further development of Renewable energy capacity and supporting transmission and evacuation infrastructure is required. Even for usage as Transportation fuel cells in vehicles, the cost has be competitive with other conventional fuels and technologies. Production of Green Hydrogen is long way away from achieving economies of scale and needs government and industry support to become self-sustaining.

Also green hydrogen adoption drive is totally dependent on reduction of electrolysers' costs by about 50% by 2030 to which will lead to levelised cost of hydrogen of $2-3 per kg. However, there has been a surge in metal prices recently because of geopolitical disruptions and if the fluctuations continue then the anticipated reduction of cost may not happen thus adverse affecting the green hydrogen propagation (Kurup, 2022)

7.2. Research and Development in Green hydrogen

The initial research and development in solar PV , wind and lithium ion batteries had happened largely outside India. Consequently India could not become manufacturing hub and still is dependent on imports especially for solar modules. Green Hydrogen being a niche technology area, Research and development in this sector should be adequately funded. At present , only Rs 25 Crore have been allocated by the government in 2020-21 budget for research in Green Hydrogen , which is inadequate and much lesser in comparison to other countries like Germany which has offered Rs 6,096 crore grants for the research (Rajshekhar, 2021). Lot of effort is required to design and develop cheap and effective electrolyzers and start manufacturing them at a large scale. In the Union budget for FY 2021-22 ,Govt of India has proposed spending INR 800 Cr by 2024. (Upadhyay and Joshi, 2021).

7.3 Generating Demand

Green Hydrogen market is evolving and is interlinked with other industries and present there is no specific or defined market for the same**.** Managing the market risk exposure is a big challenge for investors. For encouraging investments and to be considered bankable, market for utilization of green hydrogen in various applications has to be created by the government. It would require applicability Renewable Purchase Obligations (RPOs) and long-term, fixed price off-take contracts with creditworthy off-takers for Green Hydrogen Projects.

7.4 Storage and Transporting Hydrogen.

The biggest challenge for storage is the reactive nature of the gas and need to cool it to -252 degree before transportation. There is a requirement of special containers and cooling technology. Further for transportation, how to store hydrogen within vehicular constraints of volume, safety, cost and weight for normal and long driving range is still a major technological challenge. It can be transported through truck, rail, or pipeline in gaseous form and only through truck or rail in liquid form. To reduce costs and enable easy transportation of hydrogen, government has proposed usage of existing natural gas network by blending hydrogen with

CNG in small quantities of 5%–15%. However, this also would require separation and purification technology at the end point, for further use in Fuel Cell Vehicles, which itself will also raise costs. Thus there is a requirement of a dedicated hydrogen pipeline network (Kelly and Zhou, 2022).

7.5 Safety Issues

Unique chemical and physical properties of hydrogen can lead to certain specific safety issues while transporting and distributing Hydrogen. Hydrogen can embrittle materials, can easily escape from containment and has a wide flammability range with a very limited amount of energy needed to ignite it. Therefore there is a requirement to ensure that strict safety standards and regulations are enshrined right from the technological development and subsequent production and transportation stage itself (Gerboni, 2016).

7.6. Exporting Hydrogen

India aims is to be top producer and exporter of Green hydrogen. However, considering the properties of gas, transporting long-distance will be expensive and would require special infrastructure and development of supply chains. The cost factor involved can weaken its propagation and competitiveness in comparison to other conventional fuels which and may limit the export range.

7.7. Cost dependency on the tariffs of Renewables.

Green Hydrogen cost is directly linked to the tariffs of renewables. Due to huge RE potential and proactive support polices of the government in last two decades, tariffs of both Solar and Wind are competitive now and are favourable for economical Green Hydrogen production.

However, Solar industry in India is dependent on imports of all critical components like solar cells, modules and solar inverters and any rise in solar tariffs due to disruption in global supply chain, will weaken India's competitiveness in Green Hydrogen exports. Thus, there is need to ramp up domestic manufacturing of essential solar industry components long with the development of Green Hydrogen.

