



# Hydrogen Energy as Future of Sustainable Mobility

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Conventional fuels for vehicular applications generate hazardous pollutants which have an adverse effect on the environment. Therefore, there is a high demand to shift towards environment-friendly vehicles for the present mobility sector. This paper highlights sustainable mobility and specifically sustainable transportation as a solution to reduce GHG emissions. Thus, hydrogen fuel-based vehicular technologies have started blooming and have gained significance following the zero-emission policy, focusing on various types of sustainable motilities and their limitations. Serving an incredible deliverance of energy by hydrogen fuel combustion engines, hydrogen can revolution various transportation sectors. In this study, the aspects of hydrogen as a fuel for sustainable mobility sectors have been investigated. In order to reduce the GHG (Green House Gas) emission from fossil fuel vehicles, researchers have paid their focus for research and development on hydrogen fuel vehicles and proton exchange fuel cells. Also, its development and progress in all mobility sectors in various countries have been scrutinized to measure the feasibility of sustainable mobility as a future. This paper is an inclusive review of hydrogen-based mobility in various sectors of transportation, in particular fuel cell cars, that provides information on various technologies adapted with time to add more towards perfection. When compared to electric vehicles with a 200-mile range, fuel cell cars have a lower driving cost in all of the 2035 and 2050 scenarios. To stimulate the use of hydrogen as a passenger automobile fuel, the cost of a hydrogen fuel cell vehicle (FCV) must be brought down to at least the same level as an electric vehicle. Compared to gasoline cars, fuel cell vehicles use 43% less energy and generate 40% less CO<sub>2</sub>.

**Keywords:** climate change, sustainable mobility, hydrogen mobility, hydrogen fuel, GHG

## 1 INTRODUCTION

Sustainable mobility is described as a transportation system that is ubiquitous, effective, clean, and ecologically beneficial. Whilst transportation is not having its own sustainable development goals (SDGs), it is critical for accomplishing other SDGs in order to reach desired growth and development. Top-scoring countries for the SDGs have more robust and long-term mobility

policies in place, whilst countries with the lowest scores are chastised for having inadequate transportation infrastructure (Sum4all.org, 2021). **Figure 1** depicts the SDGs that are directly or indirectly met by sustainable transportation.

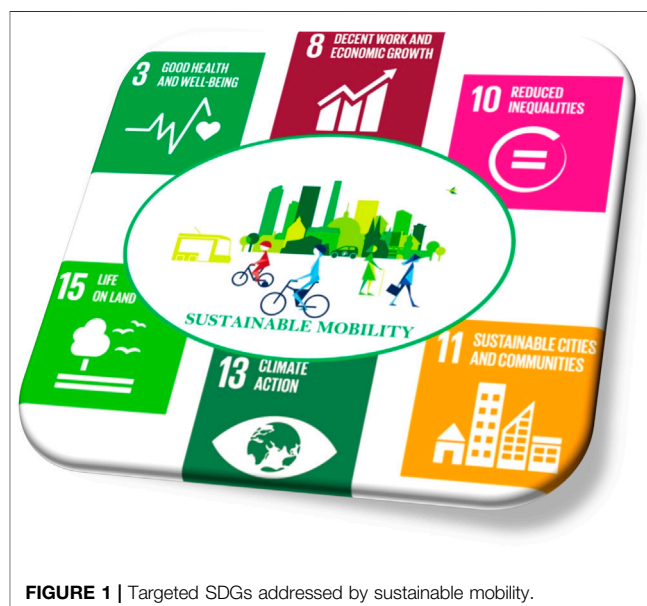
The origin of “sustainable mobility” is from the broader definition of “Sustainable development”. “Sustainable development” is “development that meets current needs without jeopardizing the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987). The infographic (**Figure 2**) depicts the broad benefits of sustainable mobility (Ransformative-Mobility, 2021), which include energy security, economic development, environmental sustainability, and social wellbeing.

The literature has a number of researches on sustainable mobility. The scope of technology in fostering a change in behaviour toward sustainable transportation has been investigated (Klecha and Gianni, 2018; Chng, 2021). Gonzales Green port strategies for reducing negative externalities in the countryside has been investigated (Gonzalez Aregall et al., 2018). **Table 1** lists the results of several studies on sustainable mobility.

## 1.1 Hydrogen: The Most Reliable Form of Energy

The global need for energy has risen intensely with the growth of the world’s population. This is because energy is required for all activities. The great majority of energy is imitative from fossil fuels, which are non-renewable resources that take longer to recharge or reoccurrence to their previous capacity. Energy imitative from fossil fuels is less costly; however, it has shortcomings when compared to renewable energy sources (Rohith et al., 2016).

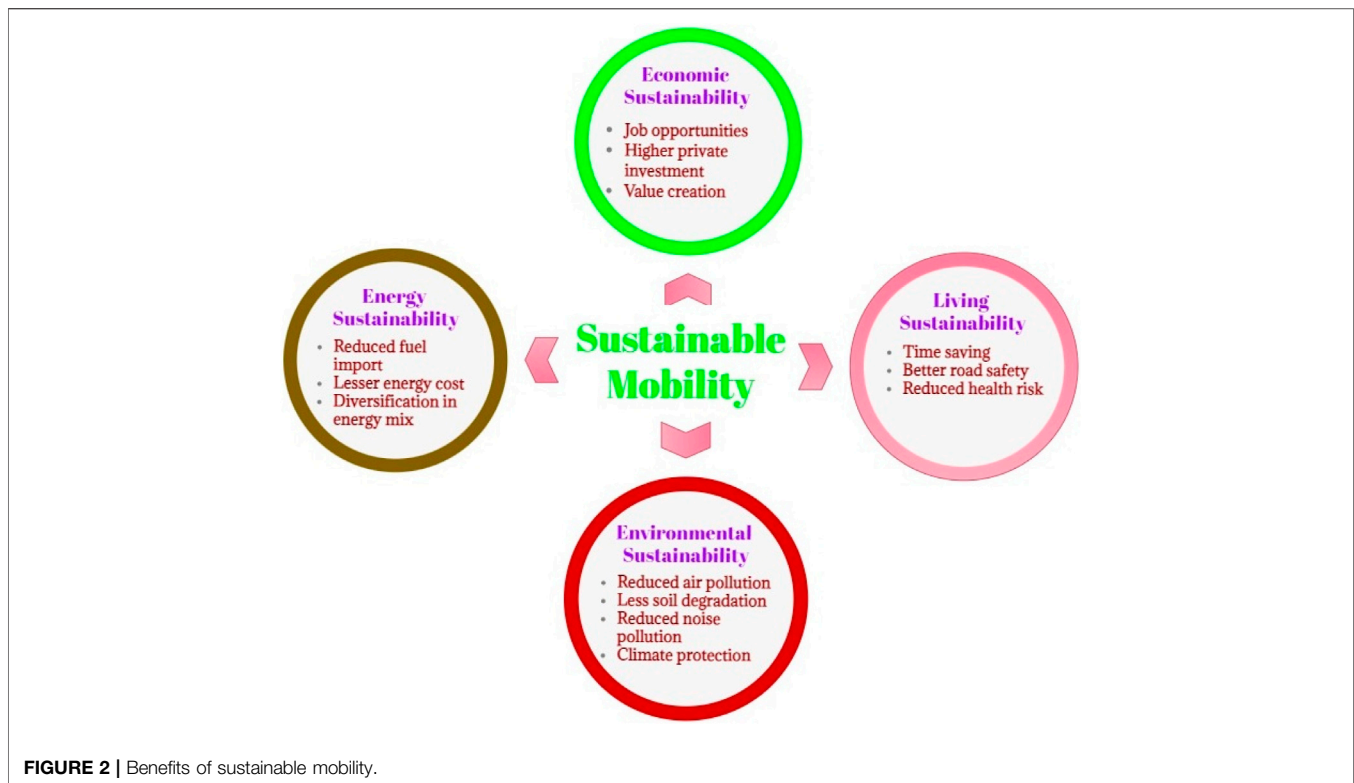
Hydrogen is an emerging and almost established fuel source for cars (Apostolou and Xydis, 2019; Staffell et al., 2019; Falcone et al., 2021). The present state of the art and future possibilities of the burgeoning hydrogen-based market in road transportation, as well as an examination of existing hydrogen refuelling station technologies, have been explored (Apostolou and Xydis, 2019). The hydrogen economy offers a multi-sectoral view of low-cost clean energy and thorough decarbonization in process sectors. The ability to store hydrogen or derivatives is a game changer for the integration of high renewable energy source shares, resulting in beneficial effects on various SDGs through lower GHG and air pollution emissions (Falcone et al., 2021). Along with biofuels and electric cars, hydrogen is one of three key low-carbon transportation choices (EVs). Hydrogen avoids the negative effects of biofuels on land usage and air pollution, as well as the restricted range and long recharge periods associated with electric vehicles (Staffell et al., 2019). Hydrogen automobiles have been shown to have a threefold lower potential for global warming than other alternative technologies (Bicer and Dincer, 2017; Dincer, 2020; Apostolou and Welcher, 2021). In Denmark, variables that may influence public acceptability of hydrogen-powered cars have been explored. To that purpose, four primary hypotheses were proposed, assuming that variables such as technical and environmental knowledge, financial standing,



**FIGURE 1** | Targeted SDGs addressed by sustainable mobility.

and infrastructure have a direct impact on the societal acceptability of hydrogen-powered private road cars in the transportation sector. Most of the hypotheses, such as environmental awareness, limited refuelling infrastructure, and media backing for this sector, were supported by the findings (Apostolou and Welcher, 2021). To explore the effects of alternative cars on the environment and human health, a life cycle evaluation of methanol, hydrogen, and electric vehicles is done. The findings of this study demonstrate that owing to the manufacturing and maintenance phases, electric cars have higher human toxicity ratings. Because hydrogen has a higher energy density than methanol, hydrogen-powered cars are a more environmental sustainable alternative in terms of global warming and ozone layer depletion (Bicer and Dincer, 2017). The Covid-19 coronavirus has made it more important than ever for people to breathe cleaner air, drink cleaner water, eat cleaner food, and use cleaner energy. We were in a carbon age with hydrocarbon fuels until the coronavirus outbreak juncture in 2020, and now we must continue to change the driver to hydrogen, which is the start of the hydrogen age, in which the use of hydrocarbon fuels (fossil fuels) will decrease exponentially while the use of hydrogen energy will increase (Dincer, 2020). The Covid-19 has thrown the transition from the carbon (C) age to the emerging hydrogen (H<sub>2</sub>) age into disarray (Apostolou et al., 2018).

As a result, renewable resources, particularly hydrogen energy, are the most promising choices for meeting energy demands. Hydrogen is found mainly in plant materials and is rare in nature. Hydrogen is a non-metallic, nontoxic fuel that can provide more energy per unit of mass than gasoline (Abdalla et al., 2018). However, a substantial study is required to investigate and design onboard applications in order to use hydrogen as a fuel.



