sustainability

Review

Hydrogen Fuel for Future Mobility: Challenges and Future Aspects

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Abstract: Nowadays, the combustion of fossil fuels for transportation has a major negative impact on the environment. All nations are concerned with environmental safety and the regulation of pollution, motivating researchers across the world to find an alternate transportation fuel. The transition of the transportation sector towards sustainability for environmental safety can be achieved by the manifestation and commercialization of clean hydrogen fuel. Hydrogen fuel for sustainable mobility has its own effectiveness in terms of its generation and refueling processes. As the fuel requirement of vehicles cannot be anticipated because it depends on its utilization, choosing hydrogen refueling and onboard generation can be a point of major concern. This review article describes the present status of hydrogen fuel utilization with a particular focus on the transportation industry. The advantages of onboard hydrogen generation and refueling hydrogen for internal combustion are discussed. In terms of performance, affordability, and lifetime, onboard hydrogen-generating subsystems must compete with what automobile manufacturers and consumers have seen in modern vehicles to date. In internal combustion engines, hydrogen has various benefits in terms of combustive properties, but it needs a careful engine design to avoid anomalous combustion, which is a major difficulty with hydrogen engines. Automobile makers and buyers will not invest in fuel cell technology until the technologies that make up the various components of a fuel cell automobile have advanced to acceptable levels of cost, performance, reliability, durability, and safety. Above all, a substantial advancement in the fuel cell stack is required.

Keywords: hydrogen fuel; sustainability; green fuel; sustainable transportation; future mobility

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1. Introduction

The advancement of technology and increasing demand for electrical power have motivated all nations to find alternate energy sources for power generation [1–3]. It is estimated that the drastic increase in power demand will deplete fossil fuel for power production [4–6]. Moreover, the environmental impacts of fossil fuel utilization in various sectors include to the emission of greenhouse gases (GHGs) and the generation of pollutants in the environment [7–9]. The aforementioned causes justify the increase in demand for renewable and sustainable energy-based power stations and the dependency of various sectors on them [10–12].

The negative environmental impact of the increase in fossil fuel-based transportation mechanisms has forced the automobile industry to find alternative fuel options. The transportation sector is responsible for 28% of greenhouse gas emissions [13,14]. Therefore, electric vehicles have gained popularity due to the fact they emit zero emissions into the environment, low refueling cost, and low maintenance cost [14]. However, electric vehicles also have some disadvantages such as a long battery charging time, limited driving range, and high purchasing costs. Therefore, more public awareness of electric vehicle utilization and technological advancement is required to overcome the aforementioned problems. Various category of mobility sectors which utilize hydrogen fuel has been presented in Figure 1.

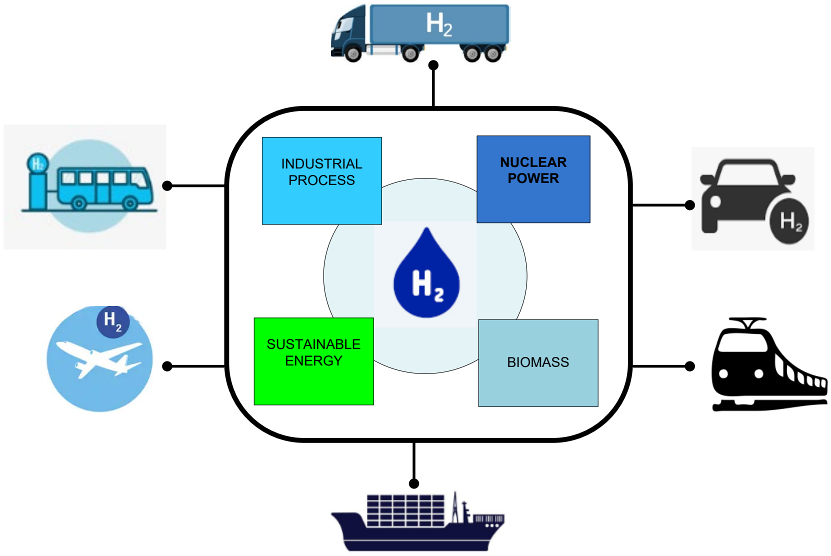

Figure 1. Structure of hydrogen generation sources at various transportation sectors.

The development of hybrid cars that can minimize the time between two consecutive refueling procedures is one potential way to mitigate the mentioned drawbacks. The addition of a second energy storage vector to a vehicle, which allows the battery to charge while driving, extends the period between refueling while also improving trip autonomy [13–15]. The tandem hydrogen and proton-exchange membrane fuel cell is one example of a hybrid device. The hydrogen-based fuel cell has demonstrated its ability to store and transform chemical energy directly into electricity, as well as several other benefits. The challenge of adopting hydrogen and fuel cell-based technologies has been added to the agenda of the world's largest car manufacturers. Despite the committed efforts made to date, an additional and more in-depth study is required for the development and application of hydrogen-based fuel cells for electric cars as well as pure hydrogen vehicles [16]. The goal of choosing hydrogen fuel is due to its clean energy feature with zero-emission and high energy transfer capability. The hydrogen fuel-based vehicle in comparison to the electric vehicle shows advantages in terms of refueling time and costs which can attract a large number of consumers [17,18].