7.8. Water Availability

Around 8.92 litres of demineralized water is used for production of each kg of hydrogen. Thus, Water becomes a very critical resource in hydrogen production. Considering its limited availability and multiple application areas, overall long-term availability water for the sector needs to be kept in overall planning. Wastewater or seawater can be processed by setting up Desalination plants for electrolysis .(Upadhyay and Joshi, 2021)

8. Impact of Green Hydrogen on various Industries.

The immediate and most significant impact of green hydrogen will be on Refining Industry not only in India but also across the world. Presently grey and blue hydrogen is being used in the refining industry. Considering the same Refining companies like BPCL, Reliance have started investing in development of green hydrogen projects. These industries will benefit if they will have captive or in-house green hydrogen production capability. Green Hydrogen economy is likely to cause huge disruption in coal and petroleum-based industries. In addition once the complete ecosystem of Fuel cells based vehicles is developed then there is a risk that even the currently evolving electric vehicles may also become redundant. In addition the renewable energy industry and battery storage industry will see potential acceleration in near term and entire value chain in the Green Hydrogen in long term.

9. The way ahead

Despite of all the challenges as discussed above, Green Hydrogen provides an excellent opportunity to our country to become energy leader in the world. The way ahead requires a coordinated effort and a strong alliance between industries, academia, R&D institutes, and government on the research and development of Green Hydrogen, its storage, transportation and in various applications in India. Major research is required in Fuel cells for vehicles to ensure the entire value chain is economically viable. Further all the agencies should work in a coordinated manner to ensure that the future investments as well as Research and Development in the Indian energy sector is oriented towards green hydrogen(Gupta, 2021).

In addition considering the overall energy matrix and the challenges associated with development of Green Hydrogen , at present it should not be considered as the best and only solution for the India's energy needs but as a complementary and a further addition to the green energy alternatives available till the technology matures and is affordable.

As the storage and transportation technologies for Green Hydrogen are long way away from being economical and cost effective , therefore the co-located production and utilization of hydrogen needs to be encouraged as of now which will help to safeguard investments against undesirable sunk costs(Upadhyay and Joshi, 2021). Potential industrial clusters can be identified or small hydrogen hubs can be created across the country like the hydrogen valley model adopted in Europe. This will converge the production, transportation and end use of Green Hydrogen in a single region and help inf reducing costs and other challenges associated with the transportation of Green Hydrogen (Agrawal and Sharma, 2022).

There is further requirement of a mandated blending of fixed percentage of green hydrogen in key sectors. Greenfield projects should use green hydrogen from a future cutoff date. Production Linked Incentive scheme should be incorporated for giving impetus to local manufacturing of electrolyzers . As Green Hydrogen cost is directly linked to that of the cost of renewables especially solar , therefore import dependency of solar modules and components should be reduced and tariffs should not increased. The export of green hydrogen should be based on Dollar linked contracts for hydrogen procurement. In applications and usage of Green Hydrogen, Government near term should focus on Refinery and Fertilizer sector. 100% Green Hydrogen should be mandatory in new urea & refining capacity as well as Blending mandate for old plants in urea and refining should be given. In medium term focus should be on green steel and in long term on Heavy duty vehicles and seasonal storage. The sector also requires establishing a credit worthy aggregator like SECI as well as Long term tax and duty incentives (WRI India, 2021).

Storage of hydrogen is also critical factor in its wider usage and further research is required to lower the storage costs and develop advanced materials. Hydrogen produced can be in different forms like compressed gas, cryogenic liquid, or chemical, All these require different and specific methods of storage and for further distribution, thus all these techniques need separate research for bringing down costs. (Gupta, 2021).The green hydrogen-producing value chain in India consists of renewable power plant, RE transmission infrastructure , electrolyser , hydrogen plant and reconversion. The competitiveness of green hydrogen industry will not only determined by RE tariffs, but also by each of these elements in the chain individually along with technological growth and right financing.

