Green hydrogen economy and opportunities for India

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Abstract. With increasing numbers of vehicles on roads, India is facing the issue of large vehicular emissions. The burning of crude oil is the major issue behind these emissions. India doesn’t have enough resources to fulfill all the energy demands of vehicles and hence, imports crude oil from oil-rich countries. To tackle the issues associated with oil imports and vehicular emissions, there is a need to search for carbon-free alternate fuel that is available locally in sufficient quantity to meet India’s energy demands. The green economy is a new concept evolving and gaining attention worldwide, the concept focuses on sustainable and environmentally friendly solutions. Hydrogen is such a carbon-free fuel that can help to achieve the targets of the green economy and the best means to store energy for a long time. Hydrogen is a high energy content fuel and has about zero greenhouse gas emissions when used in fuel cells. Hydrogen is not directly available in free form, but it can be produced using electrolyzers and various other techniques. India’s continuously growing renewable power generation capacity gives the advantage to produce hydrogen from green sources like solar, and wind at the time of lower demand. The present review work focuses on the opportunities for India in green hydrogen production as the adaption of green hydrogen offers many benefits to India including energy security, and decarbonizing the transport sector.

Keywords. Green Hydrogen, Green Economy, Fuel Cell, Energy Security, Alternate fuels, Renewable Energy.

Nomenclature

PEMFC Proton Exchange Membrane Fuel Cells
IC Engine Internal Combustion Engine
NOx Nitrogen Oxides
CNG Compressed Natural Gas
GHG Greenhouse Gases
FCEVs Fuel Cell Electric Vehicles
PHEV Plug-In Hybrid Electric Vehicles

1. Introduction

Global warming is an issue; the whole world is trying to resolve. India and China both represent around 36% of the total world population. India is also one of the largest emitters of greenhouse gases in the world. Considering, the population and pollution, it is the responsibility of India to take important steps to limit...
global warming. The burning of crude oil is one of the major reasons behind the large emission of greenhouse gases in India. To tackle the issues associated with global warming, many countries are now adopting the concept of a green economy. Hence, to effectively contribute to controlling global warming, along with other countries, India also needs to shift its focus on a green economy [1].

Globally, the automobile sector alone is responsible for 24% of CO₂ emissions while in India it contributes to 13.5% of total CO₂ emissions. General environmental management by reducing the net carbon emissions from the transport sector is an important consideration in the green economy. A large proportion of India’s energy demand depends upon fossil fuels as shown in Figure 1 [1,2].

![Figure 1. India's total installed power capacity from various renewable and non-renewable sources [2].](image)

To achieve a target of zero-emission, a hydrogen-based economy can make a great impact. Despite many advantages, the hydrogen-based green economy is still facing many challenges including hydrogen storage, commercialized acceptance in the Indian market, standards, regulating policies, safety, and cost. The low volumetric density of the hydrogen is the basic issue with its storage and limits the storage amount of hydrogen on board. The cost of fuel cell stack is a major concern, recently due to the developments and research, the cost of fuel cells has slightly reduced and is expected to be reduced further in future time. The mass production and cost-effective non-platinum catalysts can help to bring the cost down [3,4].

Considering the future scope of hydrogen in energy transition the current review work presents opportunities for India in the energy sector. Section 2 of the context represents the hydrogen as a future fuel option and focuses on hydrogen production, its storage and PEMFCs. Section 3 of the review is focused on using green hydrogen energy for Indian automobiles sector, its importance, and benefits. Section 4 of the review describes the opportunities for India in hydrogen energy and challenges related to them.

2. Hydrogen as a Future Fuel

The properties of hydrogen and its availability makes it better fuel for the future than other fuels. Hydrogen is a clean fuel with high energy density and can be used with both IC engines and fuel cells. With Fuel cells, water in the form of steam is only emittent whereas, in the case of IC engines, NOx is only emittent. Hydrogen is a light gas and non-toxic [5]. Table 1 of the context shows the properties of hydrogen and some other common automobile fuels. Clearly, hydrogen has the highest energy content and octane number when compared to other fuels. The only major issue associated with hydrogen is its low volumetric density.
Table 1. Properties of Automobile fuels [6].

