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A Roadmap to Develop Green Hydrogen Infrastructure to Drive Sustainable Solution for Transport Sector in India

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Abstract

India ranks third at the global level in terms of highest emission levels across all the sectors and has set an ambitious target to achieve carbon neutrality by 2070. The major sectors that account for the higher level of emissions include Power, Industry, Transport, etc. The emission from the transport sector is about 315 $MtCO_2eq$, which represents approximately 10% of the total national emissions. The road sector accounts for a significant 85% of these emissions and is a focus area for the government. India targets to achieve zero emission in transport sector by 2047 and is currently implementing different fuel options like Liquified Petroleum Gas (LPG), Compressed Natural Gas (CNG), Liquified Natural Gas (LNG), etc. while also exploring emerging technologies like battery electric vehicles, hybrid versions and green hydrogen. While battery electric vehicles and their hybrid versions are already under different stages of adoption, green hydrogen technology is still under development with lot of serious attention from government as well as private sector. Government of India has also allocated ₹19,744 crore ($2.5 billion) for developing green hydrogen infrastructure and expect this technology to be viable by 2030 to cover various sectors like transport, refineries, fertilisers, steel, and chemicals. This paper aims at utilizing green hydrogen as an alternate technology option that results in zero emission and presents a roadmap for implementing the green hydrogen infrastructure for road transport sector at the national level. Different aspects of green hydrogen infrastructure like production using electrolyzers, transport, storage, refuelling, etc. are evaluated along with the financial analysis and a comprehensive roadmap for adoption of green hydrogen is presented.

***Keywords**: Greenhouse Gas, Green Hydrogen, Electrolyzer, Light Duty Vehicles, Medium Duty Vehicles, Heavy-Duty Vehicle*

Introduction

There is a focus to minimize the adverse effects of climate change, such as extreme weather events, rising sea levels, and disruptions to ecosystems. To address global climate issues, an agreement was adopted in 2015 (Paris) also called Paris agreement, during COP 21 under the United Nations

Framework Convention on Climate Change (UNFCCC). 196 nations participated and committed to limit global temperature rise to well below 2°C above pre-industrial levels and pursuing efforts to restrict global warming to 1.5°C. The participating nations also agreed to take responsibility to develop their respective implementation strategies to achieve the same. Greenhouse Gas (GHG) Emission refers to the release of gases into the atmosphere that contribute to the greenhouse effect and global warming. These gases, like carbon dioxide (CO_2) and methane (CH_4), trap heat within the earth's atmosphere, causing a rise in global temperatures. The global GHG emission has increased from 50,134 $MtCO_2eq$ in the year 2000 to 53,786 $MtCO_2eq$ in year 2022 (Fig.1). Carbon dioxide (71%) is the major contributor to the GHG followed by Methane (21%) based on the global GHG data for the year 2022 even though each country has initiated significant steps towards reduction of GHG. It is also observed that based on GHG emission data for 2022 (Fig.3), China (29.2%) leads in GHG emission followed by USA (11.2%) and India (2.5%) [1-4].

The GHG emission in India has increased from 3,390 $MtCO_2eq$ in 2015 to 3,943 $MtCO_2eq$ in 2022. Total GHG emission in India in 2022 was 3,943 $MtCO_2eq$. The major contributors were power industry (31.8%), industrial (14.8%) and transport sector (7.6%) in the year 2022 (Fig.4). India has committed to achieving net zero emissions by 2070 at the COP26 climate summit in 2021. The major steps initiated by India include increasing the renewable energy capacity to 500 GW to meet 50% of energy demand by 2030 and reduce carbon emission by 1 BT by 2030 resulting in reduction in the carbon intensity of economy by 45% by 2030. Industries in India have also launched several efficiency improvement and emission reduction programs to reduce the GHG emission to meet the national target [3,4].

India Transport Sector

India transport sector comprises of road, domestic aviation, railways and IWT. In 2022, this sector produced about 299 MtCO2eq of GHG emission, which is 7.6% of the country's total emission levels. The road transport accounted for almost 85% (Fig.5) due to high consumption of fossil fuels like petrol and diesel followed by domestic aviation (12%), railways (2%) and Inland Waterways Transport (1%). All these transport sectors are developing and implementing their respective strategies to achieve carbon neutrality.