Raj, Lakhina, & Stranger, (2022) in their study for Niti Ayog and RMI on Harnessing Green Hydrogen Opportunities for Deep Decarbonisation in India suggests that India has the potential to become a major exporter of green hydrogen-based products as it has a strong manuacturing base and ample availability of cheap renewable sources. However, easy availability of long tenor and low-interest finance is the critical for viable green hydrogen projects. Till the time market oriented green hydrogen economy develops , SECI can be nominated to aggregate demand as offtaker. The study also recommends that Viability Gap Funding is required to ensure that the green hydrogen prices become equal to grey hydrogen prices. All states should also launch their own policies related to green hydrogen as well as standards for new products such as electrolysers, fuel cells, and other new products related to green hydrogen are required. Building a robust hydrogen economy and becoming key player in emerging global green hydrogen market would require focus on export of green hydrogen-embedded products in the near term and of green hydrogen itself in the medium to long term . Dollar-based tariffs for green hydrogen like the standard practice in the oil and gas sector; To further encourage the private sector, the government should establish an aspirational price decline target. Reduction or exemption of tax and duties like the GST and custom duties. Dollar-based tariffs for green hydrogen like the standard practice in the oil and gas sector as well as other measures such as revenue recycling of any carbon tax, low emission PPAs, and avenues for firming electricity supply including discounted grid electricity to complement VRE generation are required (Raj et al., 2022).

10. Limitations and Scope of Future Research

The literature available on Green Hydrogen is limited and authors had to rely on grey literature, newspaper articles and television reports etc. In addition, the sector and technology are in a nascent stage and many aspects related to the sector could have been missed out by the authors. The future researchers can study detailed implications of hydrogen economy in existing Industries. In addition, comparative analysis of status and support policies and incentives can also be studied . Detailed study is required on Green Hydrogen Supply Chain management, Storage and transportation. In addition research should also focus on pipeline transportation, risk assessment and mitigation and public safety.

11. Conclusion and Policy Implications

Green Hydrogen can be the future fuel to reduce India's dependency on fossil fuels and to achieve net zero emission target. .A huge renewable energy potential along with a stable and self-sustaining solar and wind energy industry gives India a unique chance to become global leader and exporter in near future. As it is still a niche technology and currently it is not economical. To achieve mass rollout and economies of scale, India needs to focus on a creating demand which can be initially based on a mandate /obligation across all sectors by the government. In addition the sector also requires a stable regulatory framework with right polices for market creation, reducing import dependency on raw material required in solar and electrolyzer industry along with due focus on research and development on the technology and green hydrogen supply chain. Indian government has taken a major step towards migration to green hydrogen based energy transition based by issuing green hydrogen policy in February 2022. Waiver of Inter State Transmission Charges(ISTS) , allowing developers to set up bunkers in port lands to explore export activities and banking facility are the major incentives that have been given ,which will help in increasing green hydrogen demand along and renewable energy installed capacity . Further to become technology leaders in hydrogen India also needs strong supply push and demand side policies . It also needs to ensure that adequate finance is available across the green hydrogen chain through both public and private funding .Policies and incentives for reducing import and promotion of solar and electrolyzer manufacturing in India are also required .Green Hydrogen is a sunrise sector in India and with all major industrial groups investing in green hydrogen and with the impetus and support given by government , the sector will grow manifold in coming years and help in attaining country’s twin goals of achieving energy security and decarbonisation as well as becoming energy exporter by 2030.

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BIBLIOGRAPHY

Agarwal, O.., Mulukutla, P., Malladi, K., 2022. Basics of Hydrogen Technology.

Agrawal, R., Sharma, S., 2022. OPINION: India’s Green Hydrogen ambition - Challenges and way forward [WWW Document]. ETEnergyWorld. URL https://energy.economictimes.indiatimes.com/news/renewable/opinion-indias-green-hydrogen-ambition-challenges-and-way-forward/93050915

Baruah, R., 2022. Adani Group ties up with Canada’s Ballard for hydrogen fuel cells in India [WWW Document]. Livemint. URL https://www.livemint.com/companies/news/adani-group-ties-up-with-canada-s-ballard-for-hydrogen-fuel-cells-in-india-11645461907159.html (accessed 3.28.22).