Hydrogen has lately emerged as a prospective energy carrier, and the organic chemical hydride approach offers significant advantages in terms of transportability and handling (Morel et al., 2015). The possibilities for combining stochastic power generation with hydrogen production, storage, and consumption is explained in (Korpas and Gjengedal, 2006).

## 1.2 Hydrogen as a Fuel in the Transportation Sector

“Centralized” production, where hydrogen is produced on a large scale and supplied to customers via truck or pipeline. “On-site” or “distributed” production, is where hydrogen is produced at the

end-use site, generally through small-scale electrolysis or steam methane reforming (Meraj et al., 2020).

Hydrogen can also be converted to other energy carriers like electricity, methane, or liquid fuels, which incurs conversion costs and efficiency losses but allows access to existing energy distribution networks without requiring the construction of an extensive hydrogen distribution infrastructure. The relative cost of regional basic resources for hydrogen generation and policies is vital in determining the ideal hydrogen supply pathway. Transportation of hydrogen can be done using.

- 1) Pipelines (Weinmann, 1999).
- 2) Mobile by trucks, trains, vessels (Domashenko, 2002).

**TABLE 1 |** Investigating research on sustainable mobility.

Cited reference	Year of publication	Investigated on
Ren et al. (2019)	2020	Green and sustainable logistics
Kumar and Alok, (2020)	2020	Prospects for sustainability
López et al. (2019)	2019	The impact of technological advances in bus transportation on environmental and social sustainability
Tirachini, (2020)	2019	Travel behaviour and sustainable mobility
Holden et al. (2019)	2019	Aspects of sustainable mobility in 2030
Martínez-Díaz et al. (2019)	2019	Future of autonomous driving
Letnik et al. (2018)	2018	Sustainable and energy-efficient urban transportation policies and initiatives
Ranieri et al. (2018)	2018	Logistics innovations in cost reduction vision
Taiebat et al. (2018)	2018	Automated vehicles' energy, environmental, and sustainability consequences
(Ferrero et al., 2018; Santos, 2018)	2018	Shared mobility
Biresselioglu et al. (2018)	2018	Electric mobility
Pojani and Stead, (2018)	2018	Policy design for sustainable urban transport

The use of hydrogen in onboard vehicles has hurdles owing to the high weight, volume, and cost of hydrogen. Furthermore, as the refuelling process continues, the life cycle of hydrides shortens, reducing the vehicles' efficiency. Another disadvantage is the lack of adequate hydrogen storage system standards and protocols. The infrastructure to distribute hydrogen to the user requires entirely new infrastructure; the production and delivery systems must be integrated to reduce the cost of hydrogen delivery and distribution costs. At the moment, hydrogen transportation, storage, and delivery to the site of consumption are all related with inefficient energy use. Despite having some notable disadvantages, hydrogen is heavily used in several industries such as the transportation industry, power generation industry, and building industry instead of conventional fossil fuels (Reddy et al., 2020).

This paper aims to present the future of hydrogen energy as a solution to sustainable mobility. Existing literatures are mainly focusing on utilization of hydrogen for a particular sector of transportation; the overall transportation sector is not addressed. In detail analysis of techno-economic-environmental aspects of Hydrogen as sustainable mobility solution is missing in recent literature. The goal of this research is to evaluate the potential of hydrogen energy as a solution for sustainable transportation and to analyse its environmental and social consequences. This review aims to introduce the preparation processes, storage method, and critical technical issues of its application in vehicles and related mobility sectors in a systematic manner, providing exciting insights into hydrogen-based energy, the potential large-scale deployment process on a global scale including techno-economic aspects, selected implemented projects, policies and challenges. The paper helps the policymakers and industries decide on choosing hydrogen as the future of sustainable mobility.

This paper is structured as follows. **Section 2** provides an in-depth review of hydrogen as a fuel for transportation in many sectors and its environmental and technical elements. **Section 3** deals with the generation and storage of hydrogen energy. **Section 4** concludes the in-depth analysis to suggest the scope of hydrogen to be adopted as the future of sustainable mobility.

## 2 ENVIRONMENTAL ASPECTS

Considering the fact of depletion of energy resources and the rise in global warming, challenges are encountered with the combustion of energy due to the transportation sector in the present time. Green House Gas (GHG) emissions are caused by the dominant conventional road transportations, which have existed for more than a century and has reached its upper saturation level. As per the International Energy Agency regulations, global carbon dioxide emissions must be decreased to limit the consequences of climate change (Zhao et al., 2020). To enhance the technology that has zero pollutant discharge and zero climate change effect, hydrogen Fuel cell-based vehicles production is being promoted by automotive industries. The government of various countries like the United States, Japan and South Korea have encouraged the production of Hydrogen vehicles since 2018 (Meng et al., 2021). The upcoming

subsections discuss the environmental and technical aspects of hydrogen in the mobility sector and its scope.

Transportation is the second-largest source of pollution in terms of GHG emissions, posing a serious threat to human health (Roadmap to a Single European Transport Area-Towards a competitive and resource efficient transport system, 2021). The transportation sector accounts for 23% of total CO<sub>2</sub> emissions. According to the report, the transportation sector would continue to rely on petroleum-based services for 90% of its fleet, with renewable energy sources accounting for only 10%. By 2050, carbon emissions from the transportation industry are predicted to be 33% more than they were in 1990 (Le Quéré et al., 2020).

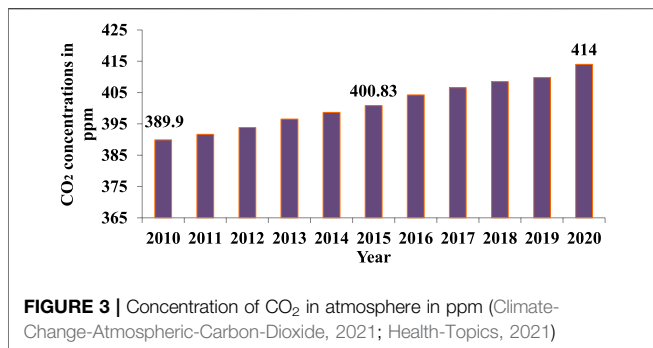
### 2.1 Climatic Change and Greenhouse Gas Emissions

Climate change is the central point of focus in the present era due to the advancement of technologies in various sectors, including the transportation industries. The combustion of biofuels for transportation has captured the mobility sector for the last two centuries. Traditional combustion fuels by vehicles lead to the generation of pollutants and GHGs to the environment, which has various adverse effects (Engel, 2012; Zhongfu et al., 2015). Hydrogen is a carrier, like electricity, rather than an energy source, and the notion of “hydricity,” or the inherent interchangeability of electricity and hydrogen, has been established (Engel, 2012). Anthropogenic GHG emissions are directly linked to the global warming trend. Climate change caused by GHG emissions is one of the most serious environmental issues confronting modern society (Ding et al., 2018). In order to stabilize the climate, it is the need of the time to reduce the emissions significantly (Liu et al., 2019). CO<sub>2</sub> is the major GHG contributor with a value of 76%, methane, while Nitrous Oxide and fluorinated gases together contributes the rest 24% (Global-Greenhouse-Gas-Emissions-Data, 2021). As illustrated in **Figure 3**, the global CO<sub>2</sub> concentration is growing rapidly.

The concentration of CO<sub>2</sub> in the atmosphere is currently at 414.00 ppm, the highest in the previous 800 k years, and it is closely connected to global temperature. The world has committed to keeping global warming below 2°C, and this goal can be met with a minimal carbon budget. According to researchers, mankind can only emit 565 Gt of CO<sub>2</sub> more and still meet the 2°C target—a limit that would be exhausted in 15 years if emissions continue at their current rate of 36.6 Gt CO<sub>2</sub> per year (Liu et al., 2019). It is also predicted that seven million people die each year as a result of illnesses caused by air pollution (Global-Energy-Related-Co2-Emissions, 2021).

During COVID-19, there is a temporary decline in daily global CO<sub>2</sub> emissions due to forced confinement. By early April 2020, daily global CO<sub>2</sub> emissions had decreased by 17% compared to the mean levels in 2019, with surface traffic accounting for half of the decline (Saleem et al., 2021). However, in the post-COVID-19 scenario, things will be different. As a result, adopting a sustainable transportation strategy is critical.

Although GHGs are released by a variety of sources, those produced by automobiles can be reduced by employing



alternative fuel vehicles (AFVs) or green vehicles. Advanced alternative fuel technologies have the potential to halve gasoline use while also cutting CO<sub>2</sub> emissions and their associated environmental consequences. Although fuel-efficient technologies help vehicles perform better in terms of environmental performance, they cannot assist cut overall emissions. This is owing to the fact that technology cannot change consumer habits on its own. So, framing a strategy that encourages consumers to choose energy-efficient vehicles over traditional one is critical, as is ensuring the use of AFVs that complies with environmental pollution-reduction measures like carpooling and using low-CO<sub>2</sub>-emitting vehicles, public transportation, or bicycles to save fuel (Oliveira and Dias, 2020; García-Melero et al., 2021; Apostolou and Xydis, 2019).

## 2.2 Hydrogen as a Zero-Emission Source

Hydrogen energy follows a zero-emission policy towards the environment, making it a fundamental attraction for researchers and industries to study and develop hydrogen transport technologies. Additionally, hydrogen has become a truly sustainable energy resource because of the zero climate change effect, as hydrogen is a highly efficient, reliable, and soundless source of power.