Domestic Aviation Sector

Indian domestic aviation industry is aiming to become a net-zero carbon emitter by 2050. The key focus areas include introducing more fuel-efficient aircrafts and exploring alternative propulsion systems like electric and hydrogen-powered aircraft. This sector is also exploring to adopt Sustainable Aviation Fuel (SAF) produced from sustainable feedstocks consisting of used cooking oil, waste animal fats, municipal solid waste, and agricultural residues. Other operational measures like improving air traffic management, optimizing flight routes, and reducing avoidable ground delays through implementation of Artificial Intelligence (AI) would also help in emission reduction.

Indian Railways

Indian railways aim to become a net-zero carbon emitter by 2030. The major approach is to achieve complete electrification of all broad-gauge tracks. Railways have also planned to install 20 GW of land-based solar plants (114 MW of solar rooftop plants already installed) and wind power plants on railway land and rooftops to meet its energy needs. Due to their increasing consumption of renewable energy, there is a plan to transport cargo and include higher passenger traffic (like metro rail, etc.). Railways have implemented various energy-efficient technologies and practices. They are also exploring to use green hydrogen (GH2) as a fuel source and are developing railway engines that use GH2.

Inland Waterways Transport

Inland Waterways Transport (IWT) sector is aiming to become a net-zero carbon emitter by 2050. Their contribution to GHG is lowest amongst all transport modes, so their strategies include shift bulk cargo movement from rail/road to waterways like coal, iron ore, major commodities, Liquid Petroleum Gas (LPG), etc. IWT is working towards developing multimodal integration like improve last-mile connectivity with roads / railways. IWT is also exploring advance technology vessels like LNG-powered bulk carriers, electric ferries, etc., and GH2 powered passenger ferries. IWT has ambitious plan to transition 50% of passenger fleets to green fuels by 2034 and achieve 100% green fuel utilization by 2047.

Road Transport

Indian road transport sector is aiming to become a net-zero carbon emitter by 2047. The road transport has been steadily increasing over last several years and so has the GHG emission (Fig.6). This sector comprises of diverse types of vehicles like Two-wheeler (transport/commercial), Three-wheelers (transport/commercial), Light Duty Vehicles (LDV), Medium Duty Vehicles (MDV) and Heavy-Duty Vehicles (HDV). The LDV include small commercial vehicles, personal cars, utility vehicles, private taxis, etc. MDV include Mid-sized trucks for regional freight, Mid-sized utility vehicles and Minibuses, mid-sized passenger carriers. HDV include large trucks for heavy cargo transport, construction/ heavy-duty machinery, coaches, etc. Fig.7 depicts the growth of road transport sector in recent years, and it may be noted that the number of vehicles has increased from 2,15,30,093 (2022) to 2,61,28,085 (2024), based on the data reported by Ministry of Road Transport and Highways [9]. This does not include specialized/non-standard vehicles e.g. agricultural tractors, military vehicles, golf carts, amphibious vehicles, vintage cars, experimental prototypes, etc. which accounted for 48,116 in 2022 and 81,314 in 2024 [4]. It is also important to note that most of the vehicles use conventional fossil fuels like petrol and diesel. Fig.8 highlights the mix of vehicles based on emission levels and it may be inferred that almost 84% vehicles are in the high polluting category during the year 2024 though the number of low-emissions and zero-emission vehicles has also increased since 2022. Ethanol is used for blending and the same up to 20% is already achieved in India. Liquified Petroleum Gas (LPG), Compressed Natural Gas (CNG), Liquified Natural Gas (LNG) are other fuel options that are also being considered. Hybrid options including batteries have also been introduced.

Though these options would result in reduction in GHG emission levels, country needs to explore other options to achieve net-zero target. Therefore, industry needs to develop alternate fuel that qualifies as clean fuel and provides a sustainable solution to the road sector.