Recently, high prices, limited power density, and a lack of hydrogen infrastructure have become the primary barriers to the widespread adoption of these cars. The most significant barrier is arguably the lack of hydrogen production and distribution infrastructure, as well as the difficulty in effectively and swiftly building it up. In the near and medium term, an on-board fuel processor enabling direct in-vehicle hydrogen conversion from hydrocarbon fuels is thus the only means of allowing FCVs to gain a market share that is acceptable. This concept is particularly appealing for safety reasons: the entire system takes up less space than a compressed hydrogen tank and facilitates refilling by utilizing existing infrastructure. Furthermore, unlike internal combustion engines, which are limited to bi-fuel operation, the same reformer may be fed by a variety of fuels, needing only minor adjustments to the operating conditions while maintaining the processor's integrity.

Hydrogen has long been recognized as a possible low-carbon transportation fuel, but it has proven challenging to integrate into the transportation fuel mix.

Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and potentially useful heat as the only byproducts [4,19].

Hydrogen-powered fuel cells are not only pollution free, but can also have from two to three times the efficiency of traditional combustion technologies. A conventional combustion-based power plant typically generates electricity at efficiencies of 33–35%, while fuel cell systems can generate electricity at efficiencies of up to 60% (even higher with cogeneration) [19].

The gasoline engine in a conventional car is less than 20% efficient in converting the chemical energy in gasoline into power that moves the vehicle under normal driving conditions. Hydrogen fuel cell vehicles, using electric motors, are much more energy efficient and use 40–60% of the fuel's energy, corresponding to more than a 50% reduction in fuel consumption, compared to a conventional vehicle with a gasoline internal combustion engine [19].

In addition, fuel cells operate quietly, have fewer moving parts, and are well suited to a variety of applications.

Fuel cell electric vehicles (FCEVs) made up a relatively small fraction of the worldwide stock of total cars in 2020, and hydrogen consumption in the industry has been confined to less than 0.01 percent of the energy used, as have electric automobiles (0.3%). However, as a result of events in Asia and the United States, the FCEV market is starting to take off. By the end of June 2021, more than 40,000 FCEVs were on the road throughout the world. From 2017 to 2020, stocks expanded by an average of 70% each year, but in 2020, stock growth slowed to 40%, and new fuel cell car registrations plummeted by 15%, matching the broader car market downturn caused by the COVID-19 pandemic. However, 2021 is a candidate to be a new record year, with over 8000 FCEVs sold in the first half of the year and monthly sales in California reaching new highs [20–22].

FCEVs are today largely compared with battery electric vehicles (BEVs) [23–28]. The related literature reveals important differences between the two technologies. BEVs are preferable due to the cheaper infrastructure investment cost and a lower vehicle cost [24]. Despite that, the relatively low autonomy makes BEV mostly suited for short-distance trips such as urban use, which is a large segment of the road market. The developments and efficiency gains in battery technology together with subsidies for public charging stations are expected to facilitate the BEV growth [24]. FCEV is still in an early deployment stage due to a higher infrastructure investment cost and higher vehicle cost. The relatively high autonomy combined with fast refueling make FCEV mostly suited for long-distance and interurban usage. In terms of efficiency, the overall efficiency of BEV is much higher than that of FCEV due to the FCEV energy losses in the entire well-to-tank–tank-to-wheel process phases [19,23,25].

2. Issues and Concerns of Present Vehicle Fuel

Nowadays, considering that climate-friendly means of transport and fossil fuels are incompatible, many countries are favoring the transition from conventionally fueled vehicles to low-emission vehicles to tackle environmental pollution issues. In particular, the European Commission has defined a mobility agenda based on sustainable targets to be achieved by 2030 [24,25] in Europe. Among the objectives of the agenda, in 2025, it is expected that the average CO_2 emissions of new heavy trucks will be reduced by approximately 15% with respect to the emissions of 2019. Moreover, a CO_2 emissions reduction of approximately 30% compared to 2019 is expected to be achieved by 2030. These targets are consistent with the European Union's commitments under the Paris Agreement and, besides the environmental benefits, will allow transport companies to achieve significant savings thanks to lower fuel consumption [25]. To reach the above goals, several legislative, research, and innovation initiatives have been put in place by the European Commission for road mobility and transport [24]. Particular attention is paid to enhancing a more diffused use of new generation vehicles such as electric and automated vehicles. It has been demonstrated that the large use of EVs instead of conventional vehicles can save approximately 60% of GHG emissions in most EU countries [26]. In particular, the use of EVs leads to an average saving of GHG emissions of approximately 50% compared to diesel in Europe [27]. Despite those important benefits, the environmental impact of battery EVs (BEVs) is not null due to the following reasons: (1) in most cases, EV batteries are charged by using non-green energy; (2) the EV's entire life cycle is responsible for some GHG emissions, also considering that the batteries need to be disposed at the end of their life. Nevertheless, there are studies comparing the BEV life cycle impact with conventional vehicles' impact on the environment, showing that BEVs can nevertheless lead to total GHG emissions that are lower than those of traditional vehicles (ICE) [28]. Moreover, if renewable energy sources are used for battery charging, the advantages and benefits for the environment of using BEVs are even more evident. However, even though BEVs are spreading across Europe and the rest of the world, we are still far from the goal of finalizing the substitution of conventional cars, motorbikes, buses, and heavy trucks with such vehicles. Further actions are needed both from governments and technology providers in order to overcome socio-economic and technological limitations.

