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Research Paper

Green Hydrogen: Augmenting the Fuel's Supply Chain

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ABSTRACT
Purpose: *The world is heading towards a major environmental changeover, leading towards a clean, low carbon source of energy. In the volatile market of fossil fuels, alternates to run the entire world is being explored, of which EV and Hydrogen is being considered as the favoured fuel system*(TERI, 2020). *India is taking a lead in this sector, by focussing on the green hydrogen, with aim of reducing the* CO_2e *and becoming a carbon neutral economy whilst simultaneously becoming a leader in production and supply of green hydrogen, globally. Green Hydrogen can abate 3.6GT of cumulative* CO_2e *by 2050, while providing a cost effective solution to the energy sector*(PIB, Green Hydrogen Is Critical to India's Economic Development and Net-Zero Ambitions: Report, 29 Jun 2022) *India is presently, looking forward to lead from the front on producing green hydrogen through state incentives and private investments in which it has already allocated funds for this sector, with 19700 crores being allocated in the Budget for FY 2023-24 for production and infrastructure development of green hydrogen. Some of the leading Indian companies have already started working towards production of green hydrogen. Plans are already underway to systematically increase the tempo in this sector by gradually replacing fossil fuels with green hydrogen in Industries, mining, transport and others. The case study looks into the Why, Where, When, What and How of the present value chain of the clean fuel and efforts being planned and undertaken for subsequent development and distribution of the same.*
Practical Implications:*Indiais gradually progressing towards becoming a carbon neutral economy, with its focus on developing an alternate fuel i.e Green Hydrogen. The Indian industries are also gearing up to meet the goal of becoming a world leader in developing and distributing green hydrogen. The challenges/ impediments that are required to be overcome with the plans in focus have been considered in the ibid case study.*
Keywords: *Green Hydrogen, Environmental Concerns,* CO_2 *emissions, Energy Transformation, Fossil Fuels, FCEV, Supply Chain, Value Chain*

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I. Introduction

1. The Government of India (GoI) approved the National Green Hydrogen Mission on 04 January 2023 and approved `19,700 crore rupees as a part of the national budget 2023(SIRU, 2023). This mission's objective is not only cutting down on carbon emissions and augmenting renewable sources of energy but making India the global hub for the production of green hydrogen under the aegis of the Ministry of New and Renewable Energy (MNRE)(Hindu, Centre clears ₹19,744-crore Green Hydrogen Mission, 2023).MNRE has seen hydrogen as an area of strategic interest since 2006 when it drew its first Hydrogen and Fuel Cell Roadmap and 2016 published a comprehensive R&D plan (TERI, 2020). Incidentally, India is the largest consumer of Hydrogen in the World(Jayakumar, Green hydrogen costs to halve to ₹160-170 per kg by 2030, 2022) but

Financial Outlay: NGHM

Total Outlay- `19,740 Crores

- **Strategic Interventions for Green Hydrogen Transition (SIGHT) Programme – `17,490 Crores**
- **Upcoming Pilot Projects – `1,466 Crores**
- **R&D – `400 Crores**

Figure 1 Financial Outlay ((Hindu, Centre clears ₹19,744-crore Green Hydrogen Mission, 2023) why is Green Hydrogen[1] being emphasised is because of its capability to slow down global warming, replacing fossil fuels. It can be used as fuel cells (breaking water into Hydrogen and Oxygen, generating electricity) in the transport sector as well as in the case of industries replacing coal. If that is the case, then where lies the delay in bringing this fuel into the market is the question that requires to be answered. The answer is the production and distribution cost of Hydrogen as they are high in terms of not only production but also infrastructure(ET, 2021), which costs ranging from `320 to `330/kg which is estimated to be cut down to as low as `160 - `170/Kg(Jayakumar, Green hydrogen costs to halve to ₹160-170 per kg by 2030, 2022).

2. How is Hydrogen Produced is not the main question but what impact it has on the environment and how energy efficient the quality depends upon how it is produced. There are several ways in which hydrogen is produced, viz Natural Gas Reforming/ Gasification[2], Electrolysis[3], Renewable Liquid Reforming[4], and Fermentation[5] are a few existing methods, High-Temperature Water Splitting[6], Photobiological Water Splitting[7] and Photoelectrochemical Water Splitting[8] are a few methods under development. The primary challenge worldwide is reducing the cost of production of Hydrogen, by employing environmentally friendly methods. As far as distribution is concerned it is being distributed in the US through three methods, viz, Pipeline, High-Pressure tube trailers and Liquified Hydrogen Tankers(USDE, 2023). As far as India is concerned, KPMG in its report titled "***India's Green hydrogen Ambition- Setting the Wheels in motion***" has laid down a comprehensive plan for increasing R&D in India with critical areas of focus onefforts to augmentthe green hydrogen economy with firm measures to develop a local supply chain to ensure indigenous capabilities(Watch, 2022).The green hydrogen demand comprises 20-30% of the overall hydrogen demand in India and is expected to jump to 12 mn Tonnes/annum (MTPA)(Jayakumar, Green hydrogen costs to halve to ₹160-170 per kg by 2030, 2022)Presently grey hydrogen[9]in India costs `160-200 per Kg but impinges on the cost of Natural Gas that is available @US $ 10-13/MMBtu, whereas, green hydrogen production costs `230-240 per Kg which is estimated to reduce to `160-170 per Kg by 2030, which come at par with grey hydrogen(KPMG, 2022).