GH2 is considered as an alternate option and is under various levels of development across the globe. Some of the vehicle manufacturers claim to have developed GH2 vehicles, however their commercial use is very limited or at an experimental stage. Table 1 shows the applicability of different fuel/technology options for vehicles and the same is summarized below:

- Two-wheelers: Petrol and BEV
- Three-wheelers: Petrol, Diesel, LPG, CNG and BEV
- LDV: Petrol, Diesel, LPG, CNG, Hybrid, BEV, GH2
- MDV: Diesel, BEV, GH2
- HDV: Diesel, BEV, GH2

This paper aims at developing a roadmap for GH2 for India to prepare the country meet the net-zero targets for the transport sector.

India Green Hydrogen (GH2) Program

With the growth in India's population and urbanization, the transport sector's contribution to emissions is likely to increase further. NITI Aayog, India presented a report in 2022 that was a result of about 12 months of intensive consultative analysis and concluded that with proactive collaboration among innovators, private sector participation and government, GH2 would be one of the new technologies that can drastically reduce CO_2 emissions, NitiAayog stressed the need to develop world’s largest electrolyzer with annual manufacturing capacity of 25 GW by 2028, world’s largest electrolysis (GH2 production) capacity of over 60 GW/5 million metric tonnes by 2030 for domestic consumption, and almost $1 billion investment into hydrogen research and development to enable breakthrough technologies like GH2 [2].

India has launched National Green Hydrogen Mission in 2023 that aims to provide a comprehensive action plan for developing a Green Hydrogen ecosystem to respond to the challenges of high emission due to fossil fuels. The target is to produce 5 million metric tonnes of GH2 by 2030. A significant portion of renewable energy (125 GW) is allocated to power hydrogen production. This is expected to reduce 50 million tonnes of CO_2 every year. Budgetary allocation to the tune of ₹19,744 crore (~$2.3 billion) is also allocated for establishing this infrastructure. The primary sectors that are expected to be covered include transport, refineries, fertilisers, steel, and chemicals. Few states like Andhra Pradesh, Gujarat, Karnataka, Kerala, Maharashtra, Odisha, Tamil Nadu, etc. have also been identified to drive this program. The program aims at developing pilot projects for long-haul heavy-duty transportation in road, railways, inland waterways transport (IWT) and domestic aviation [5]. After the launch of national GH2 mission, different states have come up with their respective plans to drive GH2 program [6].

The major advantage of GH2 as a fuel are that the main byproduct is water, making it a cleaner and sustainable alternative to fossil fuels. It may also be possible to utilize the existing ICE infrastructure, making the transition to a GH2 system less disruptive.

GH2 Engines for Road Transport

There are two types of technologies used for GH2 powered vehicles: GH2 – Internal Combustion Engine (GH2-ICE) and Fuel Cell Electric Vehicle (FCEV). They are under different stages of development several research programs are underway to develop these vehicles by different manufacturers.

GH2-ICE

It combines the concept of using GH2 as a fuel source with traditional internal combustion engine (ICE) technology for use in vehicles. This is the traditional type of engine found in many vehicles, where fuel is burned to create mechanical energy to power the vehicle. This technology aims to adapt existing ICE technology to run on GH2. Instead of gasoline or diesel, the engine would burn hydrogen, potentially offering a way to utilize existing infrastructure while reducing carbon emissions.

Fuel Cell Electric Vehicle (FCEV)

FCEV combines the technology of a fuel cell electric vehicle (FCEV) with the use of GH2 as a fuel source. GH2 is produced using renewable energy, making the entire system a zero-emission solution for transportation. An FCEV is an electric vehicle that uses a fuel cell to generate electricity. Instead of relying on a battery that needs to be charged from the grid, an FCEV has a fuel cell that combines hydrogen and oxygen to produce electricity, with water being the only byproduct.