Indeed, the diffusion of BEVs across the world is currently limited by some critical aspects and issues due to both socio-economic and technological factors.

Regarding the socio-economic and political aspects and actions to be undertaken for EV advancement, public engagement is important to effectively design and manage the passage to sustainable transport technologies. National policy directives such as guidelines for use in public roads and car parks, incentives for parking and purchasing new mobility means can contribute to the diffusion of such sustainable technologies. In this framework, the study in [29] concludes that the EV adoption rate is strongly affected by the local policy instruments of public charging infrastructure that is higher in urban municipalities than in suburban and rural cities. Furthermore, as a natural consequence, the diffusion of EVs is faster where the expansion of public charging infrastructure is higher. In this context, there are still significant differences among cities in terms of charging infrastructure investments that can limit the EV diffusion locally [29].

In addition, a qualitative comparative analysis was conducted in [30] for 15 European cities, comparing the local policies and their socio-economic effects, in order to identify the optimal configurations to foster the expansion of EVs [30]. It is remarked that single action will not succeed because the research shows that the transition towards sustainable mobility can only occur through various, place-specific configurations of measures.

Analogously, Wang et al. [31] performed a correlation analysis and multiple linear regression analyses to evaluate the relationship between incentive policies and socio-economic factors for electric vehicle adoption across 30 countries in 2015.

From the performed analysis, the authors concluded how the governments' first action should be to expand charging infrastructure and provide road priority for electric vehicles. In addition, governments could increase fuel tax to disincentivize the use of conventional vehicles and retain tax breaks, waivers on fees (e.g., parking, tolls, and ferries), and electricity supply cost reduction for EVs.

In addition, from one side, BEVs are still expensive with respect to internal combustion engine vehicles even though, more recently, many countries, such as Italy, are providing incentives to smooth the final cost for users. On the other hand, even though fast and ultra-fast charging solutions are currently available, they are not sufficiently diffused across the countries, partly due to long approval procedures, to solve the problem of BEV charging times that are still significantly longer than refueling times [24]. Moreover, in a transnational corridor that can guarantee accessibility to all EVs, implementing the direct current charging can be desirable but is far from being implemented. Additionally, other solutions such as battery swapping are being introduced onto the market today. This consists of the real-time swapping of the discharged/low charged battery with a fully charged compatible one in dedicated stations. This can be an effective technique to overcome the charging time issue, but its efficacy and long-term sustainable use are still to be adequately investigated and demonstrated. Looking at the driver experience, driving an electric car still causes range anxiety to the users that can fear that their vehicles do not have enough autonomy to reach the next charge point [32]. This is mainly due to the low range autonomy that generally affects most current BEVs on the market and the limited available charging infrastructures in many countries [33].

3. Motivation for Hydrogen Energy

In order to address the discussed issues related to BEVs, in particular the technological ones, the use of fuel cells for electricity storage has been investigated. Hydrogen is considered a clean and efficient energy carrier that can ensure energy security and sustainability [34]. Three dimensions must be considered when promoting hydrogen according to [35]: (1) Market requirements: price must be competitive compared to other environmentally friendly energy carrier-like batteries; refueling infrastructure must allow the autonomy range required by users; fast and easy storage processes are needed to enable a great autonomy for mobility; safety levels that are equal to or better than carbon-based energy sources are necessary. (2) Sustainability and climate requirements: hydrogen energy has to comply with the objectives of governments; hydrogen cars must also comply with existing legal requirements to prevent and limit waste from end-of-life vehicles and their components, ensuring that where possible, these are reused, recycled or recovered. (3) Hydrogen technology requirements: to achieve a mass-market in hydrogen mobility, there is the need to reduce the cost of cars and hydrogen fueling stations. The technology development aims to lower or replace the use of noble materials such as platinum in fuel cells and electrolyzers and achieve higher storage densities (higher car autonomy range) whilst simultaneously lowering storage pressures.

From a technological point of view, the fuel cell (FC) is an energy conversion device that can efficiently capture and use the power of hydrogen [19,28,30]. The fuel cell generates electricity through an electrochemical reaction in which hydrogen and oxygen are combined to generate electricity, heat, and water. The fuel cell is composed of an anode, cathode, and an electrolyte membrane [31,36]. In general terms, hydrogen enters the fuel cell through the anode, where it is split into electrons and protons. Hydrogen ions pass through the electrolyte which forces the electrons through a circuit, generating an electric current and excess heat. Oxygen entering at the cathode combines with electrons from the electrical circuit and the hydrogen ions that passed through the electrolyte from the anode, generating water [19,31,36]. This union is an exothermic reaction, generating heat that can be used outside the fuel cell. Stationary FCs can be used for backup power, power for remote locations, distributed power generation, and cogeneration (in which the excess heat released during electricity generation is used for other applications). FCs can power almost any portable application that typically uses batteries, from hand-held devices to portable generators, and can also power our transportation, including personal vehicles, trucks, buses, and marine vessels, as well as provide auxiliary power to traditional transportation technologies. In this context, hydrogen can play a particularly important role in the future by replacing the imported petroleum we currently use in our cars and trucks [31,36].

In particular, hydrogen technology only emits water vapor into the environment, leading to the benefit of having zero GHG emissions during use [19,36]. However, on the other hand, more energy than other technologies are necessary to produce hydrogen since it is an element not present in its natural state.