| Properties          | Gasoline | Diesel | CNG     | Hydrogen |
|---------------------|----------|--------|---------|----------|
| Molecular Weight    | 100-105  | 200    | 16.04   | 2.02     |
| Specific Gravity    | 0.72-0.78| 0.81-0.89| 0.424   | 0.07     |
| Density (kg/m³)     | 715-780  | 800-890| 0.7-0.9 | 0.08375  |
| Energy Content      | 9.3 kWh/lit| 10 kWh/lit| 13.1 kWh/kg| 33.3 kWh/kg|
| Octane Number       | 86-94    | -      | 120+    | 130+     |
| Cetane Number       | 5-20     | 40-55  | -       | -        |

2.1. Hydrogen Production

There are various methods to produce hydrogen commercially. These production methods can use both renewable and non-renewable energy sources. But still, conventional fossil fuel dominates hydrogen production with the cost of 1.34 - 2.27$/kg (~₹100 – 200/kg). Hydrocarbon reforming and pyrolysis are the two most widely used and well-developed methods of hydrogen production. Hydrocarbon reforming converts hydrocarbon fuel through reforming techniques to produce hydrogen. Steam reforming involves a catalytic conversion of hydrocarbon whereas partial oxidation is the conversion of steam and hydrocarbon into hydrogen and CO₂. Auto thermal reforming involves exothermic partial oxidation which can increase the hydrogen production rate. Pyrolysis is another important technique in which hydrocarbons go under thermal decomposition [7,8]. Pyrolysis and hydrocarbon reforming both methods consume hydrocarbons but considering fossil fuel depletion and global warming, there is a need to switch on renewable sources for hydrogen production. Grid-based electrolytic hydrogen production is more cost-effective as it increases the utilization of electrolyzers when compared to only renewable power. The cost of hydrogen production from electrolyzers can fall up to the range of 12.6 $/kg (~₹900/kg), as it depends on electricity tariffs, transportation, and storage cost, etc. [9].

Table 2. Types of Hydrogen [10–12].

| Derived From   | Grey Hydrogen         | Blue Hydrogen        | Green Hydrogen      |
|----------------|-----------------------|----------------------|---------------------|
| Method         | Natural Gas           | Natural Gas          | Water Splitting and Renewable Power Electrolysis |
| GHG Emissions | Steam Methane Reforming High | Advanced Gas Reforming Low | Zero |
| Carbon Capture | CO₂ emitted in the atmosphere | CO₂ captured and stored | No CO₂ emissions |
| Cost of Production | ₹ 100 – 200 /Kg | ₹ 300 / Kg | ₹ 350 – 400 /Kg |

Table 2 shows the classification of hydrogen based on color codings and also clarifies the other information that includes the method of production, GHG emissions, carbon capture, and cost of production. The estimated cost of Grey hydrogen in India is around ₹150 – 200/kg and with the cheapest renewable power; the cost of green hydrogen is around ₹350/kg. Hydrogen production from green energy sources can successfully help to reduce the overall carbon emissions from vehicular emissions. Hydrogen from water electrolyzers is pure enough to be used in fuel cell electric vehicles. Whereas hydrogen from gas transport pipelines requires purification before end-use in FCEVs to remove odor, dust, etc. [7,8]. Figure 2 of the context represents the approximate cost of hydrogen production by different methods.
2.2. Hydrogen Storage

The main issue with hydrogen is its storage and transportation as hydrogen is a highly combustible gas. The very low volumetric density makes it difficult to store hydrogen even in small quantities. Liquid and compressed storage are widely used to store hydrogen on a large scale [13]. The hydrogen consumes a large volume even after compressing it at very high pressure. Commercially available fuel cell vehicles opt for 700 bar storage pressure as hydrogen occupies a large space at low pressure. Similarly, high-pressure tanks for decentralized storage of hydrogen especially for transport applications are necessary. However, tanks capable of holding such high pressure are generally made up of carbon fiber which is a very expensive material. As the pressure requirement increases, the quantity of carbon fiber required for the tank rises along with the up-gradation of this compression system specification which can increase the initial cost of storage [14]. Hence many researchers are now focusing on the hydrogen production methods, transportation of hydrogen, and its storage.