The evaluation of hydrogen fuel transportation cannot be alone evaluated based upon the tailpipe gas emissions. The environmental aspects can be accounted for based on the vehicle's wheel to tank evaluation (Concawe and JRC, 2007; Yang and Ogden, 2007; Bethoux, 2020). Natural hydrogen may become a viable economic option, making fuel cell vehicles a viable and ecologically acceptable alternative to battery electric vehicles (Bethoux, 2020). The European Commission's Joint Research Centre, EUCAR, and CONCAWE have assessed the tank-to-wheels (TTW) energy usage and greenhouse gas emissions for a variety of future fuel and powertrain alternatives (Concawe and JRC, 2007). Moving our transportation sector away from petroleum-derived gasoline and diesel fuels and toward hydrogen derived from domestic primary energy resources can have a number of societal benefits, including lower well-to-wheels greenhouse gas emissions, zero point-of-use criteria air pollutant emissions, and less imported petroleum from politically sensitive areas (Yang and Ogden, 2007). Therefore, the accountability of hydrogen vehicles towards environmental effect has been studied and reported through one tool known as Ecoscore. The tool has been

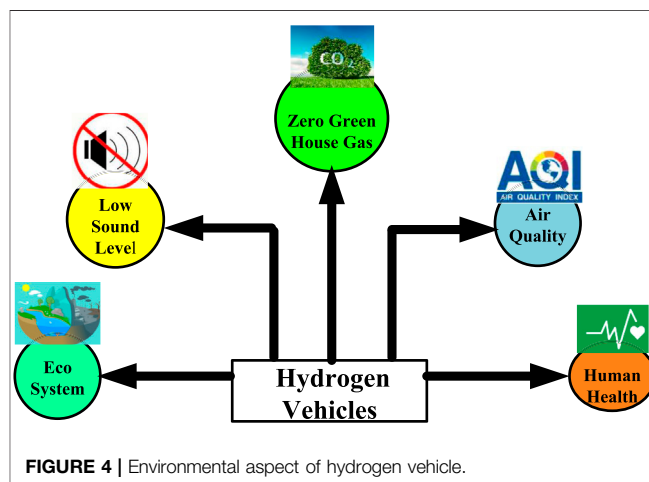
developed by the commission of the Flemish government (Sergeant. et al., 2009). This measurement is based upon the GHGs emissions, regulation of air quality and sound pollution. Apart from the three major aspects, two indirect aspects, including human lifecycle and ecosystem maintenance, are also included in the Ecoscore measurement scale (Van Mierlo et al., 2004). Environmental aspects of hydrogen vehicles are presented in **Figure 4**.

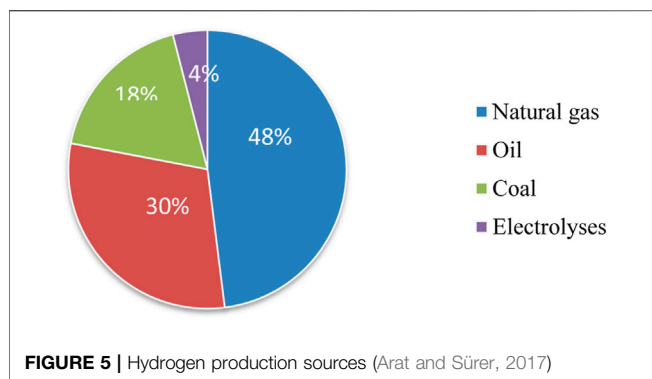
## 3 TECHNICAL ASPECTS

The study about hydrogen fuel vehicles has major issues related to high-pressure hydrogen storage. To tackle the problem of hydrogen storage, researchers have proposed the onboard hydrogen generation engines (Frenette and Forthoffer, 2009; Shusheng et al., 2020). The fuel cell electric vehicle is an onboard hydrogen-generation type in the design scheme that provides rapid hydrogen supply. Moreover, a self-heating reforming technology combining methanol vapour reforming and partial oxidation reforming being utilized (Özcan and Garip, 2020). The car is powered by a hybrid system that includes a lithium battery and a hydrogen fuel cell. The aforesaid approach is different from hydrogen storage fuel cell vehicles. It eliminates the hydrogenation process and the high-pressure hydrogen storage device, and drives the motor with the fuel cell as the primary power source, while the lithium battery as a backup. Based on the structure of the fuel cell electric vehicle designed in the literature (Li et al., 2016; Shusheng et al., 2020), the vehicle's critical components, such as a hydrogen production system, electric drive system, auxiliary power supply, and management system, were evaluated, and their management and control techniques were described.

### 3.1 Production of Hydrogen

Hydrogen may be produced using both renewable and fossil fuel technologies. Steam reforming, partial oxidation, auto thermal oxidation, and gasification are all methods for producing hydrogen from fossil fuels. By gasifying biomass/biofuels and





**FIGURE 5 |** Hydrogen production sources (Arat and Sürer, 2017)

splitting water with solar or wind energy, hydrogen can be synthesized from renewable energy sources (Apostolou, 2020). The Hydrogen production sources and technologies are shown in **Figure 5**.

The extraction of hydrogen from coal is the highest among all sources, approximately 21.5 billion tons/year, which need to be replaced by renewable resources.

### 3.1.1 Categorization of Hydrogen Based on the Source of Generation

By the adaptation of different technology and considered sources, hydrogen production has been categorized into three types according to the literature and study reports (von Döllen et al., 2021; Noussan et al., 2021). The utilization of major sources for the production of hydrogen has introduced the color conceptualization. By the application of fossil fuel for the generation of hydrogen leads to the emission of CO<sub>2</sub> and greenhouse gases. This technology of hydrogen production and its utilized source refers to grey hydrogen (Ivanenko, 2020). Blue hydrogen was introduced, while the grey hydrogen production approach was used to lower the quantity of greenhouse gas emissions in hydrogen production (Mari et al., 2016; Dickel, 2020). The utilization of fossil fuel, industrial gas, by-product gas, natural gas for hydrogen production for sustainable mobility as energy resources generally emit pollutants, and greenhouse gases to the environment (Jovan and Dolanc, 2020; Luo et al., 2020; Schiro et al., 2020). In a case study of a Slovenian hydro power plant, the possibility for green hydrogen generation was examined. If it is not burdened by different environmental fees, hydrogen can be competitive in the transportation sector (Jovan and Dolanc, 2020). Renewable hydrogen generation is a reliable alternative since this energy vector can be quickly created from electricity and injected into existing natural gas infrastructure, allowing for storage and transit (Schiro et al., 2020). The economic analysis of hydrogen was applied to hydrogen produced by natural gas, coal, and water electrolysis and conveyed in the form of high-pressure hydrogen gas or cryogenic liquid hydrogen. The cost of hydrogen produced from natural gas and coal is now cheaper, but it is heavily influenced by the cost of hydrogen purification and the price of carbon trading. Given the impact of future production technologies, raw material costs, and rising demands for sustainable energy development on hydrogen energy costs, it is

suggested that renewable energy curtailment be used as a source of electricity and multi-stack system electrolyzers be used as large-scale electrolysis equipment, in combination with cryogenic liquid hydrogen transportation or on-site hydrogen production (Luo et al., 2020). To reduce these pollutants affecting the atmosphere, literature has reported various technological modifications for hydrogen generation. Therefore, the utilization of renewable energy resources for hydrogen generation has been reported in recent works of literature (Boretti, 2020; Manna et al., 2021; Rabiee et al., 2021). Green hydrogen is also resultants of electrolyzers produced by renewable energies. It has been also noticed that green hydrogen can be also produced from bioenergy such as biomethane and biomass combustion. As the green hydrogen generated from various methodologies has net-zero gas emission, researchers and industries have more attention towards its production advancement (Manna et al., 2021; Rabiee et al., 2021). Categories of Hydrogen generation is presented in **Figure 6**.

Hydrogen production from different sources and emission from it is tabulated in **Table 2**.

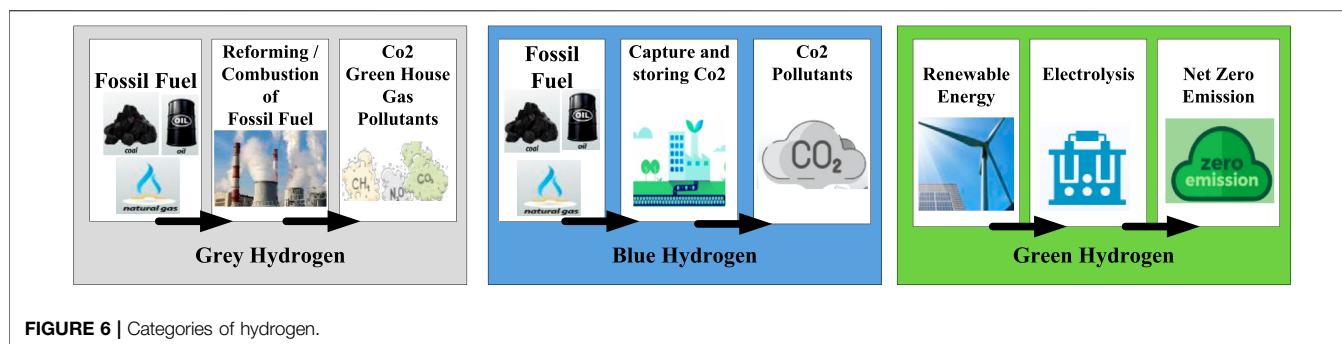
At present, coal is the primary source of hydrogen extraction, but the process emits GHGs. Hydrogen extraction through photocatalytic water decomposition with solar energy is the least popular process, with 1.8 billion tons of hydrogen annually. **Table 2**, concludes that the hydrogen production from photocatalytic water decomposition with solar energy is emission-free and the most sustainable path.

### 3.1.2 Water Electrolysis to Generate Hydrogen

Water as a feedstock is one of the most environmentally beneficial ways to produce hydrogen as it releases only oxygen as a by-product during processing. Green hydrogen is hydrogen produced by the breakdown of water using renewable energy sources. Electrolysis is currently the most established commercially accessible process for producing hydrogen from water. Water electrolysis is the process of breaking down water (H<sub>2</sub>O) into its constituent's hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>) using electric current (Hydrogen-Production-Through-Electrolysis, 1927). Positive ions (H<sup>+</sup>) are drawn to the cathode, whereas negative ions (OH<sup>-</sup>) are drawn to the anode by the electric potential. Alkaline water electrolysis (AEL), proton exchange membrane (PEM) water electrolysis, solid oxide water electrolysis (SOE), and alkaline anion exchange membrane (AEM) water electrolysis are some of the water electrolysis procedures (Chi and Yu, 2018) as depicted in **Figure 7**.

Comparative analysis of different water electrolysis processes to generate hydrogen (Hydrogen-Production-By-Electrolysis-Ann-Cornell, 2017; Hydrogen-Production-Through-Electrolysis, 2017; ArticleLanding, 2020) is tabulated in **Table 3**.

Use of AEM water electrolysis could allow low-cost transition metals to replace traditional noble metal electrocatalysts (Pt, Pd, Ru, and Ir). AEM electrolysis has garnered special interest due to its high power efficiency, membrane stability, durability, ease of handling, and low-cost hydrogen-production method (Vincent and Bessarabov, 2018), despite being a developing technology. Aside from the high energy consumption induced by the rise in

**TABLE 2 |** Hydrogen production from different sources and emissions.

Hydrogen extraction source	Quantity (billion tons/year)	Technical details	Emission	Ref no.
Coal	21.5	Homogeneous and high-speed reaction ought to its special physical and chemical process	GHG emission	(Li et al., 2010; Hui et al., 2017; Wang et al., 2020; Sun et al., 2021)
Industrial gas	12.5	Physical and chemical process	GHG emission with pollutants	(Violetto et al., 2019; Ates and Ozcan, 2020; Okolie et al., 2021)
By product gas	7.07	Physical and chemical process	GHG emission	(Violetto et al., 2019; Okolie et al., 2021)
Natural gas	4.6	Chemical process	Pollutants	(Perdikaris et al., 2010; Bicer and Khalid, 2020; Mayrhofer et al., 2021)
Electrolyzed water	2.1	Chemical process	Pollutants	(Mayrhofer et al., 2021; Sun et al., 2021)
Photocatalytic water decomposition with solar energy	1.8	Photocatalytic process	No GHG emission	(Jiang et al., 2013; Yan et al., 2013; Zhang et al., 2013; Tasleem and Tahir, 2020)
Biological H <sub>2</sub> production	2.05	Microorganisms and their metabolic mechanisms	Pollutants	(Bi et al., 2010; Cormos, 2012; Cao et al., 2020)

electrolysis voltage generated by the bubbles developed during the electrolysis process (Hu et al., 2019), high energy consumption is another barrier of hydrogen synthesis from water electrolysis. Hydrocarbons can be used in water electrolysis to reduce energy usage. Cheap metals or nonmetal composite materials, such as Ni, should be the electrodes' likely future direction.