There are several methods to produce hydrogen, such as steam reforming and biomass gasification, but a rarely used process in Europe is electrolysis. The electrolysis method consists of passing an electric current through water, and generating a non-spontaneous chemical process resulting in the release of hydrogen in the form of gas. This is a revolutionary technology that combined with the use of renewable energy sources that can make mobility even greener [24,37].

3.1. FCEV vs. BEV

To support the transition process to sustainable mobility, FCs are introduced to be used on EVs where the vehicle battery is recharged by hydrogen present in a tank [24]. A BEV uses an onboard battery pack to power the vehicle's motor, which includes varying configurations of battery cells. Despite the environmental and efficiency advantages of battery electric vehicles, lithium-ion batteries only have approximately 1% of the energy density of petrol or diesel [31,38]. For this reason, smaller and lighter vehicles appear to be the best candidates for battery electric powertrains. As vehicles increase in size, the size and weight of the battery pack required to power the vehicle, as well as the available range, begin to make battery power a less attractive option [31,38].

Hydrogen FCEVs have a far greater energy storage density than lithium-ion batteries, offering a significant advantage for electric vehicles in terms of range whilst also being lighter and requiring less space. FCEVs can also be refueled in a few minutes while BEV charge requires a much longer waiting time [24,31,38].

Therefore, FC technology can lead to the advantage of overcoming negative aspects such as range anxiety, because EVs equipped with fuel cells (FCEV) show greater autonomy and a lower charging time than EVs [39].

In addition, there are also economic advantages to using FCEVs since it is estimated that lithium-ion battery charging/discharging at 1 C (1 h) has a cost of approximately 130 USD/kW in terms of power output. On the contrary, compressed hydrogen tanks and fuel cell stacks, respectively, cost approximately 15 USD/kWh and 53 USD/kW [MODEL-BASED, 38]. Furthermore, it is also estimated that hydrogen prices at the pump are reduced to 8 USD/kg, which is equivalent to 0.24 USD/kWh [38]. Even if the technology and refueling costs are competitive with the BEVs, the cost of purchasing FCEVs generally remains high, and the refueling infrastructure is not so diffused. In terms of usage, the FCEVs generally perform better than BEVs if mainly used for long distance trips. Table 1 compares fuel cell and battery performance in electric vehicles based on several aspects [38,40–49].

Table 1. Fuel cell vs. battery in electric mobility.

	Overall Efficiency	Current Costs	Refueling Time	Range Autonomy	Energy Density	Sustainability
Fuel cell	Around 30%	~53 USD/kW (technology cost) 0.24 USD/kWh (refueling cost)	<10 min	Up to 600 km	550 Wh/kg	Common and safe materials (except for platinum)
Battery	Around 75%	~130 USD/kW (technology cost) 0.14–0.30 USD/kWh (refueling cost)	1–14 h (depend on charging power)	200–400 km (most common cases)	150 Wh/kg	Use of pollutant metals such as cobalt

In terms of the overall energy efficiency of the vehicle, for BEV, the efficiency of the battery and transportation and distribution can reach 75% [25]. For FCEV, several steps should be considered such as electricity, electrolysis, compression, transportation, and distribution. Therefore, despite a fuel cell efficiency of approximately 40–60%, the final energy efficiency of the vehicle is estimated to be approximately 30% [25].

There are also technical challenges that FCEVs are facing which must be considered such as the availability and clean production of hydrogen and the utilization of hydrogen as a power source [31,32]. The production of hydrogen requires significant amounts of energy and the way it is produced is critical to its environmental impact. The way that hydrogen is produced is referred to as a range of colors to indicate the environmental impact. Grey hydrogen is produced from fossil fuels in a process that releases CO_2 into the atmosphere. This is currently the cheapest and most common form of hydrogen even though it has the highest environmental impact. Blue hydrogen is also produced using fossil fuels, but the resulting CO_2 is captured to limit greenhouse gas emissions. The carbon capture process leads to the increased cost of blue hydrogen compared to its grey counterpart [31,32].

Green hydrogen is produced using electricity from renewable energy sources such as wind and solar, making it the cleanest form of hydrogen. One of the most promising options for green hydrogen uses electricity from renewable resources to power the electrolysis of water. The cost of green hydrogen is ultimately much greater than that of blue or grey due to the cost of the electrolyzers and the electricity required to operate them.

From the performed analysis, even though there are some disadvantages to using FC technology with respect to battery for EVs, the advantages, especially regarding sustainability, energy density, autonomy and lower refueling times, make the FC technology very promising in this sector.

As a result, today, even more countries are investing in hydrogen technology applied to electro mobility. Japan, Germany and United States are three top ranking countries in the world in terms of the number of hydrogen stations [50]. In particular, in Europe, it is expected that in 2025, the break-even point between FCEVs and EVs [51] will be achieved [52]. Among the objectives by 2030, Europe aims to have approximately 3.700 refueling stations and a fleet of 3.7 million passenger FC vehicles, and a considerable number of commercial vehicles.