Liquefaction of hydrogen requires a significant energy input as the boiling point of hydrogen is very low (-253 °C) but liquid hydrogen provides comparatively a high storage density. Liquefaction consumes about 30% of hydrogen energy. The high volumetric density is the main advantage of liquid hydrogen storage. Another means of hydrogen storage is adsorption which exhibits van der Waals bonding between hydrogen molecules and materials that store hydrogen in the solid phase. Metal hydrides and chemical hydrides exhibit these reactions and operate at low pressure. All three storage options have their respective limitations and hence currently there is no perfect solution for hydrogen storage. The cost involved for hydrogen storage for each of these options is given in Table 3. Many researchers are continuously working in this field to provide a better solution for hydrogen storage and with development, it is improving day by day [15,16].

| Hydrogen Storage Methods | Compressed Gas Storage | Liquid Hydrogen Storage | Metal Hydride Storage |
|--------------------------|------------------------|-------------------------|-----------------------|
| Hydrogen Transportation by Trailers/ Trucks | 63 – 460 Kg | 360 – 4300 Kg | Up to 500 Kg |
| Cost of H₂ Storage | 17.9 ₹/Kg H₂ | 48 ₹/Kg H₂ | 101.1 ₹/Kg H₂ |
| Cost of H₂ Transportation | 35.88 ₹/Kg H₂ | 2.16 ₹/Kg H₂ | 31.44 ₹/Kg H₂ |
| Cost of H₂ Fueling Station | 30.03 ₹/Kg H₂ | 37.95 ₹/Kg H₂ | [-] |

Figure 2. Hydrogen Production Cost by different methods [18].
2.3. Proton Exchange Membrane Fuel Cells
PEMFC’s are the oldest and well-tested fuel cells that mainly use hydrogen, methanol, and ethanol as fuel. PEMFCs are evolving as a better alternative for conventional fossil fuel vehicles [17]. Automobile companies like Honda, Toyota, and Hyundai have already started the production of commercialized PEM fuel cell vehicles; many other companies are now working in this field. Membrane Electrode Assembly is the most important component of the fuel cells consisting of the Catalyst layer, Microporous layer, and Gas diffusion layer. The Platinum catalysts are mostly used which contributes largely to the overall cost and electrochemical reaction takes place at these catalyst layers. These polymer membranes act as a charge carrier for protons and also separates reactant gases hydrogen and oxygen [18]. The only byproducts that come from the hydrogen fuel cells are heat and water. Zero greenhouse gas emissions, higher efficiency, short refilling time and high power density have placed fuel cell technologies at the top level and opened a large scope for the applications that include powering commercial vehicles, industrial trucks, boats, airplanes, portable appliances, etc. [4]. From the year 2002 to 2017 significant rise in shipments of PEMFC was observed. The transport sector is a major buyer of the PEMFC which contributes about 90% of total shipments. Major companies like Toyota, Honda, and Hyundai have already started the research and development on fuel cell vehicles, their testing and are now focusing on their commercialization [19].

3. Green Hydrogen For Indian Automobile Sector
A total of 11% of CO₂ emissions in India comes from road transport. This air pollution from vehicular emission can cause various hazardous effects like nausea, breathing difficulties, skin disease, and cancer. Vehicular pollution is also the reason due to which many Indian cities have not succeeded to maintain their air quality index with the safety guidelines of the World Health Organization (WHO) [20,21]. In India, fossil fuel-based vehicles are the major contributor to air pollution followed by industries and thermal power plants. According to the Government of India from the year 1951 to 2012, the number of vehicles has increased from 0.3 million to 159.5 million [22]. Still, the number of vehicles on Indian roads is continuously increasing. Figure 3 of the context shows the data related to total number of vehicles sold in 2019-20.

![Indian Automobile Sales Trend](image)

Figure 3. Indian Automobile Sales Trend in India in 2019-20 [22].
The rise in population and economic growth results in the large consumption of fossil fuel-based resources which contribute to the high level of emissions of harmful gases and particulates. Many Indian cities are now witnessing higher Air Quality Index values especially metropolitan areas like Delhi, Mumbai, Kolkata, etc. A major fraction of this air pollution comes from vehicular emissions and the reason behind this is unplanned urbanization, uncontrolled vehicular density, and low turnover of old vehicles [22,23]. Emissions from automobiles depend upon the type of fuel, vehicle types, and maintenance. The automobile sector is responsible for 60% of greenhouse gas emissions. One of the major reasons for large vehicular emissions is the type of fuel and the age of the vehicle. In India, a large number of passenger vehicles run on a diesel engine, which contributes heavily to vehicular emissions as compared to petrol and electrically powered vehicles [23]. Hence, there is a need to find better alternate fuel, which is emission-free and available in abundant in the local market.