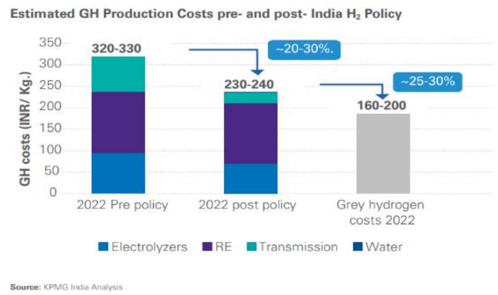

Figure 2: Estimated GH Production Costs pre- and post- India H_2 policy

Why Shift to Green Hydrogen?

3. **The Volatility of Crude Oil**: As per experts crude oil prices are volatile and thus impose a major concern to the global economy(News, 2022). India has been facing an increase in the import of crude oil, primarily, due to its domestic production volume decreasing(Jagmohan, 2022),to 116.6 mn tonnes (by 15%) with the bill surging to $90.3 billion (76% increase) in the first half of 2022-23. In the second half of 2022, the quantum of import of crude oil became stagnant at 17.6 million tonnes, however, the value of crude oil increased by 38% from the previous FY, i.e $12.8 billion in September(News, 2022).

[1]Hydrogen produced from electrolysis of water using renewable electricity

[2]Synthesis gas—a mixture of hydrogen, carbon monoxide, and a small amount of carbon dioxide—is created by reacting natural gas with high-temperature steam. It can also be created by reacting coal or biomass with high-temperature steam and oxygen in a pressurized gasifier. This converts the coal or biomass into gaseous components—a process called gasification.

[3]An electric current splits water into hydrogen and oxygen; basis of Fuel Cell technology.

[4]Renewable liquid fuels, such as ethanol, are reacted with high-temperature steam to produce hydrogen near the point of end use.

[5]Biomass is converted into sugar-rich feedstocks that can be fermented to produce hydrogen.

[6]High temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split water to produce hydrogen.

[7] Microbes, such as green algae, consume water in the presence of sunlight and produce hydrogen as a by-product.

[8] Photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sunlight.

[9]Grey Hydrogen is created from Natural gas, or Methane(fossil Fuel) and is most common form available commercially(National Grid, 2023).

4. **Environmental Concerns**: Hydrogen is Critical for decarbonizing prohibitively costly sectors such as aviation, steel, Heavy trucking Chemicals etc, that create 20% of CO2e (7Gt of CO2e/year), globally and has been identified as one of the solutions that would help us limiting to 1.5^0C[10](RMI, 2023) and India can decarbonise it's hard to abate energy-intensive sectors such as industry, power and transport by using green hydrogen(Tirtha Biswas, 2020). As per the 27^{th} Conference of Parties, Report (COP 27) at Sharm-El-Sheikh, Egypt, India's Levels are to Go Up By 6% In 2022(Perinchery, 2022). The annual emission change in million tonnes of CO_2 fell by 30 MtCO2e in 2020 which was the first time since 1982(Tiseo, 2020)and with 2.4tCO2e, India is far below the World average of 6.3tCO2e and half of the G20 average in 2022(Standard, 2023) (Refer Fig 3). The projection of 40.6 GtCO2 total emissions in 2022 is close to the highest-ever annual total of 40.9 GtCO2 in 2019(PTI, 2022). India aims at achieving Carbon neutrality by 2070, however, India continues to presently rely on fossil fuels for energy security with

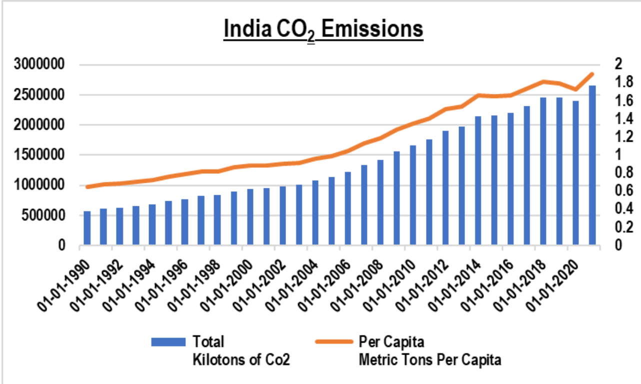

Figure 4: Indian CO2e Source (Macrotrends, 2023)

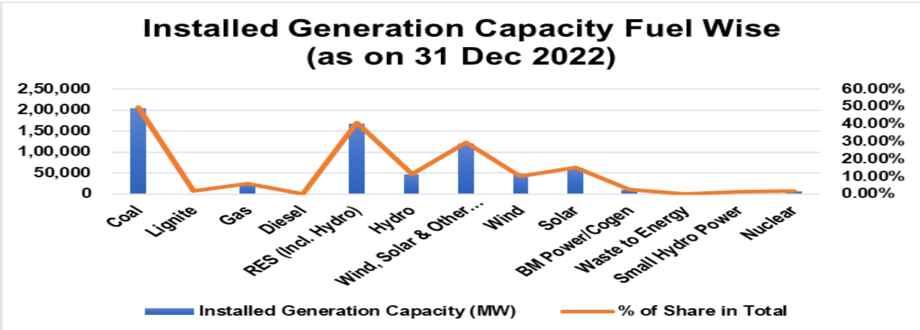

Figure 3 Installed Generation Capacity Fuel Wise(MoPower, 2023)

only 17% being produced through renewable energy sources out of a total of 400 GW of capacity with the same increasing to 3000-4000 GW in next decade(Jayakumar, India's Green Future, Built On Hydrogen, 2022). The CO_2 emission is expected to reduce by 4,650 $MtCO_2e$ in 2020-30 if India achieves 28% power generation by Non-Renewable sources (CEEW, 2019-20) .CEEWR[11]estimates 19% of India's energy needs to be met by green hydrogen between 2050-2070 and India would require $1.5 trillion for creating a green hydrogen setup for its industries.