Indeed, the diffusion of both BEV and FCEV also depends on the efficient deployment of the refueling/charging infrastructure. This is a sensitive issue, especially for FCEVs today. Indeed, the car manufacturers are not willing to sell FCEV in large series if they are not sure about the density of available infrastructure. On the other hand, nobody wants to invest in the infrastructures if there is no large fleet to refuel. Two strategies can be adopted to solve this issue according to [24]. The first strategy consists of building on a "captive" fleet that is a group of vehicles owned by companies, governmental agencies, etc. The introduction of such large fleets greatly facilitates the forecasting of fuel consumption, and the deployment needs the corresponding network. The second strategy is to rely on public subsidies to quickly set up a large infrastructure, possibly focusing first in clusters and then on expansions to interregional roads. In this way, it is expected that car manufacturers and customers will soon favor FCEV [24]. The infrastructure deployment issues of BEV and FCEV are quite different. BEV deployment needs a higher density recharge network because the range of BEV is lower than that of FCEV. The location of the charging stations needs to take into consideration the necessary time to recharge the battery. Charging points close to (or in) the users' house and on the work location are particularly appropriate. For FCEV, the range is higher and the refueling time is much quicker (less than 10 min), so the location of the station depends on the intensity of the corresponding traffic. Another important difference concerns the investment cost of the stations and their maintenance. In countries with a well-developed electrical network, the cost of BEV charging points is relatively low and there is no need for specialized maintenance [24]. On the contrary, the deployment cost of FCEV infrastructures is relatively high and requires a hydrogen distribution network.

As future perspective, in [28], a technical-economic long-term analysis was conducted to compare major vehicle technologies (internal combustion, hybrid electric, plug-in hybrid, battery, and fuel cell electric) under the uncertainty of technological progress, with projections until the years 2035 and 2050. They assume different scenarios for the progress achieved by 2035 and 2050 to represent the uncertainties of vehicle technologies.

Looking the outcomes of the study, especially comparing BEV and FCEV, in the 2035 scenarios, although the energy costs of FCEVs are 10–20% higher than those of BEVs, the 5-year (15-year) ownership cost of FCEVs are 15% (12%) lower because of lower purchase costs. Other results report that driving an FCEV will cost drivers 8 cents per mile less than the BEV with a 200-mile range for a 5-year ownership basis. This observation shows the importance of the price of hydrogen in determining the competitiveness of the FCEV. The BEV with a 200-mile driving range was estimated to be the vehicle with the highest cost in all scenarios in both 2035 and 2050. It was found that reductions in mass and fuel cell system cost per kW are major contributors. There is a need for looking at cost perspectives of hydrogen production and delivery. In addition, mass reduction and fuel cell system USD/kW cost reduction are critical in rapidly reducing FCEV ownership cost. Although mass reduction would lead to a reduced purchase cost of conventional vehicles, it would provide more benefits to new technologies such as BEVs and FCEVs. The current fuel cell system cost is approximately 53 USD/kW [28], which is a major reason for the FCEV's manufacturing cost being high compared with conventional vehicles. The Department of Energy (DOE) has set an ultimate target of 30 USD/kW [28]. To this aim, there is a necessity for continued guidance and incentives from the government on FCEV technology research and development.

In conclusion, reducing cost and improving durability are the two most significant challenges to FC commercialization. FC systems must be cost-competitive with, and perform as well or better than, traditional power technologies over the life of the system. Ongoing research is focused on identifying and developing new materials that will reduce the cost and extend the life of FC stack components including membranes, catalysts, bipolar plates, and membrane–electrode assemblies. Low-cost and high-volume manufacturing processes will also help make FC systems cost-competitive with other technologies [28,36].

3.2. Present Status of Hydrogen Fuel Utilization

In today's world, hydrogen is used in a variety of ways. Various industries, including oil refining, chemical manufacturing [36], steel manufacturing, and high-temperature heat generation, dominate the fuel market. Aside from industry, hydrogen fuel is used in transportation [53], building [54], and power production. Hydrogen fuel cells are used in automobiles, ships, and aircraft. The cost of hydrogen fuel cells and the availability of refueling stations determine the competitiveness of hydrogen fuel cell vehicles. Low-carbon fuel alternatives are restricted in shipping and aircraft, which presents an opportunity for hydrogen-based fuels. Hydrogen might be integrated into existing natural gas networks in buildings [55], but it is one of the most widely utilized chemicals for storing renewable energy in power generation, and when combined with other chemicals such as ammonia, it may be used in gas turbines to boost power system flexibility. Because almost all hydrogen is produced using fossil fuels, clean hydrogen has a great potential for lowering emissions [56].

Non-energetic utilization, indirect energetic utilization, and direct energetic usage are the three types of hydrogen demand. The use of hydrogen to manufacture chemical compounds is performed in a non-energetic manner. The direct energetic use of hydrogen as an energy carrier is achieved either in a pure form or as part of a combination, and the indirect energetic use is achieved to upgrade fossil energy carriers such as crude oil, coal, and heavy oils [57]. The present demand for natural gas and electricity, as well as the use of hydrogen in various nations, were examined in this study from the consumer's perspective. As a result of this research work aiming to harness solar energy for the large-scale production of hydrogen to be used as a main non-fossil fuel to gradually replace oil and gas in all possible areas of utilization, a comprehensive perspective of current and future hydrogen utilization in different countries and sectors was discussed in this study.