GH2 Production

GH2 production can be scaled up to meet the growing demand for clean energy in the transportation sector. The most popular technology for production of GH2 utilizes process of electrolysis. There are three different types of electrolyzers that are under different stages of development. These are:

- Alkaline,
- Solid oxide, and
- Polymer exchange membrane (PEM)

Table-2 summarizes the comparative analysis for these three production techniques. It may be noted that PEM has a distinct advantage of flexible operation that can help in effective utilization of renewable energy as these are variable and unpredictable [7]. Therefore, GH2 production by polymer electrolyte membrane (PEM) electrolysis process is widely accepted as the viable technical process. In this process, water is electrochemically split into oxygen and hydrogen. Hydrogen is produced at the cathode, and oxygen is produced at the anode. In the presence of a catalyst, water at the anode splits into protons (H+), electrons (e-), and oxygen. This process operates at a high pressure and temperature range between 20-1000^{0}C. The protons are carried to the cathode by the proton-conducting membrane. At the cathode (negative terminal), the electrons combine with hydrogen protons (H+) to produce H_2. On the other hand, the electrons travel from the anode via an external power circuit, providing the cell voltage for the reaction. The major cell components of this process include membrane electrode assemblies, which are separated into cathode and anode, gas diffusion layers (current collectors), and separator plates [8]. The reactions taking place inside the cell are:

At cathode $2 H^+ + 2 e^- \rightarrow H_2$ At anode $H_2O \rightarrow 2 H^+ + ½ O_2 + 2 e^-$

Overall reaction $H_2O \rightarrow H_2 + ½ O_2$

Transporting GH2

A pipeline network infrastructure development would be the best option to supply to multiple industrial sites and refuelling stations. This grid can allow flexible operation, and several production facilities can feed GH2 into the network and can supply the gas to multiple customers at different locations. If GH2 cannot be consumed directly, then Cryogenic tanks would need to be installed to store GH2. The liquid hydrogen is efficiently stored in such vacuum-insulated tanks and can be transported with active cooling. For bulk storage of GH2, underground caverns are a potential option. The gas must be purified and compressed before storing into the cavern.

Refueling Stations

Several GH2 fuelling stations need to be developed for fast, efficient and successful GH2 vehicle deployment.

Financial Analysis

The current cost of GH2 in India ranges from ₹200 per kg. It may be noted that LDV can cover about 100 km using 1 kg of GH2.

Several factors influence the cost of GH2 production:

- Renewable energy cost: Cost of renewable electricity is a major component of GH2 production, highlighting the importance of optimizing renewable energy sources and costs.
- Electrolyzer technology: Advancements in electrolyzer technology are crucial for reducing production costs. Optimizing renewable energy sources and improving electrolyzer efficiency are critical for cost reduction.
- Balance of plant costs: These include costs associated with the infrastructure

needed for GH2 production, such as water treatment and gas handling systems.

- Transportation and storage costs: These costs can significantly impact the overall cost of GH2, especially for large-scale projects.

The current cost of GH2 in India ranges from ₹200 per kg. The major cost component is the price of electrolyzer which currently costs 40,000 ₹/kW. The cost of solar energy is also about 1.9 ₹/kWh. These costs are expected to reduce to 10,000 ₹/kW for electrolyzer and cost of solar energy to 1.5 ₹/kWh by 2030. This sector is further expected to receive additional incentives from government through complete transmission and distribution cost waiver and reduced GST @ 5%. This should reduce the price of GH2 to ₹120 per kg making it competitive with other competing fuels [8].

Several manufacturers in India both in government and private sector have initiated various programs to produce GH2 in the country. Some of the vehicle manufacturing companies are focussing on GH2 vehicles, while technology companies are developing solutions to produce GH2 in a cost-effective manner. Some of the companies are driving refuelling program as they currently own and operate refuelling stations to sell petrol, diesel, CNG, LPG, etc. Developing robust infrastructure for transportation and storage is essential for scaling up GH2 production and utilization.

India Green Hydrogen (GH2) Roadmap

Indian road transport sector is aiming to become a net-zero carbon emitter by 2047 and GH2 is viewed as a potential disruptive technology that is making significant progress. The adoption of GH2 requires a road map that need to be developed to meet the target timelines. This would require development of adequate infrastructure and national level polices to provide momentum to implementation of this program. This section presents the recommended roadmap that should be implemented to achieve net-zero, as planned.