Biswas, T., Yadav, D., Baskar, A.G., 2020. A Green Hydrogen Economy for India Production Cost.

Business Today Desk, 2022. Nitin Gadkari drives India’s first hydrogen-powered car to Parliament [WWW Document]. Bus. Today. URL https://www.businesstoday.in/auto/story/nitin-gadkari-drives-indias-first-hydrogen-powered-car-to-parliament-327937-2022-03-30 (accessed 11.22.BC).

Cardoz, P.T., 2022. Need for Accelerated Investments for Green Hydrogen India [WWW Document]. Invest India Outlook. URL https://www.investindia.gov.in/team-india-

blogs/need-accelerated-investments-green-hydrogen-india (accessed 11.12.22).
Collins, L., 2022. China unveils national 2025 target for green hydrogen and new strategies for further H2 growth [WWW Document]. Recharg. News. URL https://www.rechargenews.com/energy-transition/china-unveils-national-2025-target-for-green-hydrogen-and-new-strategies-for-further-h2-growth/2-1-1189877 (accessed 3.27.22).
energy.gov, 2021. Hydrogen Storage [WWW Document]. Off. Energy Effic. Renew. Energy. URL https://www.energy.gov/eere/fuelcells/hydrogen-storage#:~:text=Hydrogen can be stored physically,pressure is −252.8°C.
Equitymaster, 2021. Five Indian Companies leading the Green Hydrogen Revolution [WWW Document]. Livemint. URL https://www.livemint.com/industry/energy/five-indian-companies-leading-the-green-hydrogen-revolution-11636369476063.html (accessed 3.28.22).
ET, 2022. India may soon become Middle East of Green Hydrogen [WWW Document]. ETEnergyWorld. URL https://energy.economictimes.indiatimes.com/news/renewable/india-may-soon-become-the-middle-east-of-green-hydrogen-report/89696952
Frangoul, A., 2022. Shell says one of the largest hydrogen electrolyzers in the world is now up and running in China [WWW Document]. CNBC. URL https://www.cnbc.com/2022/01/28/green-hydrogen-one-of-planets-largest-electrolyzers-up-and-running.html
Gerboni, R., 2016. Introduction to hydrogen transportation. Compend. Hydrog. Energy.
Ghosh, Ar., Chhabra, S., 2021. Case for a Global Green Hydrogen Alliance.
Green Hydrogen Catapult [WWW Document], 2021. . GreenH2Catapult. URL https://greenh2catapult.com/
Gupta, J.P., 2021. Hydrogen becoming a key enabler for a self-reliant India [WWW Document]. URL https://www.greenhydrogen-india.com/blogs/6831ec05-dfc4-49df-a1aa-0056d24ce4f0/
GWEC, 2021. Wind: The Critical Link to India’s Clean Energy Transition India Wind Energy Market Outlook 2025.
Hall, W., 2019. MAKE HYDROGEN IN INDIA: Driving India towards the clean energy technology frontier. TERI Policy Br. 1–12.
HYDROGEN’S PRESENT AND FUTURE IN THE US ENERGY SECTOR [WWW Document], 2020. . Shear. Sterl. URL https://www.shearman.com/Perspectives/2021/10/Hydrogens-Present-and-Future-in-the-US-Energy-Sector (accessed 3.27.22).
IEA, 2021. Hydrogen-More Efforts Needed.
IQAir, 2021. World’s most polluted countries & regions [WWW Document]. IQAir.
Kelly, A.C., Zhou, Y., 2022. Hydrogen fuel for transport in India.
Kumar, R., 2022. Green hydrogen policy and way ahead [WWW Document]. New Indian Express. URL https://www.newindianexpress.com/business/2022/feb/27/green-hydrogen-policy-andway-ahead-2424148.html (accessed 3.28.22).
Kurup, R., 2022. Corporates are making a beeline for green hydrogen [WWW Document]. Financ. Express. URL https://www.financialexpress.com/industry/corporates-are-making-a-beeline-for-green-hydrogen/2730135/ (accessed 11.20.22).
Moda, G., 2022. How can India unlock its green hydrogen ambitions? [WWW Document]. EY India. URL https://www.ey.com/en_in/energy-resources/how-can-india-unlock-its-green-hydrogen-ambitions (accessed 10.18.22).
MoP, 2022. Green Hydrogen Policy.
Patel, S., 2021. Countries Roll Out Green Hydrogen Strategies, Electrolyzer Targets [WWW