3.3. Utilization Hydrogen Fuel in Different Countries and Sectors

The demand for energy in the automotive and industrial sectors is dramatically increasing across the world. Conventional energy sources will be insufficient to meet rising energy demand, and pollution is a major concern. As a result, an alternate fuel for transportation and industry is critical. It was observed in the literature and reports that various states (such as India [36], Philippines [58], Southern Africa [59], Japan [60], Germany [61], Patagonia [62], Saudi Arabia [63], California [64]) have taken initiatives towards achieving green hydrogen production and utilization.

Various methods of green hydrogen production have been developed worldwide. Steam-methane reforming (SMR), electrolysis, and using anaerobic digester gas (ADG) are the most popular ways of producing hydrogen in various countries [56]. Coal gasification with carbon capture, utilization, and storage (CCUS), as well as natural gas conversion with CCUS, are employed in the SMR production technique to produce hydrogen fuel [61]. Electricity generated from renewable sources (solar and wind) or nuclear energy, or fossil fuels (coal, natural gas, and petroleum) can be used to obtain hydrogen through the electrolysis technique [57]. Biomass is transformed into gas or liquids and hydrogen is separated in the ADG production method. Green hydrogen is utilized in refining, industry, transportation, electricity, ammonia fuel, buildings, and grid injection [64]. The possible production routes and utilization pathways of green hydrogen are summarized in Figure 2.

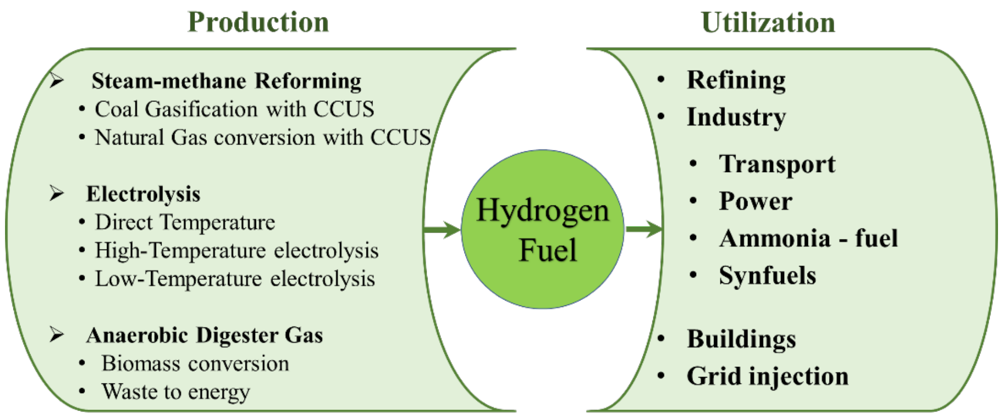

Figure 2. Production and utilization of hydrogen fuel.

As per the report published by the International Energy Agency (IEA), with ten countries around the world adopting hydrogen policies, 2020 was a record year for policy action and low-carbon hydrogen generation. Nearly 70 MW of electrolysis capacity was added, more than tripling the previous year's total, and while two plants generating hydrogen from fossil fuels using CCUS began operating, the output capacity was increased by nearly 15%. However, under the Net Zero Emissions by 2050 Scenario, this development falls well short of what is required. Furthermore, the demand for low-carbon hydrogen for novel uses is still confined to road transport [65]. An estimate of global hydrogen demand by sector published by the International Energy Agency (IEA) is given in https://www.iea.org/reports/hydrogen (accessed on 27 March 2022) [66]. As a result, further efforts in creating demand and lowering emissions related to hydrogen generation are required.

3.4. Consumer Perspective

Although transportation is unquestionably important in daily operations across the world, its energy consumption and use of non-renewable energy have major negative repercussions for the environment and global climate [67,68]. For a long time, hydrogen gas was considered a viable transportation fuel. It is viewed as a low-carbon alternative to refined oil products and natural gas, as well as a supplement to other low-carbon options such as electricity and advanced biofuels. Fuel cell electric vehicles (FCEVs) are rapidly gaining popularity as a zero-emission transportation technology [67]. Hydrogen FCEVs will minimize local air pollution since they have no exhaust emissions, similar to BEVs [69]. The consumer perspective of hydrogen fuel has been mentioned in Figure 3. The following are some of the potential applications for hydrogen and its derived products in transportation:

- Due to the non-availability, storage, and emission concerns with hydrogen fuel in many nations, most light-duty vehicles (cars and vans) and heavy-duty vehicles (trucks and buses) now use non-renewable fuel. This opens up several opportunities to minimize the refueling time, storage requirements, and emissions in hydrogen fuel production and utilization. In addition, hydrogen fuel cells use less material than lithium batteries. However, 11,200 automobiles, predominantly in California, Europe, and Japan, use hydrogen fuel [55]. Long-distance travel and poor filling station usage are still major issues in hydrogen-based transportation [70].
- The use of hydrogen fuel in maritime transportation has been studied and proven in small ships. By 2030, the use of hydrogen fuel in ships will reduce air pollution while simultaneously increasing freight activity by roughly 45 percent. Because hydrogen fuel has a lower density than conventional liquid fuels, it has significant hurdles in terms of storage costs and cargo capacity.