5. India is presently relying on grey hydrogen (6.7MT),mainly being utilised by refineries, chemical companies and fertiliser plants, which is likely to increase to 23 MT by 2050, through green hydrogen. Green Hydrogen presently accounts for 0.1% of Global Hydrogen Production (Jayakumar, India's Green Future, Built On Hydrogen, 2022), which reached 94Mt in 2021, with 6% of Natural Gas and 2% of coal being used to produce grey/ black hydrogen respectively(Gil, 2022). Most of this demand was met by grey hydrogen, which still harmsthe climate(IEA, Sept-2022). India presently looks to lead from the front in producing green hydrogen through state and private incentives, playing an important role in decarbonising its industries. The Government announced its long-term low-emission development strategy with a target of producing 25 Mn Tonnes by 2047 in 2021 and adding 175 GW of green hydrogen-based energy in the next decade(Sarkar, 2022). Green Hydrogen has the potential, being a low-cost, low Carbon footprint option, to make a paradigm shift in the steel, shipping, aviation and fertilizer sector economies, by transforming the energy system (RMI, 2023). As

> "Green hydrogen can help to reduce emissions from hard-to-abate sectors such as steel and fertilisers. It can also help in greening long-haul freight and transportation,"
> Srinivas Krishnaswamy, CEO, Vasudha Foundation

[10]In 2015 at the United Nations climate summit in Paris, an agreement aimed to keep global temperature rise below 2^0 C above pre-industrial levels with an effort to limit it even further to 1.5^0 C by the end of the 21st century in order to prevent the worst of climate impacts(Deborah Ramalope, 2022).

[11]Council for Energy, Environment and Water Research, New Delhi based Not-for-profit Think Tank

Per NITI Aayog Green hydrogen can reduce CO_2 emissions by 3,6 Gigatons by 2050 (PIB, Green Hydrogen Is Critical to India's Economic Development and Net-Zero Ambitions: Report, 29 Jun 2022). NGHM also aims to promote the development of hydrogen through water electrolysis, steam methane reforming and biomass gasification alongwith financial and technical support to various companies due to R&D on green hydrogen(SIRU, 2023).

Energy Transformation Potential of Green Hydrogen

6. Green Hydrogen is being considered as an alternate fuel of the future as not only would it shift the focus of power generation from fossil fuels(RMI, 2023) but also would be comparatively more economical thananother Non-renewable source of power generation. This can be established by the mere fact that 1 kg of Hydrogen gas can produce the same amount of energy as produced by 2.8 Kg of Petrol. Moreover, the gas having a low volumetric density can be easily stored in compressed form to be used in transport, aviation and other hard-to-abate sectors. These tanks can be filled in comparatively less time to a capacity of 5000 psi. For this reason, the US Government in its Energy Policy act of 1992 had considered hydrogen as an alternative fuel(USDE, 2023). If we look at the technology learning curve of green hydrogen has an S-curve profile[12]wrt cost reduction and scaling, i.e the scale of the innovation rapidly(Yuki Numata, 2022), with learning rates estimated at 13-18%(RMI, 2023)post arriving at "tipping points"(Yuki Numata, 2022) which can create large opportunitiesfor the fuel as at \$2.60/kg, green hydrogen is already crossing the economic thresholds wrt other hydrogen variants and is likely to approach levels that could dwindle the value chains of industries such as steel etc in the coming decade(RMI, 2023). This is because a reducing trend in the cost of fuel has been observed which implies that the innovation has progressed from a nascent stage to the creation of new markets by linking early supply and demand. Being versatile, green hydrogen has the potential the transform systems and value chains over time and therefore massive scaling, opening new value pools(RMI, 2023). The demand for green hydrogen is likely to expand in new industrial applications viz, Fertilizers (green ammonia plants), Steel (hydrogen-based steelmaking methods with commercial production), Shipping (Companies such as Maersk are putting green methanol-powered ships in service by 2025), Aviation (Airbus ZEROe programme employing hydrogen-combustion propulsion system)(Yuki Numata, 2022). However, all the ibid discretions impinge on the premise that the policymakers don't lose the vision to make early investments, inordinate obligations that might slow the changes in systems threatening the value chains already in place.

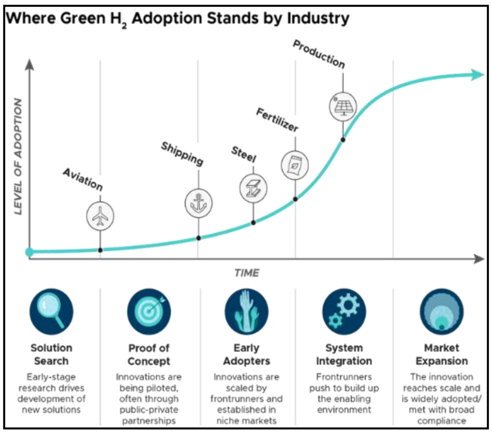

Figure 5 Green Hydrogen Adoption stands by Industry (Yuki Numata, 2022)

7. **Opportunities and Initiativesin Green Hydrogen: Production, Economy and Challenges**