Following key assumptions are made for the development of the roadmap:

- GH2 technologies would be applicable to LDV, MDV and HDV segments only.
- BEV would cover all the segments primarily two-wheelers (100%), three-wheelers (100%) and LDV (80%). Some MDV (50%) and HDV (20%) may also be covered by BEV.
- Based on the trend during the period 2022-2024, LDV, MDV and HDV segments are expected to grow at a CAGR of 8%, 6% and 4% respectively until 2050.
- It is also considered that the commercial vehicles would be phased out in 10 years and private vehicles would be replaced on an average after 15 years.
- Total GH2 demandis projected at 5 million metric tonnes of annual production by 2030 and 90 million metric tonnes of annual production by 2040.

- GH2 vehicles would be commercially available by the end of year 2030 and this would include development of GH2 vehicles, electrolyzers and establish GH2 production capacities in different states, create few GH2 refuelling stations and implement demonstration projects.
- Phase-1 (2031-35) shall be the initial phase of commercial implementation and is expected to be provide valuable learnings from initial implementation and as such the growth is expected to be slower during this period. LDV, MDV and HDV may segments may witness penetration levels of about 5%, 12.5% and 20% respectively. This would be achievable provided adequate GH2 production capacity is allocated to transport sector and about 100 refuelling stations are set up on the national highways that connect major cities. It would be important to target metro cities and state capitals for initial roll-out. Utilization of existing refuelling stations with a possibility to convert them to store GH2 should also be considered.
- Phase-2 (2036-40) shall witness faster growth. LDV, MDV and HDV may segments may achieve penetration levels of about 10%, 25% and 40% respectively. This would be achievable provided higher GH2 production capacity is allocated to transport sector and at least a total of 500 refuelling stations are set up on the national and state highways that connect major tier-1 and tier-2 cities. Develop GH2 highways to provide momentum to the program ensuring nearly 100% coverage of MDV and HDV segments.
- Phase-3 (2041-Onwards) the GH2 technology should have achieved full maturity level and as such. LDV, MDV and HDV may segments should be able to achieve penetration levels of about 20%, 50% and 80% respectively. This would be achievable provided higher GH2 production capacity is allocated to transport sector and total of 1000+ refuelling stations are set up on the highways to connect the rest of the country

Fig.9-11 shows the expected demand growth in LDV, MDV and HDV segments during 2031-2050 and the expected share of GH2 vehicles in these respective categories. Fig.12 shows the overall demand and share for GH2 vehicles between 2030-2050.

With the increasing growth of GH2 vehicles in the country, the demand for GH2 would also increase, Fig.13 shows the demand projection for GH2 between 2031-2050. Fig.14 indicates the quantity of GHG that can be avoided due to establishment of GH2 infrastructure. With 5 million metric tons of GH2 market @₹120 per kg, the GH2 economy is expected to kick-start at a significant $ 7B after 2030.

Conclusions

A clean transport system would need coordination between different transport systems (Road, Aviation, Railways and IWT) and the town planning needs to incorporate these aspects effectively. While the key issues around road transportation in India include different challenges like lack of smart traffic solutions and insufficient public transport, and connectivity resulting in traffic congestion, safety concerns, and long travel time. More numbers of vehicles on the roads have impacted the air quality in many Indian cities creating serious health and environmental issues. Moreover, the fleet is ageing and so resulting in higher level of emissions. LDV, MDV and HDV heavily depend on diesel that cause higher pollution and shifting to other fuels like LPG, CNG and LNG would help reduce the emission level in short-term. GH2 provides a clean and sustainable solution and requires the desired infrastructure to be developed until 2030. The production of GH2 at economical price would drive the success of the program. Pilot projects for downstream use of solar thermal and green hydrogen in different segments need to be implemented. Some clarity on the higher cost resulting from the giving up of the use of fossil fuels as well as the potential for cost reduction with scale would emerge on completion of pilot projects.