- In rail transportation, hydrogen fuel-based trains are utilized in Germany. As a result, there are several opportunities to use hydrogen fuel in rail freight. Both hydrogen and battery electric trains with partial line electrification are viable replacements for non-electrified operations, which are prevalent in many areas [61].
- In aviation, hydrogen fuel utilization is demonstrated using small projects. Therefore, this brings a major opportunity to use hydrogen fuel in a fast-growing passenger transport mode. The redesign of the aviation model is needed to accommodate large storage volume. Additionally, the use of hydrogen fuel can be applied in airports for on-board energy supply.

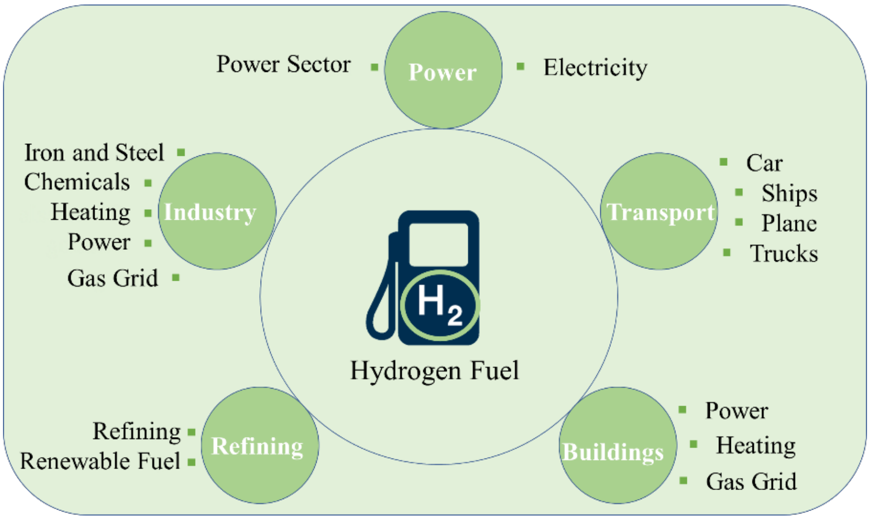

Figure 3. Consumer perspective of hydrogen fuel utilization.

When it comes to the direct use of hydrogen in mobility applications, light-duty FCEVs now receive the most consumer attention [71]. FCEVs, on the other hand, have been used in material handling (mostly forklifts), buses, trains, and trucks [72–74].

4. Adaptation of On-Board Hydrogen Production Technology for Vehicles

The environmental impact of using fossil fuels can be noticed from signs such as air pollution, global warming, and emissions. Therefore, the utilization of alternative sustainable fuel sources for the transportation sector is essential. Among the sustainable fuels, hydrogen has the highest energy by weight with zero-emission properties. Still, due to some issues, hydrogen fuel adaptation for transportation is not popular. The on-board hydrogen production and hydrogen storage systems in vehicles are not fully developed and lack customer satisfaction. As hydrogen has low-energy density property, the research related to its storage in vehicles must be enhanced. In the meantime, on-board hydrogen generation by a fuel reformation process may be a suitable option for hydrogen fuel adaptation. In recent years, it has been noticed that concentration on the on-board hydrogen production technologies has been enhanced and researchers are engaged to solve the demerits. The focus of the research on the on-board hydrogen-based vehicles can be schematized as in Table 2. Table 2 also describes the economic benefit, commercialization potential and efficiency of the concerned hydrogen generation methods.

Table 2. Studies on economic and commercial benefit and efficiency of hydrogen-based mobility.

Reference	Fuel for Hydrogen Production	Economic Benefit	Commercial Potential	Efficiency
[75]	Methanol fuel processors	✓	✓	High
[76]	Methanol	✓	✓	High
[77]	Ethanol	×	×	Low
[78]	Dimethyl ether (DME) a	✓	✓	Average
[79]	N-heptane fuel processor	×	×	Low
[80]	Naphtha	×	×	Low

In addition to the mentioned studies, there are several literatures works available which show the various categories of methods for the generation of on-board hydrogen for sustainable vehicles. In this regard, various technologies have been adopted by researchers for the development of an on-board hydrogen generation system.

4.1. System Designs for On-Board Hydrogen Production

For the efficient generation of on-board hydrogen, different topologies have been discussed in the literature for sustainable transportation. An on-board Pd-Ag MR procedure to produce hydrogen has been adopted by [81]. By heat exchanging with water and air in heat exchangers and evaporators, the combustion chamber creates high-temperature flue gas, which may be used to generate steam and hot combustion air. The steam and hot air created are employed in the membrane reformer. The feasibility of installing a revolutionary on-board MR capable of producing pure H_2 was investigated in this theoretical paper. In [82], on-board autothermal reactor modeling-based hydrogen production was listed. For each tested hydrocarbon, the auto thermal reformer is changed to enhance the system efficiency. The ability of a fuel cell hybrid vehicle with an on-board auto thermal reformer to deal with various fuels under various running situations was explored. The significant investment prices and space needs of the complete power train are still big issues that must be addressed by this auto thermal reformer process. The latest developments in the methane steam reforming process include a brief discussion of catalysts and the principles of membrane reactors for hydrogen generation. By integrating the reforming reaction for creating hydrogen and its separation in only one stage, membrane reactors are a viable alternative to fixed bed reactors [83]. However, because of the necessity to handle load-following transients, fuel cell systems for vehicle applications are substantially more complicated than stationary systems, recognizing this requirement as a key issue of on-board hydrogen fuel reforming [84–86]. For on-board hydrogen synthesis in an ammonia-fueled vehicle, an economical, efficient, and small technology is required. To investigate the viability of cutting-edge technology for on-board hydrogen production, the ammonia Cracking Hollow Fibre Converter (HFC), which is made up of a number of HFR units [87].