7.1. **Production:** The Indian Intellect and thinkers have rightfully assessed the gainsin the renewable energy sector, based on its current progress, that green hydrogen is bound to make an impact on the nation's overall energy sector. It is presumed and appreciated that under the "Make in India" program India is likely to capture the global market by commencing the production of electrolyzers[13] and fuel cells.In this, the abundant sea resource available to the Indian subcontinent can now be optimally utilised in the production of electrolysis, postR&D(Ujjwal Sontakke, 2021). Already Indian companies have geared up and are in the race for green hydrogen production. The 10 top companies are(Jain, 2022):-

7.1.1. **Reliance Industries Ltd**–Company is constructing Dhirubai Ambani Green Energy Giga Complex in Jamangar for the production of green hydrogen, with assistance from various companies viz, Faradion, Lithium Werks, REC Solar Holdings etc

7.1.2. **GAIL –**Building a PEM-based project supporting a 10 MW capacity production of green hydrogen through the mixing of Natural Gas, at Guna, MP. This would be the largest energy generation in India.

[12]S Curve implies that the technological progress is gradual abinitio, then rises rapidly and thereafter subsequently flattens

[13]Electrolyzers consume about 9 liters of water to produce 1 kg of hydrogen.

7.1.3. **NTPC –** Planning to produce green hydrogen through a floating solar project through a 240 kW of solid oxide electrolyzer.

7.1.4. **IOC –** Planning to convert their refineries at Panipat and Mathura, targeting to achieve 5GW of renewable energy generation by 2025.

7.1.5. **L&T –** Setting up a plant at Hazira, Gujarat can produce 45 kgs of green hydrogen daily. This plant would generate power through a process blending 15% hydrogen with natural gas.

7.1.6. **Adani New Industries Ltd** – The company has entered into a partnership with Total Energies, France to produce 1MT of green hydrogen annually by 2030.

7.1.7. **JSW Steel** – Their subsidiary JSW Energy is in collaboration with an Australian company for working on the potential project.

7.1.8. **Jindal Stainless** – To bring down CO_2e by 2700 MT/annum, the stainless company has partnered with Hygenco India Private Ltd to set up plants of green hydrogen.

7.1.9. **ONGC** – Has signed an MoU in July 2022 with M/s GreenkoZeroC Private Limited, to explore the opportunities to make green hydrogen and its derivatives. This MoU, for two years, would make India a centre for green hydrogen on a worldwide scale.

7.1.10. **BPCL** – Plans to setup 5 MW electrolyzer plants for the production of green hydrogen, in phases at Ahmedabad and Aurangabad. This gas would be produced for commercial, domestic and industrial purposes.

7.1.11. **Oil India Ltd (OIL)**: Has commissioned India's first 99% pure green hydrogen plant in Assam's Jorhat (Hindu, Insights Editorial Analysis: Green Hydrogen: Fuel of the future, 2022)

7.2. The various sectors, which pose an opportunity to fruitfully adopt green hydrogen technology: -

7.2.1. The Automobile sector is the one that is likely to be targeted ab-initio amongst the major sectors in the fray to decarbonise. In road transport, the EVs are now trying to make their way into the marketand are more developed and in an advanced stage than Fuel Cell Electric Vehicles(FCEV) which are hydrogen-powered (Green/blue hydrogen). However, the FCEV technology is scaling up faster(Jain, 2022), as EVs don't have the endurance to travel a longer distance with heavier loads, hence, the shift towards hydrogen fuel(Wood, 2022). The first indigenously developed Hydrogen FCEV wasrolled out in Pune in 2022. This vehicle has been developed by CSIR in association with KPIT private ltd(News18.com, 2022). Fuel Cells technologies that are presently available or under development are protein exchange membrane fuel cells (PEM), phosphoric acid fuel cells, and alkaline, solid oxide are a few common types of FCs available in the market(Jain, 2022). Globally, the maritime sector is also focussing on the adoption of green hydrogen-based fuels to be completed by 2050(Champions, 2022). The other major sector that holds potential is the aviation sector, where hydrogen-derived biofuels[14]hold the potential to fly larger and longer(Wood, 2022). Airbus[15], presently developing an ambitious hydrogen-powered, zero-emission aircraft, likely o enter service by 2035, is presently looking at India amongst other global markets, as a source for green hydrogen(PTI, 2022). HDW, Germany in 2004 introduced the U212 and U214 variant fuel cell-powered submarines, that run on 34kW Siemens PEM FC. The submarine has the potential to remain submerged for up to 3 weeks(Atlas, 2004). It is appreciated that FCEVs are likely to become cost competitive in the coming years and with a fully indigenised supply chain, would form the basis for a clean transportation segment. Under the GoI initiative,6 Cell buses by TataMotors Ltd., 50 hydrogen-enriched CNG (H-CNG) buses in Delhi by Indian OilCorporation Ltd. in collaboration with Govt. of NCT of Delhi, 2 hydrogen-fueledInternal Combustion Engine buses (by IIT Delhi in collaboration with Mahindra &Mahindra) have been developed as a technology demonstrator. (PIB, National Hydrogen Mission, 2023). The CNG-powered vehicles in India are likely to be benefitted most, as they can run on hydrogen-blended CNG[16] with

[14] A 60 MW electrolyzer plant powered by North Sea offshore wind farms (Netherland based) to produce 100,000 tonnes of green hydrogen aviation biofuels / year is likely to be commissioned by 2024(Wood, 2022)

[15]Airbus has entered a partnership agreement with HyPort to set up low-carbon hydrogen production and distribution station at the Toulouse-Blagnac airport in France

[16]The CNG engine was tested with 18% hydrogen blended CNG. It was found that there was 5% reduction in fuel consumption, 20% reduction in CO_2e an d10% increase in NO_xe

some modifications. Even the existing CNG filling stations can be converted to HCNG fuel stations[17](Ujjwal Sontakke, 2021).