The following are the major future directions to be investigated in the water electrolysis process of hydrogen generation:

- In-depth investigation of the reaction process in order to improve hydrogen generation efficiency and achieve conversion by combining chemical and electrical energy;
- Reduction in energy intake in the electrolysis process of water using renewable energy;
- In-depth investigation of the reaction process in order to improve the efficiency of hydrogen production;
- Improvements in electrode stability and corrosion resistance for increased longevity and lower electrode costs;
- Development of new catalytic electrodes and catalysts to improve reaction efficiency (Gao et al., 2019; Huang et al., 2019).

Hydrogen power is a promising technique for storing fluctuating Renewable Energy (RE) to establish a 100% renewable and sustainable hydrogen economy (Dawood et al., 2020). Hydrogen can be stored as gas or liquid form. High-

pressure tanks (350.00–700.00 bar tank pressure) are primarily used to store hydrogen as a gas. Cryogenic temperatures are required to store hydrogen as a liquid (Hydrogen Storage, 2021). Sapru (2002) have given an summary on hydrogen storage systems, based on storage tanks integrated with fuel cells.

### 3.2 Hydrogen Storage

Hydrogen holds excellent potential to be an energy carrier, especially for fuel cell applications. With high calorific value, it is also termed as regenerative and environmentally friendly fuel. Additionally, it has energy density of 142 MJ/kg, which is three times of petroleum (47 MJ/kg) (Kaur et al., 2016). This makes hydrogen as the most efficient fuel to replace petroleum-based vehicular. Thus, fossil fuel reliability can be reduced to fulfil all the global energy demands (Muir and Yao, 2011). Carbon and Hydrogen cycle are shown in **Figure 8**. The combustion process is shown below in blue arrows. The cycle shows how CO<sub>2</sub> released causes global warming (presented by black arrows). On the other hand, the hydrogen cycle is presented by green arrows and pointing towards renewable energy sources (Kaur et al., 2019).

Hydrogen energy has also been projected as a widespread resolution for a secure energy future to increase energy security and strengthen developing countries' economies (Marrero-Alfonso et al., 2009). Various technological, significant scientific, and economic challenges must be overcome before hydrogen can be used as a clean fuel source and the transition

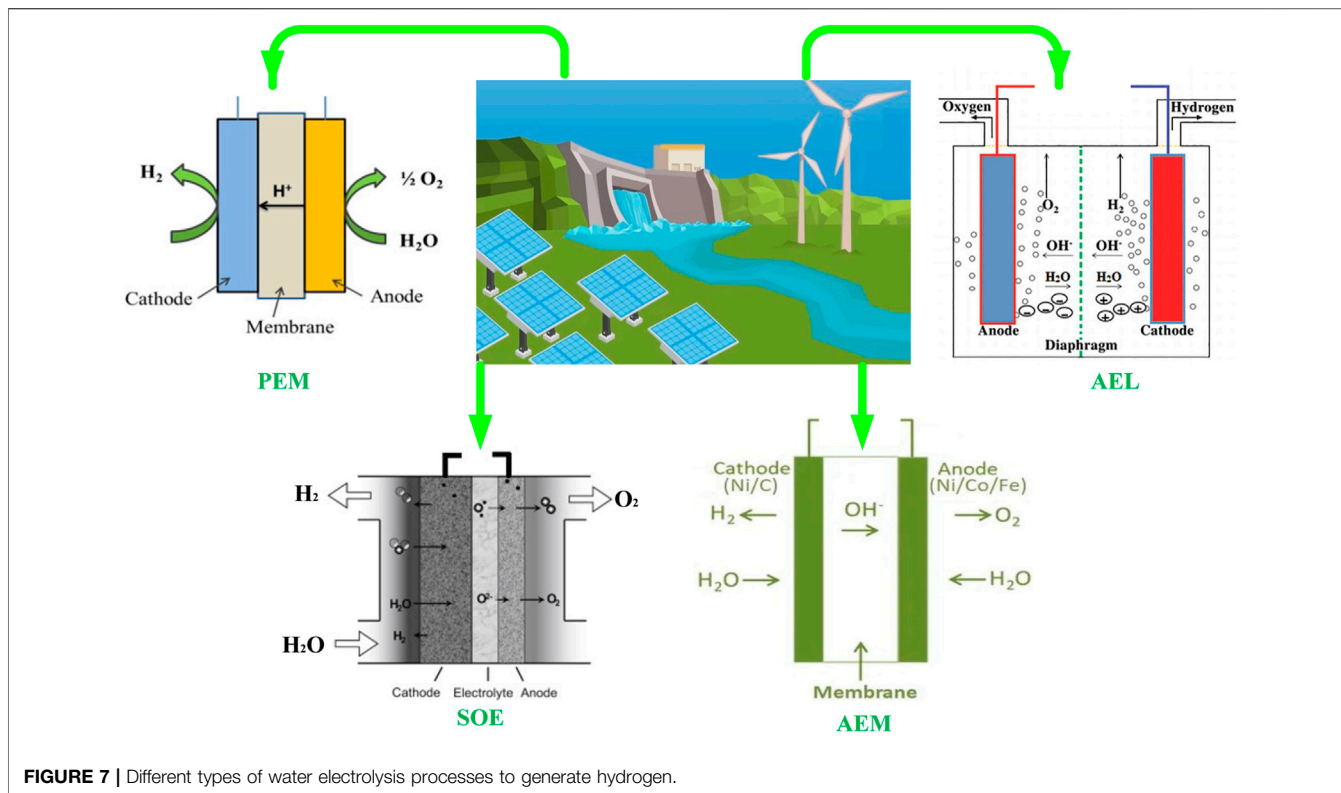


FIGURE 7 | Different types of water electrolysis processes to generate hydrogen.

TABLE 3 | Comparative analysis of different types of water electrolysis process to generate hydrogen.

Technology	AEL	PEM	SOE	AEM
Electrolyte	Aqueous KOH (20–40 wt%)	Proton exchange ionomer (e.g., Nafion)	solid-oxide	Anion exchange ionomer (e.g., AS-4) + optional dilute caustic solution
Cathode	Ni, Ni–Mo alloys	Pt, Pt–Pd	Ni-YSZ (yttria-stabilized zirconia)	Ni and Ni alloys
Anode	Ni, Ni–Co alloys	RuO <sub>2</sub> , IrO <sub>2</sub>	Lanthanum strontium manganate	Ni, Fe, Co oxides
Charge carriers	OH <sup>-</sup> , K <sup>+</sup>	H <sup>+</sup>	O <sup>2-</sup>	OH <sup>-</sup>
Operating temperature	100°–150°C	70°–90°C	700°C–800°C	50°C–60°C
Cell voltage (V)	1.8–2.4	1.8–2.2	1.6–1.8	1.8–2.2
Technology status	Mature	Commercial	Not yet commercial Pilot scale	R&D

from a carbon-based fossil fuel energy system to a hydrogen-based economy can be completed (Shashikala, 152012).

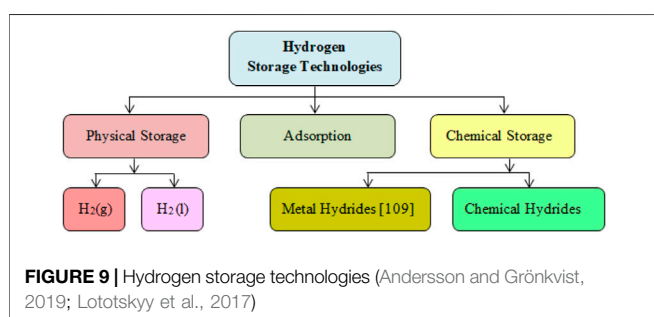
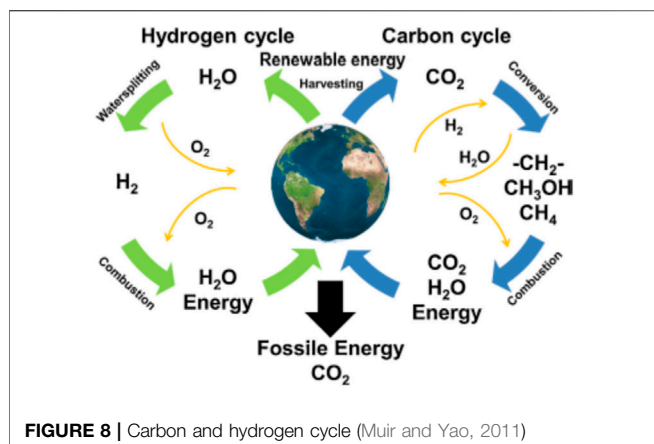
Additionally, in the transportation sector, hydrogen storage technologies are in consideration and gradually move towards designing highly efficient systems. For example, specific criteria are looked into, such as thermal stability of the system, gravimetric and volumetric densities and cost of the operating systems. Many of these sectors are being worked on, and improvements in hydrogen production and storage for various

automotive applications have been made and deployed (Shang and Chen, 2006).