3.1. Hydrogen as an Alternative Fuel for Indian Vehicles
Since 1970, over 90% increase in CO2 emissions has been recorded as per the United States Environmental Protection Agency [24]. Many nations are now focusing on shifting to electric vehicles by replacing their fleets of ICE vehicles. The reason behind this is very low emissions from electric vehicles. Also, overall emissions can be reduced if renewable electricity sources are available to power electric vehicles [25]. With the increase in demand and positive governmental policies, interest in research and development in this field has been increased. Many improved battery systems are now available in the market, which is the outcome of new research. Li-ion batteries are now the first choice for many automobile companies with their low weight, high energy storage capacity and continuously decreasing price [26]. Two types of electric vehicles are more popular in the market, plug-in hybrid electric vehicles (PHEV) and battery-powered electric vehicles (BEV).
vehicles. PHEV is powered by both internal combustion engines and batteries whereas BEVs are fully electric-powered and take power from batteries alone [27]. These are considered potential solutions to the current environmental challenges. Battery recharge time, less availability of charging infrastructure, and low travel range are the main reasons because of which BEVs are still not popular in India. However, with research and development in this field, electric vehicles are now gaining the attention of the public. To overcome all these issues associated with PHEV and BEV, fuel cell electric vehicles are now becoming a more popular option.

Fuel Cell Electric Vehicles are equipped with fuel cells that consume hydrogen to supply the necessary power to the vehicle’s motor. These fuel cells are more efficient and also more environmentally friendly as compared to many other conventional energy conversion systems. Fuel cells available in the market are of various types and can be differentiated based on load requirement, type of electrolyte used, operating conditions, fuel used, and the type of application [17]. The proton exchange membrane fuel cell phosphoric acid fuel cells, alkaline fuel cells, and solid oxide fuel cells are the common types of fuel cells. Among all this, Hydrogen based PEMFC’s are more popular in the automobile sector. Some automobile manufacturers have already started working on the manufacturing of commercial fuel cell-based vehicles. These vehicles have great potential considering the range and short refueling time to replace diesel and gasoline-based vehicles. The availability of hydrogen is not an issue as it is abundant in nature, but it is not readily available. Hydrogen can be a better solution for an energy transition. Hydrogen has a huge potential to provide an economical and environmental solution to greenhouse gas emissions.

3.2. Indian Renewable Power Generation Capacity and Green Hydrogen

A large quantity of hydrogen produced worldwide comes from steam reforming of natural gas, coal gasification which contributes heavily to greenhouse gas emissions. To adopt a green hydrogen economy, hydrogen production from renewable sources must be the priority. But a major hurdle in the adoption is its efficiency and cost. Table 1 of the context represents the features, uses, opportunities, and challenges for the future adoption of hydrogen. Coupling solar PV modules and other green energy sources with electrolyzers can greatly benefit the future of green hydrogen production and will help to replace the fossil fuel-based economy with a green hydrogen economy [28]. Ibrahim Dincer in his article [28] has presented many alternatives to produce green hydrogen and some case studies on the same.

![India's Installed Renewable Capacity (MW)](image)

Figure 5. India's Total Installed Renewable Energy Capacity 2019 [29].

From the last decade, a significant fall in the cost of renewable energy has been noticed. Much ongoing research has successfully contributed to the cost reduction of renewable energy. These declining costs will help to produce hydrogen economically where abundant solar and wind energy are available.
Currently in India, the cost of renewable power is near ₹4/KWh and it needs to fall up to ₹1.5/KWh to successfully compete with the grey hydrogen [30]. The government of India is continuously focusing on the increase in renewable source installations. The main intention behind this is to reduce the dependency on fossil fuel consumption and to reduce emissions.

The wind and solar installation in the region can produce sufficient electricity. At the time of lower energy demand, this excess energy can be significantly utilized to produce hydrogen on-site and then can be transported for end-use. Figure 5 of the context gives a detailed idea of India’s renewable power generation capacity. India’s huge potential in renewable energy gives many advantages to produce green hydrogen which can be then utilized to decarbonize the industries and transport sector significantly. The next section of the context reviews the status of hydrogen and fuel cell technology in India.