7.2.2. The Indian Industry is likely to replace fossil fuels with Green Hydrogen, which would reduce the Fossil-Fuel imports being used for steel, fertilizers, and petrochemicals. The total demand for coking coal for the steel industry was 58.37 MT of which 51.83 MT is ex-import. Moreover, 15% of the 15MT of Ammonia consumption for fertilizer production is being met through imports(PIB, National Hydrogen Mission, 2023).Presently,India imports 85% of its oil, 50% of its natural gas and 30% of its coal(WMW, 2021). The indigenised produced hydrogen is likely to be priced competitively, globally, which would enable Indian industries to shape up around exports of green hydrogen and hydrogen embedded low carbon commodities, for which the government is required to invest in early pilots and explore procurement conduits to meet the demand(EnergyWorld, 2022). Dutch hydrogen provider HyGear and Indian bioenergy technology, GPS Renewables are developing state of art green hydrogen projects in India(WMW, 2021).

7.2.3. Development of Green Corridors is also being contemplated in the maritime sector, wherein, fuels, vessels and infrastructure are being developed for a mass-market rollout for full decarbonisation of the maritime sectors(Fahnestock, 2022). India is also gearing up for the same with NGHM identifying shipping as a potential sector for pilot projects. It intends to setup green ammonia bunkering facilities in at least one port by 2025 with similar facilities to be created in all major ports by 2035(news I. s., 2023). The Hydrogen Energy Supply Chain (HESC), a joint projectof Japan and Australiato ship hydrogen via sea route from Australia to Japan. The HESC is being developed in two phases, initially as pilot and thereafter on a commercial scale (NITI Aayog, 2022).

"If Green Corridors succeed, in 2030 zero-emission shipping will be a commercially viable option anywhere"

7.2.4. Green Hydrogen is also being viewed as an opportunity to foster India's strategic aim to defeat China's String of Pearl Strategy by building a global value chain for countries of the third world especially African nations to adopt green hydrogen as fuel of future. India and Africa have long shared close ties, engagement between the two regions is yet to reach its full potential. However, amid the global green transition and attempts to enhance energy security, green hydrogen—increasingly seen as the 'fuel of the future'—could provide a new avenue for cooperation between the regions. Such a partnership, focused on building a global value chain for the large-scale adoption of green hydrogen, will accrue long-term socioeconomic benefits for India and African countries.

7.3. **Economy:** Post COP27, suddenly green hydrogen has come to the limelight, with the member nations now giving precedence in the production of the fuel of the future. India has been using few clean energy technologies viz, solar, wind, and lithium-ion batteries etc, and has albeit seen the costs of these technologies fall (refer to figure 6) but these were being developed and manufactured by technologies that have occurred largely outside India, most of which comes from China(TERI, 2020), as per NITI Aayog and RMI's Harnessing Green Hydrogen report,India is in a good position to translate these costs into a globally competitive green hydrogen industry (EnergyWorld, 2022). The green hydrogen mission is likely to fetch $96.6 billion by 2030 through public and private sector investment in electrolyzer and green hydrogen production(news I. S., 2023). However, High technology costs, risk of undesirable sunk cost, absence of dedicated government policy, and lack of public awareness have been significant barriers in front of India's hydrogen economy.Hydrogen trains are considered more cost-effective than electric trains (Wood, 2022)., The NGHM aims to create favourable policies and regulatory environmental conditions to foster the growth of hydrogen in India, including tax incentives and a reduction in import duties besides establishing hydrogen manufacturing and distribution pan India. It also is endeavouring to create a skilled workforce, having requisite technical and professional skills(SIRU, 2023). As per the data available due to the competitive levelised cost of electricity and

The opportunities around green hydrogen are palpable and real and so are the challenges. Policy Push is needed on both the demand and Supply
Source: (EnergyWorld, 2022)

[17] India has only 2 fuelling stations that are used majorly for research purposes. Indian Oil R&D Center, Faridabad; National Institute of Solar Energy, Gurugram.

electrolyser costs are likely to decline, and hence, it is more beneficial to produce green hydrogen vis-à-vis blue/grey hydrogen. Albeit challenges in fray, (NITI Aayog, 2022).

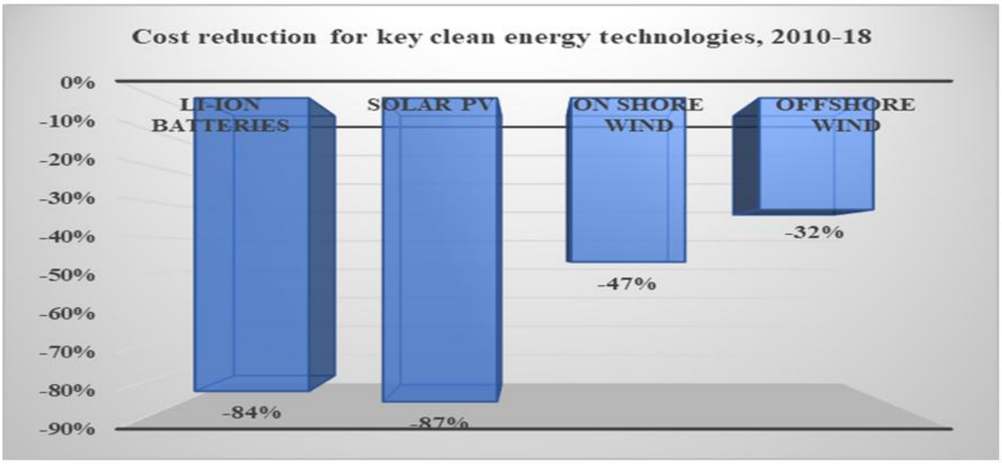

Figure 6: Source (TERI, 2020)