### 3.2.1 Hydrogen Storage Methods

Hydrogen storage methods can be categorized into three groups, as shown in Figure 9. Molecular hydrogen can be stored as (1) a gas or a liquid without any significant physical or chemical bonding to other materials; (2) molecular hydrogen can be adsorbed onto or into material and held in place by relatively weak physical van der Waals





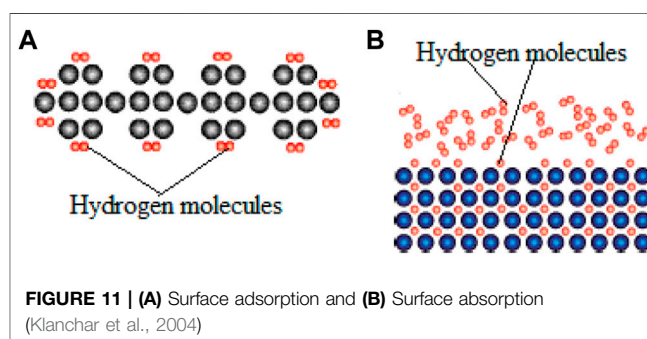
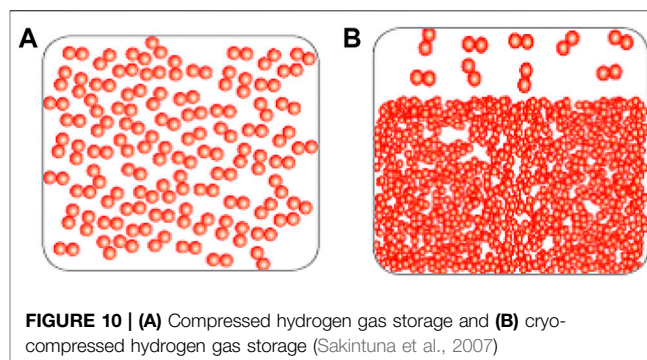
bonds; (3) atomic hydrogen can be covalently bound (absorbed). The spread of hydrogen fueling stations across the transportation network, as well as investment in hydrogen fueling stations, can lead to increased profits (El-Taweel et al., 2019).

### 3.2.1.1 Compressed/Physical Hydrogen Storage

Hydrogen is stored at high pressure and in compressed form and specifically designed hydrogen cylinders reinforced by carbon fibre that can withstand very high pressure. Various concerns should be handled before using this technology, like high-pressure requirements, low volumetric density, energy required to compress hydrogen gas, and cylinder weight and to reduce the overall cost (Sakintuna et al., 2007).

Hydrogen can also be stored in cyro-compressed form by cooling hydrogen gas to  $-253^{\circ}\text{C}$ ; this process increases the volumetric storage capacity of hydrogen gas by 4 times. However, this process is highly energy intensive due to energy requirements for compressing and liquifying hydrogen gas. There are further limitations, such as liquid hydrogen being very volatile and potentially forming an explosive combination with air if evaporated. Thus, this system should be designed to cover all the safety concerns (Sakintuna et al., 2007). **Figure 10** shows hydrogen gas in the form of compressed gas and cryogenic liquid.

The weight, volume, cost, efficiency, codes, and standards are the primary problems in hydrogen storage. New materials, particularly polymers, must be developed as barrier materials to limit hydrogen leakage in storage tanks with high energy-to-weight ratios (Macher et al., 2021).



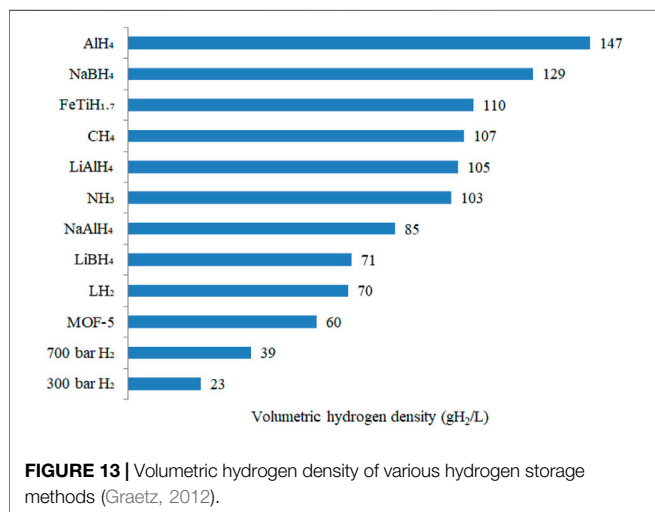
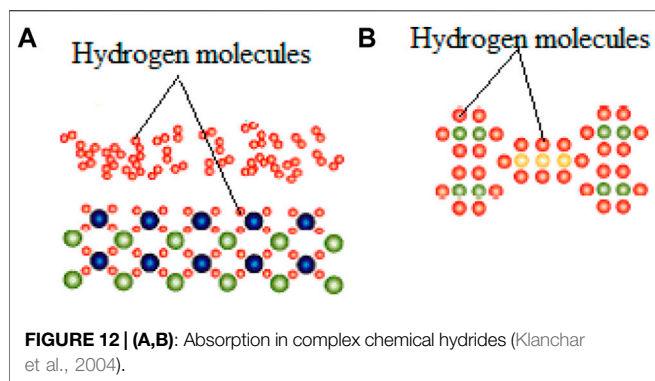
### 3.2.1.2 Material Based Hydrogen Storage

In materials, hydrogen is generally stored as absorption, adsorption, and chemical reaction. If hydrogen is stored on the surface, then the phenomenon is called adsorption, and if it is stored within the solids, it is called absorption. The main difference is in the density as it increases from adsorption to absorption. Adsorption is further divided into chemisorption and physisorption based on their mechanism. Physisorbed hydrogen is weakly bonded than chemisorbed hydrogen molecules. Also, it involves highly porous materials with high surface areas to efficiently uptake and release hydrogen molecules from the materials, such as metal hydride hydrogen storage.

However, absorption involves hydrogen atoms attached with strong bonds within the chemicals. Here, hydrogen is stored in large amounts with small quantities of materials also could be released at low temperature and pressure. For example, in complex and chemical hydrides, hydrogen is absorbed in the materials, as shown in **Figure 11** (Klanchar et al., 2004).

### 3.2.1.3 Chemical Hydrogen Storage Pathway

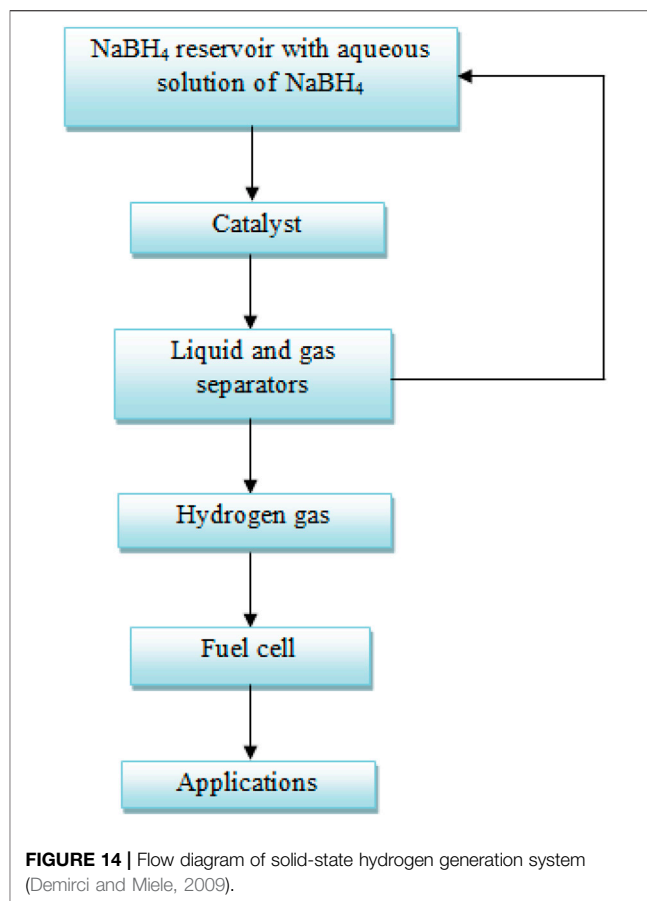
When hydrogen is generated and released through the chemical reaction, then the storage technology is defined as chemical hydrogen storage. The basic reactions involve the reaction of chemical hydrides with water and alcohols. However, this technology suffers lack of reversible onboard reactions and require spent fuel and by-products to be removed off-board. Here, hydrogen is strongly bonded as hydrogen atoms within the molecular structures of the chemical compounds, as presented in **Figure 12**. Therefore, for hydrogen generation and storage, a chemical reaction is required.



As hydrogen is stored in chemical hydrides, these hydrides in the form of materials have high gravimetric and volumetric densities. Thus, hydrogen is released in the form of chemical reactions. There are two methods of hydrogen release; the first is hydrolysis, and the second is thermolysis. The former one requires low temperature and pressure, and the theoretical storage efficiency is very high. The latter one involves highly sophisticated technologies and energy requirements to break the hydrides by thermal pathways. Considering that few common chemical hydrides that release hydrogen by hydrolysis pathway are sodium, lithium, magnesium, calcium, titanium hydrides, and few of complex hydrides are sodium borohydride, lithium aluminium hydride and lithium borohydride (Klanchar et al., 2004).

**Figure 13** presents various hydrides per their volumetric storage densities, with AlH<sub>3</sub> having the highest value and pressurized tanks with the lowest values (Graetz, 2012). As shown in **Figure 14**.

The catalyst for the reaction is supplied in the form of an aqueous solution of NaBH<sub>4</sub> as a chemical hydride. This solution is run through a separator, which separates the pure hydrogen gas from the rest of the mixture. This pure hydrogen gas is then pumped into the fuel cell, where it can be used. After the recycling procedure, the by-products might be returned to the liquid reservoir and used again (Demirci and Miele, 2009).



As a clean resource, hydrogen energy might minimise energy savings and emissions caused by the use of fossil fuels, and it will likely play an increasingly important role in the future (Zhang et al., 2019a). In recent decades, the PEMFC (proton exchange membrane fuel cell or polymer electrolyte membrane fuel cell), which effectively transforms the chemical energy inherent in hydrogen into electricity without producing pollutants, has piqued interest in automotive applications (Ogungbemi et al., 2021).

### 3.3 Proton Exchange Fuel Cells

FCVs (fuel cell vehicles) powered by PEMFC have recently reached mass production, such as Toyota's Mirai, Honda's Clarity, and Hyundai's NEXO. Performance should be increased at a cheaper cost to improve its commercial uses.

The European Union and the US alone stand out alone in the majority to consume all petroleum products and energy demands. This has led to the development of alternative energy sources, with the best ones stated as hydrogen, synthetic fuels and biofuels. These energy sources are investigated for their suitability to sustain a clean form of energy (Ogungbemi et al., 2021). The source where hydrogen is produced from renewable energy to electricity by PEM fuel cells are under investigation. The PEM cells are capable of producing sufficient power to sustain commercial and residential usage under varying temperatures.