3.3. The Blending of Hydrogen in CNG
Natural gas is currently available in various forms such as LNG, CNG, LPG, and also LCNG. Similarly, a new form of natural gas i.e. HCNG (Hydrogen and CNG) is now becoming popular. Hydrogen as a better alternative fuel can be used with CNG. Many kinds of research have shown that Hydrogen blended with CNG (i.e. HCNG) improves the engine performance and significantly reduces emission [31]. Hydrogen can be blended with compressed natural gas in various proportions ranging from 8 to 50% of hydrogen. The combustion of hydrogen only emits NOx and there is no emission of major pollutants like CO, HC, SOx. These benefits from hydrogen blending are gaining the attention of the international community. The blending of hydrogen in CNG even in fewer amounts (5 to 30%) improves the calorific value and flame characteristics of the fuel [19]. With 18% Hydrogen blending in CNG, Sehgal et al. tested the SI engine and found that there was a 5% reduction in fuel consumption, 20% reduction in HC emissions, and 10-20% increase in NOx with better performance characteristics. NOx emissions depend on combustion temperature. The exhaust gas circulation significantly reduces the reaction temperature and hence NOx emission also reduces. Existing vehicles which use CNG as fuel can also run on hydrogen blended CNG with modifications. Similarly, Existing CNG refueling stations can also easily be made compatible with HCNG with some modifications [11,12].

4. Opportunities for India in Green Hydrogen Economy and Challenges
4.1. Opportunities for India
Based on India’s current progress in the renewable energy sector, it is clear that green hydrogen will make a greater impact on India’s overall energy sector. Green hydrogen will help to provide a sustainable solution for the Indian transport sector. The Energy and Research Institute (TERI) of India has predicted that the demand for hydrogen will increase from 6 Mt to 28 Mt by 2050 and the cost of hydrogen from renewables will fall by 50% by 2030. TERI claimed that about 80% of hydrogen in India will be produced from renewables by 2050 [32]. India has fewer reserves of natural gas and green hydrogen production from renewables can make a difference in this scenario. Under the ‘Make in India’ program, India has the opportunity to start the production of electrolyzers and fuel cells which will allow capturing a large share in this market worldwide. As compared to other parts of the world, India has a low cost of electricity from the solar photovoltaic systems, this generated power in the future will be helpful to scale up green hydrogen production. Water consumption by electrolyzers is another issue that needs to be discussed. Electrolyzers consume about 9 liters of water to produce 1 kg of hydrogen. In this scenario, seawater electrolysis may be helpful that requires further development and research work [32].

The existing hydrogen infrastructure is not enough to promote the larger acceptance of fuel cell vehicles. For further developments, hydrogen refueling stations will be playing a very important role. At the end of 2019, there were 470 operating hydrogen refueling stations in the world. Countries like Japan, Germany, the United States, and China have a large number of hydrogen stations. Currently, India has only two established hydrogen refueling stations one at the Indian Oil R&D Center, Faridabad, and the second at the National Institute of Solar Energy, Gurugram. To give a boost to the public acceptance of fuel cell
vehicles in India, the number of hydrogen fuel stations need to be increased. Figure 6 shows the number of fueling stations in some of the major countries where it can be seen that India has only 2 fueling stations that are used majorly for research purposes [29,33].

For a country like India with its growing economy, controlling pollution and energy security is an important issue. In this scenario, the great potential of hydrogen is far away from gaining popularity in India. India is exploring renewables especially solar, wind and hydropower but hydrogen application is still not in focus. Many Indian institutions including the Indian Space Research Organization (ISRO), Indian Oil Corporation (IOCL), Bharat Heavy Electricals Limited (BHEL), and Tata Motors are actively working on hydrogen and fuel cell technologies. This ongoing research will help India to face challenges regarding fuel cell acceptance, regulations, and standards formulations, etc. [3]. Most of the sustainable energy technologies are developed and manufactured outside India. However, the sizable renewable power generation capacity of the country provides the opportunity to produce green hydrogen and maximize the benefits from the energy transition. In the future, India will see huge growth in the heavy transport sector. Features of fuel cell electric trucks like zero carbon emissions with long-range travel and fast refueling time make these trucks better alternatives for diesel trucks for the Indian heavy transport sector. The increase in the use of locally produced green hydrogen can significantly reduce the dependency on petroleum imports in India. In the same scenario, Table 4 of the context shows some important benefits, opportunities, and challenges of shifting to hydrogen energy.

![Number of Hydrogen Refueling Stations](image)

**Figure 6.** Hydrogen Fuel Stations by Countries [33][29].

Following are some benefits of using green hydrogen as a fuel in India (Source: Department of Science and Technology, New Delhi).
- Reduced Petroleum Imports and Energy Security,
- Decarbonization of Transport sectors,
- Integration of Renewables with Hydrogen production,
- Addresses Climate Change Issues.