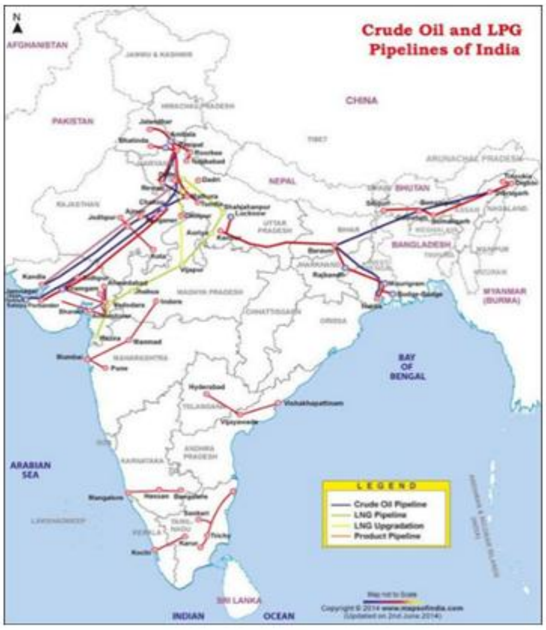

Figure 8: Distribution of Petroleum & Mineral oil in India (pmfias, 2018)

7.4. **Challenges**: Green Hydrogen, even though promises a better alternative to fossil fuels, poses incredible challenges, because of high costs, complex supply chain management, policies and regulatory environmental conditions, that need to be addressed: -

7.4.1. There is a lot of scope for R&D in the production of Green Hydrogen. is still in the nascent stages, with ongoing efforts to reduce cost of production, storage and transportation of hydrogen(Hindu, Insights Editorial Analysis: Green Hydrogen: Fuel of the future, 2022). The low knowledge of optimal plant designs, limited market demand and the anticipated returns have made production more costly and stringent(Sylvie Ouziel, 2021). Albeit, India is a budding pivot for production of Green Hydrogen; it doesn't have the wherewithal to sustain its production, to include safety and financial security(Ujjwal Sontakke, 2021).

7.4.2. The cost of electrolysers (ranging between \$7/kg & \$4.10/kg) and electricity has a significant impact on Green Hydrogen prices. Besides this, there are operating costs, cost of transmission and distribution, GST and electricity tariffs(NITI Aayog, 2022). Producing these indigenously through renewable power generation capacity would reduce the cost considerably(Ujjwal Sontakke, 2021)

7.4.3. The storage and distribution are another grey area that merits concern due to the characteristics of hydrogen gas, being highly combustible, lower density, embrittlement and ease of diffusion. The setup requires massive investment in infrastructure upgrades.(NITI Aayog, 2022).

7.4.4. Monetising Green hydrogen is a challenge in itself as the fuel can be cost-effectively produced in sunny places, requiring an exclusive pipeline network, related lead times and costs. The processes are still in the nascent stages and prone to a lotof criticism/ debates(Sylvie Ouziel, 2021).

7.4.5. There is a likelihood of increase in demand of hybrid vehicle using both fossil fuel and fuel cell, in future, which would affect the global supply chain of crude oil and Natural Gas(Ujjwal Sontakke, 2021).This is further augmented by the lack of supporting infrastructure, which is still underdeveloped(Hindu, Insights Editorial Analysis: Green Hydrogen: Fuel of the future, 2022).

7.4.6. In media res, an insecure demand may not lure the shareholders, as there is a likelihood of them getting usurped due to lack of interest in expensive alternatives.

8. **Impediments in Introduction of Green Hydrogen Commercially in the Market**: In order to make Green Hydrogen commercially available in short-time duration, India needs to identify and address the impediments that would delay the introduction of the fuel in Indian market: -

8.1.1. India has a limited skilled workforceand infrastructure to support the production as well as sustenance of Green Hydrogen, including storage and transport(Sylvie Ouziel, 2021).

8.1.2. Being a highly flammable gas with low volumetric density, it requires special pipelines as well as carriers(Sylvie Ouziel, 2021). The low volumetric density makes the gas volatile and exorbitant to handle. (Ujjwal Sontakke, 2021).

8.1.3. The Supply chain is a complex process resulting in significant loss of energy at almost every stage of the supply chain :-

Hydrogen is today enjoying unprecedented momentum. The world should not miss this unique chance to make hydrogen an important part of our clean and secure

8.1.3.1. The typical efficiency of electrolyzers is between 75-80%(Franz, 2018); 30-35% of the energy used to produce green hydrogen is lost during this process(Sylvie Ouziel, 2021), 5-35% lost during compression /cooling (Franz, 2018), conversion to Ammonia- about 13-25% and transportation amounting to 10-12% of hydrogen's energy. It is also opined that there would be an additional 40-50% energy loss in the use of fuel cells.

8.1.3.2. In direct feed of the gas, conversion efficiency of 70% is assumed and with the heat produced during reconversion process another 50% is lost, which arrives to an overall efficiency of 35%(Franz, 2018).