For example, a PEM fuel cell generator with Na metal and water chemical reaction generated hydrogen with minimum emissions and noise. This has extended its use to medium and high duty vehicular applications. Despite all such uses, PEM fuel cells face few disadvantages (Ijaodola et al., 2019) and studies are in progress based on economics, policy framework and advancements in electrolysis process to facilitate the use of PEM fuel cells for vehicular and general use. Due to myriads of advantages like low operating temperature, solid electrolyte and high power density, durability and reliability proton exchange, fuel cells can be used in several areas like on-site hydrogen generation, automotive, and portable electronic devices as discussed. The parameters of PEM fuel cells are based on operating conditions, and to accurately estimate its characteristics; research is also in progress with efficient mathematical modelling. It can disclose more about operating parameters linked with the PEM fuel cells (Rao et al., 2019a; Kandidayeni et al., 2019). Studies are also in progress to study the dynamic loading on the performance of PEMFC (Zhang et al., 2019b; Huang et al., 2020). The situation arises when unreasonable loading conditions increase and could even lead to failure (Mayyas et al., 2014) thus, adding to the disadvantages of the fuel cells. This could be explained as when PEM FC is used as a mechanical power source, it undergoes dynamic loading and response voltage becomes lower than the steady-state conditions; subsequently, the voltage increases gradually. This could lead to unfavourable operations of PEM fuel cells, and thus, dynamic performance needs to be studied.

Proton Exchange fuel cells have wide application in various sectors like power plants, transportation, digital devices etc. However, the short life span due to the degradation and reusability of fuel cells limits its applications in the commercial sector (Chen et al., 2019). Considering the lifespan of fuel cells in mobile applications, it is 3,000 h, but the demand rises to 5000 h to be used commercially. As per DOE (United States Department of Energy), the set future goals for transportation and stationary applications of PEM fuel cells as 5,000 h and 40,000 h, respectively, by 2020 with performance degradation that should be less than 10% (Ren et al., 2020). The considerable difference between stationary and transportation can be attributed to different designs as fuel cells in vehicles encounter harsh conditions like the open-circuit voltage, dynamic load, startup and shutdown, overload and freezing thaw. Thus, the decay of fuel cells in vehicular applications is also thoroughly studied by developing various test protocols. With the performance of fuel cells, cost factors are also in consideration like The Strategic Analysis Inc. studied the most influencing factors on the cost of FC's in 2012 and 2017 (Li et al., 2020). The report (2012) concluded that the fuel cell stack and platinum loading are the most important factors which affect the cost of the fuel cells. Since then, the study has also focused on a low Pt-based catalyst that made significant development in Pt-M alloys, Pt-based core shell, and Pt-based nanostructure. Gradually this development led to Pt-free catalysts like carbon alloy catalysts in commercial markets in Japan. Thus, it can be stated that PEM fuel cells hold the potential to establish a hydrogen economy for a secure and sustainable future.

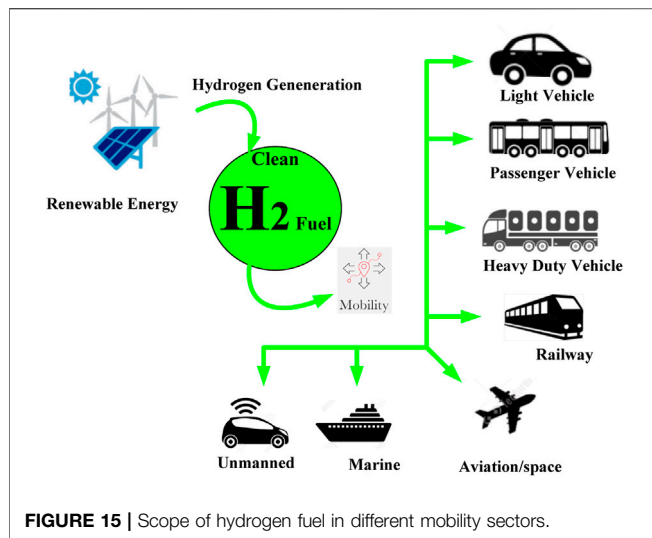
## 4 HYDROGEN BASED MOBILITY

Promotion of hydrogen vehicles as the future transportation platform has been chosen due to its zero-pollutant discharge characteristic. Hydrogen fuel cell vehicle technology has the scope to various categories of mobility sectors. This technology can replace lightweight vehicles, heavy goods vehicles, heavy passenger vehicles, trains, and unmanned vehicles. Adopting the concept of hydrogen fuel for heavy vehicles has attracted New Zealand and Paris to meet the zero climate change commitments. As reported in (MBIE, 2019), the proper examination of feasibility for adopting clean hydrogen for heavy vehicles exceeds 30 tons has been discussed in (Concept Consulting Group, 2021; Perez et al., 2021).

Apart from the development of hydrogen fuel, heavy and very heavy-duty vehicles, public lightweight vehicles, and passenger buses require a shift towards utilization of clean hydrogen (Topler and Lordache, 2017; Air Liquide Will Build the First High-pressure Hydrogen Refueling Station for Long-haul Trucks, 2021). Air Liquide has announced the opening of Europe's first high-pressure hydrogen filling station, which will support the first fleet of long-haul hydrogen vehicles (Air Liquide Will Build the First High-pressure Hydrogen Refueling Station for Long-haul Trucks, 2021). This investment is in line with the Group's objective of accelerating hydrogen energy adoption through large-scale initiatives, notably in the heavy vehicle category. Vulnerabilities of Hydrogen Energy in Emerging Markets describes strategies and developments for hydrogen civilization efforts implemented by various stakeholders in different countries and at different stages of the development cycle, including authorities, institutes, research, industry, and individuals (Topler and Lordache, 2017). Considering these facts, Germany has taken the lead in the global market for the commercialization of Hydrogen vehicles, along with the collaborators from Japan, Korea and the United States (Galich and Marz, 2012; Trencher and Edianto, 2021). Hydrogen and fuel cell technologies have the potential to help create a more environmentally friendly and emission-free transportation and energy system (Galich and Marz, 2012). Policymakers and automotive players throughout the world attempt to expedite the electrification of road transport using hydrogen (Trencher and Edianto, 2021). They examined and contrasted the factors impacting the production and market penetration of privately owned fuel cell electric passenger vehicles (FCEVs) and fuel cell electric buses (FCEBs) in public transportation fleets.

### 4.1 Hydrogen Vehicles

In the present time, railway is the most economical transportation preferred by the common citizen as well as it is also used for goods transportation. The conventional railway depends upon the fossil fuels leads to the emission of GHGs and the generation of sound pollution. In the line, to meet zero-emission and zero sound railway transportation, InnoTrans in 2016 of Berlin developed the Coradia iLint. This has been commercialized and launched in 2020 to run for 100 km between Cuxhaven, Bremerhaven, Bremervoerde and Buxtehude in northern Germany (Low et al., 2020). Understanding the requirement and need for replacing clean hydrogen fuel transportation with the second largest railway



network in the world, the Indian Railway has also started developing and testing passenger fuel cell train set (Jhunjhunwala et al., 2018).

Conventional fuel engines utilized in the shipping industries release the air pollutants and GHGs into the environment. In the regulation of these harmful gases, International Maritime Organization (IMO) has passed an article to prevent pollution from the ships under (World's First Hydrogen Train Runs Route in Germany, 2021; Traction: India to trial fuel cell trainset, 2021). Enhanced efficiency of the marine fuel cells for various applications of onboard ships has motivated the researchers to focus on hydrogen fuel-based marine engines. Electricity generation, emergency power supply and power propulsion are the major power requirement in an onboard ship, which can be generated through clean hydrogen fuel cells by replacing conventional fuels (Sattler, 2000; IMO, 2012a; IMO, 2012b). Fuel cells have a lot of potential for usage on ships. Fuel cells on merchant ships and naval surface ships can be used for a variety of purposes, including: (1) emergency power generation; (2) electric energy generation, particularly in waters and harbours with strict environmental regulations; (3) small power output for propulsion in special operating modes (e.g., very quiet run); and (4) electric power generation for the ship's network and, if necessary, the propulsion network on ships equipped with fuel cells (e.g., naval vessels as all-electric ships, AES) (Sattler, 2000). The actual requirement, replacement and advantage of combustion fuel engine by clean hydrogen fuel cell-based engine have been discussed in detail in (Leo et al., 2010; Tronstad et al., 2017). Submarines are now the most common marine use of fuel cells. In this industry, hydrogen/oxygen polymer electrolyte membrane (PEM) fuel cells are often utilized (Leo et al., 2010). The scope of hydrogen fuel in different mobility sectors is depicted in **Figure 15**.

The target to achieve limited emission fuel to protect the climate, world aviation industries have also focused on clean hydrogen as an efficient candidate for short and long-range aviation and space transportation (de-Troya et al., 2016). The research and development in aviation and space sector industries have reported continuous progress for choosing clean hydrogen fuel. The aviation and space industries of the United States

(Committee on Air Force and Department of Defense Aerospace Propulsion Needs, 2006; Cecere et al., 2014; van Biert et al., 2016), Japan (Dawson, 2004; Dale Reed and Lister, 2011), Europe (Negoro, 2007), India (Sekigawa and Mecham, 1996; Chopinet et al., 2011), China (Rao et al., 2019b) and Russia (Lele, 2006) have already reported the developmental progress for hydrogen fuel technology adaptation.

The advancement of transportation in different segments and requirements has led to the development of unmanned vehicles. The most popular sector under this category is unmanned cars and unmanned Aerial vehicles (UAV) (Tan, 2013). For UAV applications, various countries have focused the efficiency to cover longer distances and enhanced performance by replacing conventional fuel with clean hydrogen fuels (Sergienko, 1993; Wang et al., 2013). The development of Hydrogen mobility in different sectors are tabulated in **Table 4**.

It has been studied and reported that utilization of hydrogen fuel cell vehicles has been pointed in the United States and 5,899 hydrogen vehicles developed for commercialization (Bayrak et al., 2020). For the promotion of hydrogen utilized vehicles, companies like Toyota Mirai, Honda Clarity, Renault–Nissan, General Motors and Honda have formed alliances for the joint production (Giacoppo et al., 2017; Dudek et al., 2021).

## 4.2 Fuel Cells Electronic Vehicles







Vehicle manufacturers began producing hydrogen fuel passenger vehicles in 2002 (Tanç et al., 2018) due to an increase in the number of researchers interested in Fuel Cell Electronic Vehicles (FCEVs). They've been manufacturing a variety of models up to now. In addition to passenger automobiles (Lee et al., 2019; Tanç et al., 2020), these manufacturers are known to work with light commercial vehicles (Matulić et al., 2019), buses (de Miranda et al., 2017), and trucks (Lee et al., 2018). **Table 5**, lists all commercially available FCEVs, as well as their manufacturers and special features.

In recent years, the majority of passenger car manufacturers have started developing FCEVs. General Motors, Toyota, and Honda produce their own FC stacks, whereas Ford, Mazda, DaimlerChrysler, Mazda, Hyundai, Fiat, and Volkswagen purchase them from FC manufacturers. It is apparent from the specifications of available FCEVs that battery hybridization is currently favoured. Furthermore, automakers such as Honda, Hyundai, and Mercedes have recently developed plug-in FCEVs. Proton Exchange Membrane Fuel Cell is the most prevalent FC stack, and its efficiency for FCEVs is improving continuously. Detail specifications of the commercialized presently dominating FCEV for sale or leasing (Wasserstoffautos, 2021) are tabulated in **Table 6**.