The flexibility of fossil fuels to use wherever we want and their high density is not available with renewables. However, hydrogen production integrated with renewables can bring this flexibility. Various Governmental and public agencies in India are investing in the research and development of hydrogen technology, particularly in the development of new materials, processes, systems, etc. India is one of the
participants in Mission Innovation (MI) and working on MI’s eight Innovation Challenges (IC8) that are focused on renewable and clean hydrogen. Many Indian Institutions and Researchers are constantly working on improvement in hydrogen production, its storage, and transport which will in the future help to increase the utilization of hydrogen [12,29]. Similarly, many organizations and researchers are working on developing more economical and efficient fuel cells to promote their commercial use for the transport sector. Indian organizations are also promoting many demonstration projects. The ongoing developments by the Indian government and public organizations created a lot of opportunities to become a major player in the energy sector.

Table 4. Hydrogen Energy - Features, Uses, Opportunities, and Challenges [34].

| Features                                                                 | Uses                                                                 |
|--------------------------------------------------------------------------|----------------------------------------------------------------------|
| Potential - Clean, secure, and affordable future energy source.           | Industry - Metalworking, Oil refining, Flat glass production, Generator Cooling, etc. |
| Versatile – It can be produced from many resources such as renewable energy, nuclear energy, coal, natural gas, etc. Also, hydrogen is the leading option for energy storage. | Transport – Hydrogen fuel cell-based Passenger cars, Aircraft, Material handling equipment, Buses, Trains, etc. |
| Application – Hydrogen can be used in wide applications such as transport, industry, building, and power generation, etc. | Building – Hydrogen blending with natural gas in commercial buildings, Heating and Cooling purposes in buildings, etc. |
|                                                                          | Power Generation – Gas turbines, Backup power, Stationary fuel cells for remote applications, etc. |

| Opportunities                                                                                                          |
|------------------------------------------------------------------------------------------------------------------------|
| Industrial ports, logistic parks – Make industrial ports, logistic parks, etc. hydrogen compatible and encouraging them to shift to a green hydrogen economy. |
| Building a hydrogen infrastructure – To adopt a hydrogen economy and to take advantage of the future market scenario.    |
| In transport – Using hydrogen in transport for freights, fleets, and corridors.                                        |
| In trade – International hydrogen trade needs to start soon which can make an impact on the global energy market.       |

| Challenges                                                                                                          |
|---------------------------------------------------------------------------------------------------------------------|
| Hydrogen production from renewable energy – The cost of hydrogen production from green energy is not efficient and costly. Mass manufacturing of fuel cells, electrolyzers, refueling equipment is not still implemented which contributes heavily to their price. |
| Slow development of hydrogen infrastructure – Less number of refueling stations and other hydrogen infrastructure slows down the wide adoption of hydrogen. |
| The purity of produced hydrogen for fuel cell applications.                                                          |
| Governmental regulations - for safety in storage and transportation for large volumes of hydrogen.                   |

4.2. Challenges
The hydrogen economy is a broad concept from the production of hydrogen to its distribution. The successful implementation of which requires great effort. The hydrogen production from renewables is very costly as compared to fossil fuel-based production. Similarly, the mass acceptance of hydrogen requires
further improvements in both fuel cell technology and electric drivetrains. Hybrid vehicles bring the benefits of both conventional and fuel cell vehicles, hence their demand will increase in the future. These developments will heavily affect the crude oil and natural gas market worldwide, which can be a major challenge for the global supply chain [35].

In the current scenario, the cost of fuel cells, electrolyzers, and refueling equipment is very high. Mass production of this equipment locally in India can decrease their cost significantly. India is an evolving manufacturing hub but has no major manufacturer of this equipment in the country, which is an issue that needs to be solved. Another challenge for India is to increase the hydrogen production capacity by simultaneously reducing the cost of hydrogen by utilizing its renewable power generation capability [36].

The important challenge associated with the hydrogen economy is the development of hydrogen storage facilities and delivery networks. The low volumetric energy density makes the handling of the hydrogen difficult and more expensive. Safety and financial security is also an important concern need to be addressed with 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 [36,37].