8.1.4. If we draw a comparison between Hydrogen technology and other renewable /non-renewable fuel sources; the drop in lithium batteries prices of around 20% / year, less storage costs and efficiencies above 90%, makes it a preferred choice. Moreover, the market prices of Natural Gas have also fallen worldwide, due to fracking and LNG transport, whereas, the high cost of water electrolysis, hydrogen, abinitio, might not be a preferred alternate economic choice(Franz, 2018).

8.1.5. The techno-commercial challenges to the trade of green hydrogen globally, unlike Australia and US, is a green field venture (NITI Aayog, 2022).

Augmenting the Green Hydrogen Supply Chain: Proposals andInitiatives by India

9. The impediments and challenges as brought out above can be addressed by harnessing significant renewable energy to supply green hydrogen electrolyzers to compete with end-use electrification(Sylvie Ouziel, 2021). The implementation of new improved technologies and research. Government policies and regulations will play a major role in the whole development. Under the FAME India scheme, the Government of India

provides attractive subsidies on electric vehicles to increase awareness and acceptance in its population. Such kind subsidies, if given will encourage the building of a market for hydrogen fuel cell vehicles and hydrogen infrastructures. India under "Make in India" initiative is developing the semiconductor industry in India, which is also looking forward to Green Hydrogen as a reliable and cheap renewable energy source (Vaishnaw, 2023). With Lithium deposits now found in India, near Reasi, of 5.9 million tonnes, India's initiative towards providing cheaper EV to the consumers, fosters the semiconductor chip industry initiative of India as also paves way for the introduction of green hydrogen in Indian market(Reuters, 2023).

10. It is estimated that Indian Green Hydrogen,could by 2030 and would by 2050, be competitive at the margin for select geographies such as Australia, US (NITI Aayog, 2022). India needs to take the following measuresto augment the Fuel's supply chain: -

10.1. Cost reduction in the production of green hydrogen by taking steps to improve upon measures such as inter-state transmission charges waivers, subsidies, open access for green hydrogen as well as green ammonia production to reach a price of less than \$1/kg by 2050 (NITI Aayog, 2022).

10.2. Aligning the transport technologies by identifying opportunities where EV/battery technology would be workable solution in tandem with green hydrogen and where green hydrogen would take the lead. in all major sectors. As per TERI Analysis (FTI, Dec 2020)

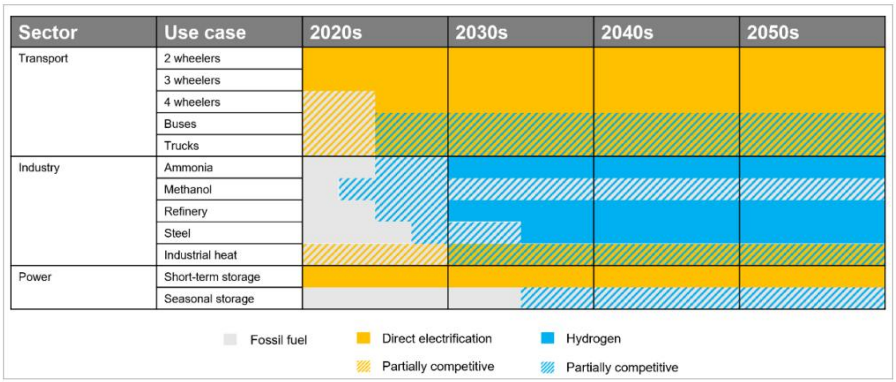

Figure 8: TERI Analysis (FTI, Dec 2020)

10.3. Make its industrial ports the nerve center for beefing up the usage of green hydrogen and reducing the costs of its production (iea, 2019).

10.4. Infrastructure, new as well as existing Natural Gas pipelines can be utilised to transport hydrogen demand and drive down costs (iea, 2019). Pipelines are typically reserved for high volume flows and are one of the fastest and cost-effective methods to transport such like gases.

10.5. Focus on Automated IoT(AIoT), such as Digital Twins to model multiple designs and scenarios to minimise risk and maximise returns on investments. AIoT offers rapid real time monitoring, sensors to detect anomalies, reducing costs by 10-20% through lower energy consumption and streamlined workforce. The real-time data to automate input to GoO (Guarantee of Origin) issuers to ensure end -to-end traceability along the entire life cycle of the green hydrogen from womb to tomb(WEF, 2021).

11. A roadmap has already been formulated for augmenting the green hydrogen supply chain in India. GoIintends to:-

11.1. Implement it in a two phased manner (MNRE, Jan 2023): -

11.1.1. Phase I (FY 2022-23 to 2025-26) – Incentives aiming at indigenisation of the value chain & increasing Green Hydrogen's domestic production. Also lay foundation of future energy transitions giving impetus to required R&D in all hand-to abate sectors.

11.1.2. Phase II (FY 2026-27 to 2029-30) – Allowing accelerated growth in production of Green Hydrogen and intensifying dissemination across all major sectors with scaled up R&D activities.

11.2. Integrate mission strategy that encompasses all concerned ministries, departments agencies and institutions under Central and State Government for coordinated efforts in achieving the ibid mission.

11.3. Aims to identify and develop Green Hydrogen hubs and ports infrastructure capable of supporting large scale production. These would be mapped under PM Gati Shakti to ensure optimum and synchronized development (MNRE, Jan 2023).