For a shift from a carbon-based (fossil fuel) energy system to a hydrogen-based economy, three key technological hurdles (Chang et al., 2019) must be overcome that are as follows.

- 1) To compete with other options, the cost of efficient and sustainable hydrogen generation and transport must be considerably decreased.
- 2) In order to, offer an appropriate driving range, new generations of hydrogen storage technologies for vehicle applications must be created.

**TABLE 4** | Development of Hydrogen Mobility in different sectors.

Mobility type	Country	Status	Ref no.
Heavy Duty Vehicles 	New Zealand	<ul style="list-style-type: none"> <li>• Examination of feasibility</li> <li>• Energy strategy</li> <li>• Assessment of Potential</li> </ul>	(MBIE, 2019; Concept Consulting Group, 2021; Perez et al., 2021)
	Paris	<ul style="list-style-type: none"> <li>• Development of Vehicles</li> </ul>	Air Liquide Will Build the First High-pressure Hydrogen Refueling Station for Long-haul Trucks, (2021)
• Fuel Station Light weight vehicles 	Germany	<ul style="list-style-type: none"> <li>• Development</li> <li>• Commercialization</li> </ul>	(Galich and Marz, 2012; Topler and Lordache, 2017; Trencher and Edianto, 2021)
	Japan	<ul style="list-style-type: none"> <li>• Development of cars by 2030</li> </ul>	Low et al. (2020)
	South Korea	<ul style="list-style-type: none"> <li>• Development</li> <li>• Commercialization</li> </ul>	Low et al. (2020)
	US	<ul style="list-style-type: none"> <li>• Development</li> <li>• Commercialization</li> </ul>	Low et al. (2020)
Railway transportation 	India	<ul style="list-style-type: none"> <li>• Development</li> <li>• Research</li> </ul>	Jhunjunwala et al. (2018)
	Northern Germany	<ul style="list-style-type: none"> <li>• Commercialized (Germany)</li> </ul>	World's First Hydrogen Train Runs Route in Germany, (2021)
	India	<ul style="list-style-type: none"> <li>• Developmental (India)</li> <li>• Commercialization Process</li> </ul>	[137]
Shipping industries 	United Kingdom	<ul style="list-style-type: none"> <li>• Developmental stage</li> </ul>	(Sattler, 2000; IMO, 2012a; IMO, 2012b)
	Norway	<ul style="list-style-type: none"> <li>• Risk &amp; Safety aspects Analysis</li> </ul>	(Tronstad et al., 2017; Leo et al., 2010; de-Troya et al., 2016; van Biert et al., 2016)
Aviation and Space 	United states	<ul style="list-style-type: none"> <li>• Developmental Progress</li> </ul>	(Dawson, 2004; Committee on Air Force and Department of Defense Aerospace Propulsion Needs, 2006; Dale Reed and Lister, 2011)
	Japan	<ul style="list-style-type: none"> <li>• Progress, Testing and Safety Assessment</li> </ul>	Negoro, (2007)
	India	<ul style="list-style-type: none"> <li>• Developmental Progress</li> </ul>	(Lele, 2006; Rao et al., 2019b)
	Europe	<ul style="list-style-type: none"> <li>• Testing</li> </ul>	Tan, (2013)
	China	<ul style="list-style-type: none"> <li>• Testing</li> </ul>	Wang et al. (2013)
Unmanned Cars, Unmanned Aerial vehicles 	Turkey	<ul style="list-style-type: none"> <li>• Developmental Progress</li> </ul>	(Sergienko, 1993; Tan, 2013; Wang et al., 2013)
	Italy	<ul style="list-style-type: none"> <li>• Progress, Testing and Safety Assessment</li> </ul>	(Giacoppo et al., 2017; Bayrak et al., 2020)
	China	<ul style="list-style-type: none"> <li>• Developmental Progress</li> </ul>	Chang et al. (2019)

3) Fuel-cell and other hydrogen-based technologies must be less expensive while having a longer useful life.









In this context, the future market of hydrogen transportation and distribution are determined mainly by four factors (Edwards et al., 2008; Olabi et al., 2021): (a) Cost of hydrogen in future, (b) the rate of advancement of various hydrogen-based technologies, (c) restriction in GHG emission, and (d) the cost of competing for alternative transportation systems. Hydrogen has the potential to be a long-term option for sustainable mobility with several social, economic, and environmental benefits (Forsberg, 2005). It can

minimize reliance/dependency on fossil fuels and reduce carbon emissions from the transportation industry in the long run.

### 4.3 Techno Economic Aspects






The cost and performance competitiveness of fuel cell electric vehicles (FCEV) in the car industry will determine their future. FCEV adoption in the present transportation industry is still modest. Many governments have yet to take a firm stance on hydrogen for transportation. In this regard, comprehensive energy plans for the road transportation sector are required. The use of energy systems modelling (ESM) to support energy planning is frequently advised in

**TABLE 5** | Commercially available FCEVs.

Model	Manufacturer	Appearance	Type	Range (km)	Top speed (km/h)	FC (type)	Interval (Year)	Leased/Marked in	Ref no.
Gumpert Nathalie	Gumpert Always Automobile (RG)		FC and Battery hybridization	820	300	Direct Methanol Fuel Cell (DMFC)	2021	Germany, China	Rolandgumpert, (2021)
Hyundai Nexo	Hyundai		FC, Battery and UC hybridization	600	179	PEMFC	2018-Present	South Korea, California, and Europe	Hyundai, (2021)
Toyota Mirai	Toyota		FC and Battery hybridization	502	160	PEMFC	2015-Present	Japan, California, Europe, Québec and United Arab Emirates	Energy.Gov, (2021)
Honda Clarity	Honda		FC and Battery hybridization	590	178	PEMFC	2016–2021	Japan, Southern California, Europe	Automobiles.Honda, (2021)
Hyundai ix35 FCEV	Hyundai		FC and Battery hybridization	594	160	PEMFC	2014–2018	South Korea, California, Europe and Vancouver	Environment Hydrogen-Fuel-Cell, (2021)
Mercedes-Benz F-Cell (B class)	Daimler AG		FC and Battery hybridization	402	132	PEMFC	2010–14	southern California	Mercedes-Benz, (2021)
Honda FCX Clarity	Honda		FC and Battery hybridization	560	160	PEMFC	2008–2015	United States, Europe and Japan	Matsunaga et al. (2009)
Chevrolet Equinox FC	General Motors		FC and Battery hybridization	320	141	PEMFC	2007–2009	California and New York	Eberle et al. (2016)

(Continued on following page)

**TABLE 5 |** (Continued) Commercially available FCEVs.

Model	Manufacturer	Appearance	Type	Range (km)	Top speed (km/h)	FC (type)	Interval (Year)	Leased/Marked in	Ref no.
Mercedes-Benz F-Cell (A-Class based)	Daimler AG		Full FCEV	160–180	132	PEMFC	2005–2007	United States, Europe, Singapore and Japan	Mercedes-Benz-Cars, (2021)
Nissan X-Trail FCV (2005 Model)	Nissan		FC, Battery and UC hybridization	500	150	PEFC	2003–2013	Japan and California	Nissan-Global, (2021)
2003 Model			FC and Battery hybridization	350	145	PEFC			
Ford Focus FCV	Ford		FC and Battery hybridization	320	129	PEMFC	2003–2006	California, Florida and Canada	Hydrogencarsnow, (2021)
Honda FCX-V4	Honda		FC and UC hybridization	315	140	PEMFC	2002–2007	America, Japan	Global.Honda, (2021)

this context, since it provides a scientific basis for the prospective evaluation of energy systems based on technical and economic factors across time (Bhattacharyya and Timilsina, 2010). Furthermore, by using life-cycle sustainability variables in the future evaluation, ESM studies might be improved (García-Gusano et al., 2016). A variety of pathways and important conversion technologies for biomass and organic solid waste to hydrogen have been investigated (Aziz, 2021). The potential for a techno-economic and environmental assessment

of the hydrogen production mix that might meet the hydrogen demand for road transport under various scenarios for FCEV penetration in Spain has been addressed (Navas-Anguita et al., 2020). Due to the reasonable costs of natural gas and the maturity of the technology, the hydrogen demand associated with the eventual penetration of FCEV in the Spanish road transport system may be totally met by conventional steam reforming of natural gas. The worldwide view on hydrogen energy systems, on the other hand,

**TABLE 6 |** Technical specifications of FCEVs which are presently dominating the market.

Model	Type	Range (km)	Electric motor (kW)	Tank capacity (kg)	Fuel consumption (H <sub>2</sub> ) Kg/100 km
Toyota MIRAI II	Fuel cell vehicle	650	135	5.6	0.76
Hyundai NEXO	Fuel cell vehicle-5th generation	756	120	6.33	0.84
Mercedes-Benz GLC F-CELL	Electric vehicle with fuel cell and li-ion battery	478	141.557 (Li-ion battery 13.8 kWh)	4.4	0.97
Honda Clarity Fuel Cell	Fuel cell vehicle	589	130	5	
Hyundai ix35	4th generation Fuel cell vehicle	594	100	5.64	1

refers to a hydrogen economy based on environmentally friendly solutions. Lin et al. (Lin et al., 2013) used a cost-based consumer choice model to examine the market adoption and social advantages of FCEVs from 2015 to 2050. For the Indian urban driving cycle, Shakdwipee and Banerjee compared fuel cell cars against petrol and CNG automobiles (Manish Shakdwipee, 2006). Primary energy consumption (MJ/km), CO<sub>2</sub> emissions (kg CO<sub>2</sub>/km), and cost (Rs./km) were used as comparison criteria. Fuel cell vehicles, they discovered, are more energy efficient and environmentally friendlier than gasoline automobiles. Fuel cell vehicles consume 43% less energy and emit 40% less CO<sub>2</sub> than gasoline automobiles. A techno-economic analysis is conducted to assess the feasibility of deploying Fuel Cell Electric Trucks (FCET) on the Oslo-Trondheim route in Norway (Diva-Portal, 2022). The output of the infrastructure's techno-economic model, which included various configurations and combinations of both hydrogen producing units (HPU) and hydrogen refuelling stations (HRS), was given in the form of a cost curve function based on the FCET's fleet size. The cheapest set-up was found, consisting of a 350-bar HRS for a type 3 onboard tank with hydrogen production connected directly to it. Future cost curves for FCETs and infrastructure that indicate development in 2030 were investigated. Chen and Melaina (Chen and Melaina, 2019) established a techno-economic analysis framework to analyse the cost and performance of main vehicle technologies (internal combustion, hybrid, plug-in hybrid, battery and fuel cell electric) under various advancement scenarios for the years 2035 and 2050. Based on a 5-years or 15-years ownership term, their findings suggest that the prices per mile for FCEVs are 36% or 22% more than those of regular gasoline automobiles in the 2035 scenarios. FCEVs have 15-years ownership costs that are equivalent to gasoline automobiles with comparable engineering performance in 2050 scenarios. Fuel cell cars have a cheaper driving cost in all of the 2035 and 2050 scenarios when compared to electric vehicles with a 200-mile range. To encourage the use of hydrogen as a passenger car fuel, the cost of an FCV must be reduced to at least the same level as that of an electric vehicle.