Document]. Power. URL https://www.powermag.com/countries-roll-out-green-hydrogen-strategies-electrolyzer-targets/

Prasad, R., 2021. Adani group aims to be one of the largest green hydrogen producers in the world [WWW Document]. Econ. Times. URL https://www.livemint.com/companies/news/adani-group-ties-up-with-canada-s-ballard-for-hydrogen-fuel-cells-in-india-11645461907159.html%0A%0A (accessed 3.28.22).

Priya, L., 2021. India's National Hydrogen Mission and Prospects for Cooperation with GCC. Manohar Parrikar Inst. Def. Stud. Anal.

Raj, K., Lakhina, P., Stranger, C., 2022. Harnessing GREEN HYDROGEN.

Rajshekhar, M., 2021. INDIA NEEDS TO STEP ON THE GAS TO WIN THE GLOBAL GREEN HYDROGEN RACE [WWW Document]. CarbonCopy. URL https://carboncopy.info/india-needs-to-step-on-the-gas-to-win-global-green-hydrogen-race-2/?s=08

Ralston, J., 2022. Hydrogen for transport [WWW Document]. Energy Clim. Intell. Unit. URL https://eciu.net/analysis/briefings/transport/hydrogen-for-transport

Reuters, 2021. China's Sinopec targets 500,000 T of "green" hydrogen capacity by 2025 [WWW Document]. Reuters. URL https://www.reuters.com/business/sustainable-business/chinas-sinopec-targets-500000-t-green-hydrogen-capacity-by-2025-2021-06-09/

Sarkar, S., 2022. India's initiatives on green hydrogen could help global decarbonisation [WWW Document]. Mongabay. URL https://india.mongabay.com/2022/11/indias-initiatives-on-green-hydrogen-could-help-global-decarbonisation/ (accessed 11.20.22).

Satyapal, S., 2017. Hydrogen: A Clean, Flexible Energy Carrier [WWW Document]. Off. Energy Effic. Renew. Energy. URL https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier#:~:text=Hydrogen is an energy carrier,electricity%2C or power and heat.

Sridhar, V., 2022. Ballard to Supply Fuel Cell Modules for India's First Hydrogen-Powered Trains [WWW Document]. Mercom India. URL https://mercomindia.com/ballard-supply-fuel-cell-indias-hydrogen-trains/

Subrahmanyam, S.N., 2022. Going Green: How India can gradually shift to renewable energy [WWW Document]. Econ. Times. URL https://economictimes.indiatimes.com/industry/renewables/going-green-how-india-can-gradually-shift-to-renewable-energy/articleshow/88949214.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst (accessed 2.3.22).

The Ten Point Plan for a Green Industrial Revolution [WWW Document], 2021. . Dep. Business, Energy Ind. Strateg. URL https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title#point-2-driving-the-growth-of-low-carbon-hydrogen

Upadhyay, M.K., Joshi, P., 2021. Green Hydrogen: Opportunities and Challenges for India [WWW Document]. Financ. Express. URL https://www.financialexpress.com/opinion/green-hydrogen-opportunities-and-challenges-for-india/2341349/

Varadhan, S., 2022. India plans to produce 5 mln tonnes of green hydrogen by 2030 [WWW Document]. Reuters. URL https://www.reuters.com/business/energy/india-plans-produce-5-mln-tonnes-green-hydrogen-by-2030-2022-02-17/

WRI India, 2021. India's Approach to Green Hydrogen, with Mr Amitabh Kant, CEO, Niti Ayog. India.