11.4. Aspire to launch 10 potential H_2 national projects that includes(FTI, Dec 2020)(NITI Aayog, 2022):-

11.4.1. H_2 India Trucking Project for manufacturing10,000 H_2 powered (FCEV) heavy duty truck fleet with infrastructure on Delhi -Mumbai Industrial Corridor (DMIC), to include refuelling stations, storage and H_2 system components.

11.4.2. 1000 H_2 industrial clusters in ports, logistics, steel, fertilisers, mining sectors.

11.4.3. 1000 mobile FCEVs for heavy duty machinery. Equipment, plant fleet/trucks in steel, fertilisers, mining clusters.

11.4.4. Municipal bio-gas hydrogen projects.

EV-hydrogen bi-mode Freight Trains along the DMIC – a possibility

A similar H2Bharat Rail Consortium (starting with rail freight) along the same corridor, bringing together India Railways and other private operators could also be explored. Bi-mode trains that run on both electric/ batteries and hydrogen have already been launched in Europe. India could aspire to have an aspirational 10 electric-hydrogen bi-mode freight trains within the next decade

(FTI, Dec 2020)

11.4.5. 10% (100 MMT) Coal gasification H_2 projects to be converted for green H_2 production.

11.5. Aims to introduce fiscal incentives for large-scale national H_2 projects and formation of an industry consortia (FTI, Dec 2020), developing a cluster-based production and utilisation model keeping technical and logistical challenges of transporting hydrogen over large distances, helping in economies of scale along with converging critical infrastructure requirements in geographically areas in vicinity(MNRE, Jan 2023).

11.6. Creating demand of the fuel in both global (100 MMT) and domestic (5MMT) markets by 2030 with an aim to potentially export around 10 MMT of Green Hydrogen/Ammonia per annum. The export of fuel and its derivatives would also facilitate building up strategic partnerships globally(MNRE, Jan 2023).

11.7. Aim to develop a comprehensive incentive programme facilitating growth of the fuel's industry value chain by launching specific incentive schemes to support domestic production of electrolysers and production of green hydrogen(MNRE, Jan 2023).

11.8. Undertake Risk mitigation in(MNRE, Jan 2023):-

11.8.1. Supply Chain disruptions in critical inputs through diversification of supply chains.

11.8.2. Operational level risks wrt water/ land availability through optimising locations of production plants and land banks.

11.8.3. Market risks mitigation through various incentives in creating domestic manufacturing ecosystem.

II. Conclusion

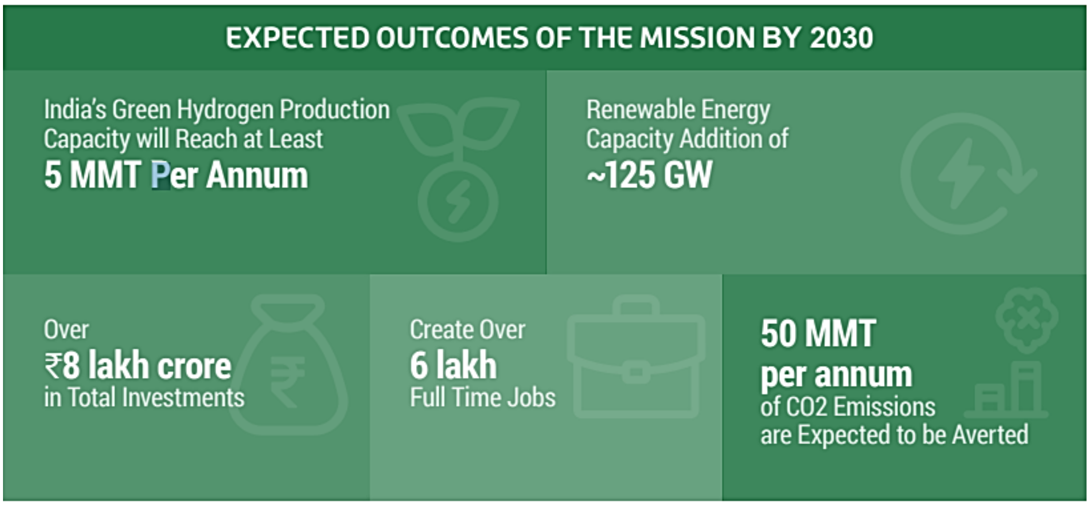

Figure 9 :(MNRE, Jan 2023)

12. The ambitiousNational Green Hydrogen Mission promises to provide the requisite momentum as well as responsiveness towards the emerging trends in the geoeconomics of energy to reap the benefits of green hydrogen opportunity(EnergyWorld, 2022). Green Hydrogen would play a critical role in facilitating India's energy transition through industrial competitiveness while simultaneously focussing on achieving net zero CO_2e in stipulated time frame. The way India is progressing in this sector has been recognised world over who are now placing big-bets and investing in hydrogen-based technologies. A policy push is what was required both on the demand and supply side which is being targeted with the launch of the National Green Hydrogen Mission(NITI Aayog, 2022). Production of electrolysers,albeit in nascency, is emerging, India needs to invest in R&D, material value chain, and increasing demand in the domestic market to take on the ever-increasing costs of fossil fuels, reduce imports from China which is aggressively inching towards leadership position, andalso achieve net zero carbon emission(EnergyWorld, 2022). India's immediate steps in these directions and pertinent policy decisions will set the context for the role of green hydrogen in energy transition effectively. While it is imperative that India pushes ahead, the government has to ensure mass manufacture and a firm supply chain in place to enable cost reductions and the alternate fuel becomes the only preferred fuel available

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