The production of renewable energy at economical costs is already more or less achieved. Also, the development of fuel efficient GH2 vehicles would be extremely important. Allocation of GH2 to transport sector would be a key step as GH2 is likely to support railways and IWT apart from road transport to provide a sustainable solution. Further refineries, fertilisers, steel, and chemicals would also need the GH2 for their process needs. As such the requirement of GH2 would increase exponentially resulting in further cost reduction. Considering the advantages of GH2 for heavy-duty, long-haul vehicles, certain routes may be designated as Hydrogen highways. The necessary GH2 production projects, distribution infrastructure and refuelling stations may be built along such highways. Financial assistance would be needed to promote GH2 vehicles in the initial years. The learnings from the pilot projects would also be extremely important as the users would need to learn about the operational aspects including safety in view of the new technology adoption. While GH2 would majorly address the GHG emission due to LDV, HDV and HDV, the remaining transport segments would need to be addressed by BEV to achieve the net-zero target by 2047.

Creation of sinks through afforestation would be one option. Carbon capture and storage and carbon capture utilization and storage would be the other options. These may need to be utilized for the last steps in the journey to becoming net zero and contribute to India continuing to display climate leadership while accelerating its transition to becoming a developed globally competitive green economy.

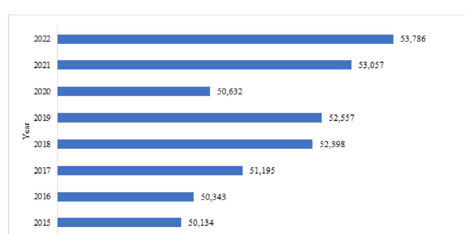

Figure 1 Global GHG emission ($MtCO_2eq$)

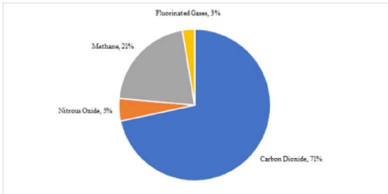

Figure 2 Average GHG emission mix in 2022

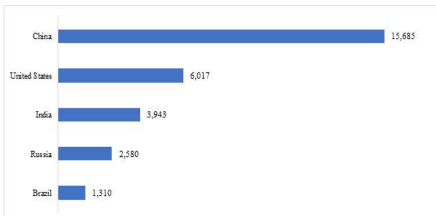

Figure 3 Major GHG ($MtCO_2eq$) emitting countries in 2022

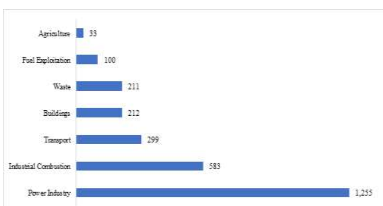

Figure 4 Sector-wise GHG Emission ($MtCO_2eq$) in India in 2022

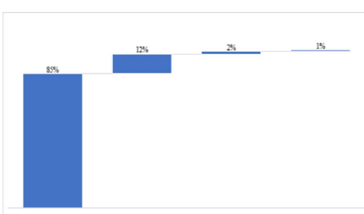

Figure 5 Sector-wise GHG Emission (%$MtCO_2eq$) in India in 2022

Figure 6 GHG Emission in India from road transport

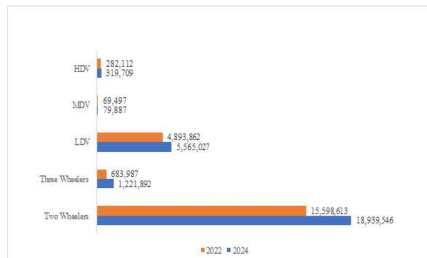

Figure 7 India road transport vehicles mix in the years 2022 and 2024

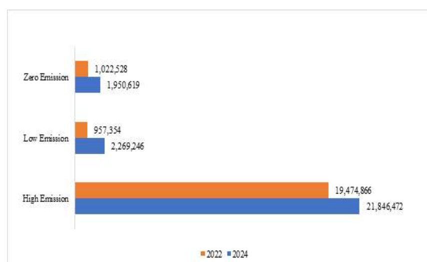

Figure 8 Category of vehicles based on emission in India in the years 2022 and 2024