#### 4.4 Selected Implemented Projects, Policies and Challenges

Throughout the world many demonstration projects are implemented on hydrogen mobility. Some important implemented projects are discussed here. Han (2014) investigated the hydrogen fuel cell car demonstration projects in China, as well as their marketing methods. Their research indicated that hydrogen fuel cells are the most promising technology for reducing urban air pollution, saving energy, achieving sustainable mobility, and promoting technical change in the automobile sector. The Chinese government has adopted an ambitious strategy and is providing significant financial assistance for the development of hydrogen and related technologies. Aditiya and Aziz examined the possibility of establishing an inter-state hydrogen energy system on selected countries in the Asia-Pacific region, based on individual evaluations from the nexus of technology, social, and economic perspectives, and utilising the respective strengths to identify an inter-state hydrogen network strategy in the Asia-Pacific region, dubbed the "Asia-Pacific Hydrogen Valley"

(Aditiya and Aziz, 2021). Indonesia, Malaysia, Brunei Darussalam, the Philippines, Singapore, Vietnam, Thailand, Japan, South Korea, Australia, and New Zealand are among the countries assessed. According to the findings, countries with active hydrogen policies and high R&D capacity may lead the strategy, whilst countries with high primary energy supply capacity and an economic edge would aid the group in catering energy and commercial resources, respectively. The feasibility of using hydrogen cars in various modes of transportation, including personal automobiles, taxis, and shared mobility, was investigated (Turon., 2020). Hype is the first hydrogen-powered taxi fleet in the world. The first five cars were introduced to the system on 7 December 2015 at COP 21 by Société du Taxi Electrique Parisien ("STEP") (Hype, 2019). The fleet now consists of about 100 cars. Before the end of 2020, 600 cars are expected to be in use. The system's taxis have a range of more than 500 km. As a result, their charging time might be as long as 5 min (Hype, 2019). In 2016, the first attempts were made to develop a car-sharing system based on hydrogen-powered vehicles. The Linde Group commenced operations at that time by launching a service under the BeeZero brand in Munich, Germany. The system has a 50-vehicle fleet. Unfortunately, the system failed to work in June 2018 after 2 years of operation (Gas World Portal, 2018). The corporation claims that economic unprofitability was the cause for its demise. Unfortunately, one of the issues that car-sharing companies face is this type of issue (Gas World Portal, 2018). This is because car-sharing is a new type of urban transportation that is now being developed among today's communities that are accustomed to owning rather than renting a car (Turoń and Cokorilo, 2018). The introduction of hydrogen automobiles in the form of zero-emission buses is another alternative that allows the vehicle to reach the biggest number of people. A bus that uses electric energy generated by hydrogen in fuel cells or merely the engine whose cycle does not result in the production of greenhouse gases or other substances covered by the greenhouse gas emission management system (Polish Electromobility Act, 2018). An operator operating in Cologne or Wuppertal, Germany, is an example of how this type of bus may be implemented. Furthermore, this mode of transportation was so well received that a tender for the supply of a fleet of 40 cars was signed. Despite numerous dubious appraisals and public worries, primarily due to ignorance, hydrogen-powered cars appear to have a chance to becoming a viable alternative to conventional automobiles. The current condition of such vehicle use in various nations reflects a growing interest in green transportation technology and the hunt for diverse solutions that can assist transportation's long-term growth.

Many nations have strong hydrogen support policies, and hydrogen energy will become an essential element of the future global energy plan. Japan, the European Union, the United States, and South Korea all responded enthusiastically and pushed aggressively, with national policy support focusing on hydrogen energy fuel cell cars. Foreign subsidy programmes primarily targeted the consumption connection and were paid in the form of a purchase tax credit or a purchase subsidy. The United States is the first country to use hydrogen and fuel cells as an energy source. It first proposed the notion of "hydrogen



economy” in 1970, and in 1990, it passed the Hydrogen Research, Development, and Demonstration Act. The National Roadmap for Hydrogen Energy Development was announced by the US Department of Energy in November 2002, kicking off the methodical execution of the National Hydrogen Energy Plan (Wang et al., 2015). The United States of America designated October 8 as National Hydrogen and Fuel Cell Day of Remembrance in 2018. The total number of fuel-cell cars sold and leased in the United States as of 1 April 2020 was 8,285. Japan has implemented a variety of beneficial regulations aimed at speeding up the commercialization of hydrogen energy and fuel cells, with encouraging outcomes. Japan was the first country in the world to establish a comprehensive government strategy for the development of hydrogen and fuel cell technology, and the Basic Hydrogen Energy Strategy 2017 recommended that the government prepare for hydrogen and fuel cell development. Japan aims to build 320 hydrogen refuelling stations in 2025 and 900 in 2030, according to the Basic Hydrogen Energy Strategy issued in late 2017 (Wei and Chen, 2020). The Japanese government has spent hundreds of billions of yen on development and promotion of hydrogen and fuel cell technologies during the last 30 years. The EU sees hydrogen energy as a critical component of energy security and transformation. The EU Fuel Cell and Hydrogen Joint Action Plan (FCH JU) initiative offers major funding for the development and promotion of national energy and fuel cells across Europe. For the years 2014–2020, the entire budget was €665 million (European Commission, 2020). In Europe, there were 152 hydrogen refuelling stations in service by the end of 2018, with expectations to increase to 770 in 2025 and 1,500 in 2030, with roughly 1,080 fuel cell passenger cars being deployed. Since 2014, China has enacted a number of policies and measures reflecting the country’s commitment to the growth of the hydrogen and fuel cell industries, as well as the obvious trend of Chinese policies supporting the hydrogen industry’s development. According to the Ministry of Industry and Information Technology’s (MIIT) 2018 fuel cell vehicle subsidy criteria, the state provides up to 200,000, 300,000, and 500,000 yuan in subsidies for fuel cell passenger cars, medium commercial vehicles, and large commercial vehicles, respectively (Liu and Zhong, 2019). As a first step toward the National Hydrogen Mission, the Indian government announced the first phase of its Green Hydrogen Policy in 2021. The mission’s goal is to turn India into a green hydrogen centre that will assist the country reach its climate goals. It aims to produce five million metric tonnes per annum (MMTPA) of green hydrogen by 2030, as well as build renewable energy capacity in the process (Power-Technology, 2022).

Successful implementation of Hydrogen policy required extensive R&D to overcome the technical challenges to expedite the acceptance of hydrogen as future of sustainable mobility. The majority of hydrogen is now generated in a traditional manner, coming from the burning of fossil fuels, which emits a significant quantity of CO<sub>2</sub>. As a result, the primary difficulty is to create hydrogen utilising sustainable energy sources. This is a major step forward in the direction of green hydrogen. Only a few recharge stations exist across the

world. Even though some governments are willing to invest in the building of hydrogen charging stations, demand remains low, and these terminals do not now make enough profit. Hydrogen produced from renewable sources is highly costly and inefficient when compared to hydrogen produced from natural gas. Furthermore, hydrogen is still exceedingly explosive. It must be kept and transported in big containers under pressure. This creates security, logistical, and financial issues that continue to obstruct its usage (Solarimpulse, 2022). According to hydrogen features and behaviour, hydrogen monitoring needs, including international partnerships and formal agreements, legislation, codes, and standards, Foorginezhad et al. (Foorginezhad, 2021) investigated the safety difficulties with hydrogen fuel cell cars. The detection performance of hydrogen sensor types relevant to fuel cell cars, such as catalytic hydrogen, electrochemical, semi-conductive metal-oxide, thermal conductivity, optical, palladium (alloy) film-based, and combination technology-based sensors, is also reviewed. Finally, future options for sensing and monitoring technologies, as well as obstacles ahead in the use of hydrogen fuel cells in automobiles as a replacement for traditional equivalents, are presented.

## 5 CONCLUSION

To reduce climate change and the adverse effect of pollutants from conventional fuel vehicles, sustainable transportation development and commercialization have evolved rapidly in the last few years. The purpose of this study is to draw attention towards the sustainable mobility and implementation of sustainable development since there is substantial potential for establishing convergence between climate change mitigation efforts and sustainable development goals in the transportation sector. Focusing on the rise in environmental concerns like greenhouse gas emissions and environmental sustainability, hydrogen energy-based technology is considered the potential for future transportation. Technical aspects presenting hydrogen generation and storage methods reveal that hydrogen is the only future fuel satisfying the criteria for sustainable mobility and designing hydrogen-based vehicles.

The review also presents exciting insights into hydrogen-based vehicles in the marine, railways and aerospace industry and concludes that hydrogen-based fuel cell vehicles should be commercialized worldwide. The review findings would also guide academia about various technical features of fuel cell electric vehicles, and they would benefit from recommending more advanced technologies for the coming future. However, the transportation and distribution of hydrogen is another significant challenge, and this is a crucial consideration while transitioning to a hydrogen economy. Investigation into hydrogen fuel vehicles and their utilization in different mobility sectors have been rigorously reviewed. Undeveloped hydrogen technologies have a high implementation cost for proper commercialization, discouraging vehicle manufacturers from adopting the technology.

Nevertheless, a potentially significant advantage in terms of zero-emission to climate has attracted the researchers for its

early development and progress to enhance more widespread. Different nations' governments must coordinate their energy requirements for the future to increase the use of hydrogen as a transportation fuel. Policy and regulatory measures and increased worldwide funding for research and commercialization initiatives would undoubtedly pave the way for taking the first steps toward a hydrogen economy, which guarantees energy security. Hydrogen holds much promise in the transportation industry if the appropriate steps and procedures are taken to make it safe, dependable, and robust.

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## AUTHOR CONTRIBUTIONS

Writing—Original draft, conceptualization, analysis, visualization and data curation, SC; writing—original draft, visualization, investigation, methodology, SD; resources, supervision and data curation, RE; Writing—original draft, visualization, validation and investigation, AK; Writing—Original draft, visualization, review and editing, DE; review and editing, SM; data curation, PK; review and editing, ZS. All authors have read and agreed to the published version of the manuscript.

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**Conflict of Interest:** Author AK was employed by the companies CPS Technologies and Steering Committee (Hydrogen Society of Australia).

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