5. Conclusion
India has a large growing population and economy, but comparatively has limited availability of fossil fuels to fulfill its energy demands. The consumption of fossil fuels is contributing to the heavy emission of greenhouse gases. A large number of vehicles that are based on petroleum are the major reason for increased petroleum imports in India. To reduce the environmental pollution and petroleum imports in India, there is a need to look for an alternate fuel for the transport sector. Considering the need to search for an alternate fuel, the context focuses on the opportunities offered by Green Hydrogen Economy and related challenges.

The concept of Green hydrogen economy brings many opportunities for India to become energy independent. For the last decade, India is constantly focusing on growing its renewable energy capacity by taking advantage of its geography. Integrating hydrogen production with these renewables can scale up the green hydrogen production in India. India can take the advantage of its renewable energy scenario and can scale up its hydrogen production facilities. The mass production offers India an opportunity to export green hydrogen to other nations. Green Hydrogen when used with fuel cells can help India significantly reduce its petroleum imports and environmental pollution. Renewable energy in India provides the opportunity to produce green hydrogen and to develop hydrogen infrastructure but for adoption, many challenges still need to be solved. These challenges include hydrogen production cost, storage, transportation, policies, regulations, public awareness, etc.

The world is slowly moving towards the adoption of a Hydrogen economy and India is also taking important initiatives. Indian organizations which include both government and public are investing in the research of hydrogen technologies. Many Ongoing research and demonstration projects are very important to develop hydrogen and fuel cell technology economically. The progress in this development will play a key role in the commercialization of the technology. Well-developed fuel cell technology and locally produced green hydrogen will be key players to decarbonize the Indian transport sector by replacing the current petroleum-based vehicle engines.

6. Reference
[1] Warner KJ, Jones GA. The 21st century coal question: China, India, development, and climate change. Atmosphere (Basel) 2019;10:1–17. https://doi.org/10.3390/atmos10080476.
[2] Ministry of Power G of I. Power Sector at a Glance ALL INDIA 2021. https://powermin.gov.in/en/content/power-sector-glance-all-india.
[3] Medisetty VM, Kumar R, Ahmadi MH, Vo DVN, Ochoa AAV, Solanki R. Overview on the
Current Status of Hydrogen Energy Research and Development in India. Chem Eng Technol 2020;43:613–24. https://doi.org/10.1002/ceat.201900496.

Rath R, Kumar P, Mohanty S, Nayak SK. Recent advances, unsolved deficiencies, and future perspectives of hydrogen fuel cells in transportation and portable sectors. Int J Energy Res 2019;43:8931–55. https://doi.org/10.1002/er.4795.

Ansari A, Hapani B, Kathrotia D, Gokani R, Ajudiya CD. A Review Paper on Hydrogen Gas as Alternate Fuel for Four Stroke IC Engine. IRE Journals 2017;1:11–5.

DOE US. Alternative Fuels Data Center - Fuel Comparison Chart 2021;100:1–4.

Staffell I, Scannan D, Abad V, Balcombe P, Dodds PE, Ekins P, et al. Environmental Science The role of hydrogen and fuel cells in the global energy system 2019:463–91. https://doi.org/10.1039/c8ee01157e.

Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611. https://doi.org/10.1016/j.rser.2016.09.044.

Mallapragada DS, Gencğer E, Insong P, Keith DW, O'Sullivan FM. Can Industrial-Scale Solar Hydrogen Supplied from Commodity Technologies Be Cost Competitive by 2030? Cell Reports Phys Sci 2020;1:100174. https://doi.org/10.1016/j.xcrp.2020.100174.

Woodside Energy. Hydrogen - Woodside Energy. WoodsideComAu n.d. https://www.woodside.com.au/what-we-do/hydrogen (accessed March 23, 2021).

Matthey.com. Hydrogen for a cleaner future. MattheyCom n.d. https://matthey.com/en/markets/energy-generation-and-storage/hydrogen (accessed March 23, 2021).

Department of Science and Technology ND. India Country Status report on Hydrogen and fuel cells 2020.

Acar C, Dincer I. Review and evaluation of hydrogen production options for better environment. J Clean Prod 2019;218:835–49. https://doi.org/10.1016/j.jclepro.2019.02.046.

Deloitte China, Ballard. Fueling the Future of Mobility Hydrogen and fuel cell solutions for transportation. Financ Advis 2019;1:Volume 1.

Yadav K, Sircar A. Hydrogen Compressed Natural Gas and Liquefied Compressed Natural Gas: Fuels for Future. J Energy Manag 2017;2:29–33.