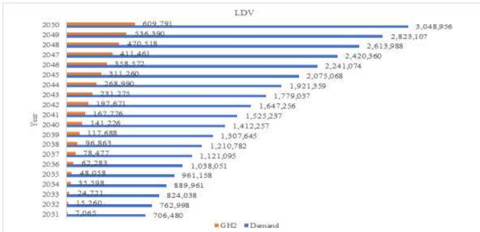

Figure 9 Expected growth of number of GH2 LDV between the years 2031-2050

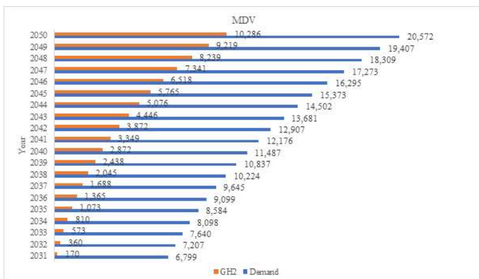

Figure 10 Expected growth of number of GH2 MDV between the years 2031-2050

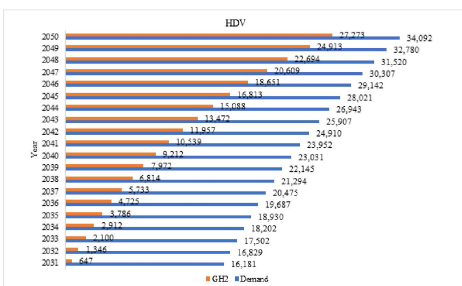

Figure 11 Expected growth of number of GH2 HDV between the years 2031-2050

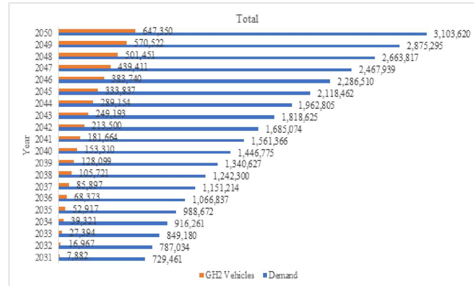

Figure 12 Total number of GH2 Vehicles required between the years 2031-2050

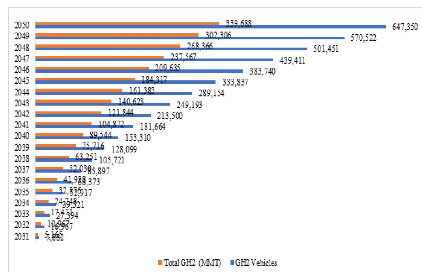

Figure 13 Total GH2 demand between the years 2031-2050

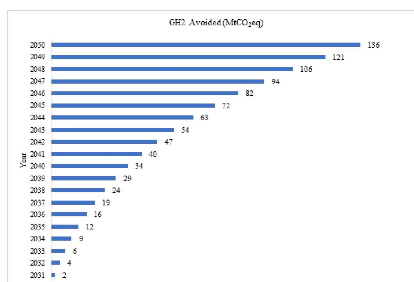

Figure 14 Total GHG avoided aue to addition of GH2 vehicles between the years 2031-2050

Table 1 Technology applicability for different vehicles and fuel options

Emission	Fuel	Technology Applicability				
		Two-Wheeler	**Three-Wheeler**	**LDV**	**MDV**	**HDV**
High	Petrol	ü	ü	ü	û	û
	Diesel	û	ü	ü	ü	ü
Low	LPG	û	ü	ü	û	û
	CNG	û	ü	ü	û	û
	LNG	û	û	û	û	ü
	Hybrid	û	û	ü	û	û
Zero	BEV	ü	ü	ü	ü	ü
	GH2	û	û	ü	ü	ü

Table 2 Different types of Electrolyzers for GH2 production

Criteria	Alkaline	Solid oxide	PEM
Electrolyte	KOH (20%–30%)	Yttria (Stabilized Zirconium)	Polymer Nafion
Current efficiency (%)	60	80	55
Specific energy Consumption system (kWh/Nm^3)	4.5–7.5	2.6–3.5	5.8–7.3
Technology maturity	Fully commercial	Laboratory scale	Demonstration scale
Catalyst	Ni/Co/Fe, Ni/C-Pt, Non-noble metal	Ni-Cu	Platinum, Iridium oxide
Operating cost	Low	Medium	High
Advantages	Mature technology High nominal output	High efficiency	Highest H_2 purity High load gradient: Ideal for fluctuating renewable energy systems

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