Anderson J, Gronskvist S. Large-scale storage of hydrogen | Elsevier Enhanced Reader 2019.

Abdelkareem MA, Elsaid K, Wilberforce T, Kamil M, Sayed ET, Olabi A. Environmental aspects of fuel cells: A review. Sci Total Environ 2021;752. https://doi.org/10.1016/j.scitotenv.2020.141803.

Peighambardoust SJ, Rowshanzamir S, Amjadi M. Review of the proton exchange membranes for fuel cell applications. vol. 35. 2010. https://doi.org/10.1016/j.jhydene.2010.05.017.

Wang Y, Ruiz Diaz DF, Chen KS, Wang Z, Adroher XC. Materials, technological status, and fundamentals of PEM fuel cells – A review. Mater Today 2020;32:178–203. https://doi.org/10.1016/j.mattod.2019.06.005.

Yadav SK, Sahay M. A Study on Automobile Industry Growth in India and Its Impact on Air Pollution 1991:1–7.

Khandar C, Kosankar S. A review of vehicular pollution in urban INDIA and its effects on human health. J Adv Lab Res Biol 2014;V:54–61.

Gurjar BR, Ravindra K, Nagpure AS. Air pollution trends over Indian megacities and their local-to-global implications. Atmos Environ 2016;142:475–95. https://doi.org/10.1016/j.atmosenv.2016.06.030.

Arunkumar M, Dhanakumar S. Vehicular pollution and its implications. Poll Res 2019;38:634–47.

United States Environmental Protection Agency. Global Greenhouse Gas Emissions Data | Greenhouse Gas (GHG) Emissions | US EPA n.d. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed June 10, 2021).
[25] Towoju OA, Ishola FA. A case for the internal combustion engine powered vehicle.pdf 2020:315–21.
[26] Iclodean C, Varga B, Burnete N, Cimerdean D, Jurchiș B. Comparison of Different Battery Types for Electric Vehicles. IOP Conf Ser Mater Sci Eng Pap 2017. https://doi.org/10.1088/1757-899X/252/1/012058.
[27] Shafiq S, Irshad U Bin, Al-Muhaini M, Djokic SZ, Akram U. Reliability Evaluation of Composite Power Systems: Evaluating the Impact of Full and Plug-in Hybrid Electric Vehicles. IEEE Access 2020;8:114305–14. https://doi.org/10.1109/ACCESS.2020.3003369.
[28] Dincer I. Green methods for hydrogen production 2011;7. https://doi.org/10.1016/j.ijhydene.2011.03.173.
[29] Ministry of New and Renewable Energy G. Hydrogen Energy | Ministry of New and Renewable Energy, Government of India. MnreGovIn n.d. https://mnre.gov.in/new-technologies/hydrogen-energy (accessed March 23, 2021).
[30] MEC Intelligence. Abridged India Hydrogen and Fuel Cells Show 2020 | MEC + 2021. https://mecintelligence.com/mec-perspectives/articles/abridged-india-hydrogen-fuel-cells-2020/ (accessed June 10, 2021).
[31] Yadav S. Review On Effectiveness Of Hydrogen Enrichment In Cng Fuelled International Conference on Efficient Engineering Systems 2020. Int Conf Effic Eng Syst 2020 Conf Proceeding Vol 01 *Corresponding 2021.
[32] Hall W, Spencer T, Renjith G, Dayal S. The Potential Role of Hydrogen in India. Energy Resour Inst 2020:1–24.
[33] Bermudez J, Hasegawa T, Bennett S. Hydrogen – Analysis - IEA. Track Report, IeaOrg 2020. https://www.iea.org/reports/hydrogen (accessed March 23, 2021).
[34] The Future of Hydrogen – Analysis - IEA. IEA 2019. https://www.iea.org/reports/the-future-of-hydrogen (accessed March 23, 2021).
[35] Tseng P, Lee J, Friley P. Hydrogen Economy: Opportunities and Challenges * n.d.
[36] Pudukudy M, Yaakob Z, Mohammad M, Narayanan B, Sopian K. Renewable hydrogen economy in Asia - Opportunities and challenges: An overview. Renew Sustain Energy Rev 2014;30:743–57. https://doi.org/10.1016/j.rser.2013.11.015.
[37] Ministry of Heavy Industries and Public Enterprises G of I. National Automotive Board (NAB) 2020. https://fame2.heavyindustry.gov.in/ (accessed June 13, 2021).