4.2. Power Electronics for On-Board Hydrogen Production

An on-board hydrogen production system, a fuel cell system, a direct current/direct current (DC/DC) converter (electrically coupled device), a motor drive system, an auxiliary battery (the concept range of the peak power source in this article includes power battery packs, and the concept range of the power battery packs includes lithium batteries), and a management system are the main components of the vehicle-mounted hydrogen generation fuel cell electric vehicle studied in this field. This field focuses on hybrid drive and control system design, as well as fuel cell and auxiliary battery management [88,89].

In order to perform the functions of hydrogen generation and purification, the on-board hydrogen production system is primarily made up of a burner and reformer, a methanol storage tank, and a purifier. In order to create power and output the main power output, the fuel cell system primarily consists of a fuel cell stack, a fuel supply and circulation system, an oxidant (O_2) supply system, a hydrothermal management system, and a control system. The peak power system is also a key component of the fuel cell electric vehicle's hybrid electric powertrain [89]. This technology releases stored electrical energy, decreases the fuel cell's peak power consumption, and makes its operating conditions more stable when the fuel cell cannot deliver the driving power required by the automobile (such as starting, accelerating, climbing, and so on). When the fuel cell generates more power than the car requires (for example, during idle, low speed, or deceleration), this device can store excess energy and absorb brake energy, improving vehicle energy efficiency [90,91].

5. Adaptation of Internal Combustion Production Technology for Vehicles

Different fuels can be used in an internal combustion engine. This requires proper engine control unit calibration and the material compatibility of engine components with various fuels [92,93]. The use of hydrogen as a fuel for internal combustion engines (ICEs) provides a number of benefits [94]. The most essential among them are increased contamination tolerance, ICE technical maturity, lower consumption of rare resources, and the ICE's ease of adaption to run on hydrogen. Since the previous century, hydrogen-fueled ICEs have been the area of study. Verhelst and Wallner discussed the fundamentals of hydrogen combustion, the various mixture formation strategies and their emissions characteristics, measures to convert existing vehicles, dedicated hydrogen engine features, the state of the art of increasing power output and efficiency while controlling emissions, and modelling [95]. To take advantage of hydrogen's combustion properties, Wallner et al. [96] developed a high-efficiency hydrogen direct-injection engine at Argonne National Laboratory. The efficiency maps of the hydrogen engine exhibited a high braking thermal efficiency of 45.5 percent along with nitrogen oxide maps which showed emissions of less than 0.10 g/kW h during much of the operating regime. Sopena et al. [96] adapted a Volkswagen Polo 1.4's spark ignition gasoline-fueled internal combustion engine to operate on hydrogen. With the modified engine, the hydrogen-fueled Volkswagen Polo attained a top speed of 140 km/h, with adequate reserve power for the car to go on ordinary urban routes and routes with slopes of up to 10%. The technical challenges were successfully addressed by Yamane [97] to make a hydrogen automobile a viable option for both electric and traditional fossil fuel vehicles. He addressed the following challenges:

a. Hydrogen's lack of lubrication damages the injector nozzle's sealing surface.
b. Injectors must be very tiny to fit into the engine head where the four valves on each cylinder are placed.
c. A strong dynamic reaction is required for multi-injection.
d. Due to frictional heat, the internal pump of the liquid hydrogen tank would fail while delivering liquid hydrogen (LH2) to the required high-pressure levels.

To tackle the current challenges, a hydrogen ICE solution that included high-pressure LH_2 pumps, hydraulically operated common-rail-type tiny gaseous hydrogen (GH2) injectors with no hydrogen gas leakage, and a cryogenic LH_2 fuel tank was presented. Dimitriou and Tsujimura [98] discussed how hydrogen may be used in a cylinder as the main fuel or in a dual fuel system. The impacts of different injection techniques, compression ratios, and exhaust gas recirculation on the combustion and emission characteristics of a hydrogen-fueled engine were thoroughly investigated.

The hydrogen-powered internal combustion engine is currently the only internal combustion engine that complies with stringent EU rules [99]. In comparison to a diesel engine, a hydrogen-powered engine generates substantially less other harmful species. Only nitrogen oxides (NO_2) are major pollutants that might be released as a result of H_2 combustion. NOx emissions may be reduced to near zero, utilizing an improved combustion method and a relatively basic after treatment system. A significant benefit of a hydrogen-powered ICE is that the technology can be swiftly brought to market and hence widely distributed with minimum delay if diesel cars are gradually phased out in future years [100–103].

5.1. Properties of Hydrogen as Fuel for Internal Combustion Engine

Hydrogen's physical and molecular characteristics are vastly different from traditional fossil fuels [103–106]. Several essential features of hydrogen have had a significant influence on internal combustion engine design changes and technological advancements. Researchers are concentrating their attention on hydrogen as an alternative fuel in internal combustion engines because of these qualities. Table 3 lists the characteristics of hydrogen.

Table 3. Properties of hydrogen compared with diesel, gasoline and methane [103–106].

Parameter	Hydrogen	Diesel	Gasoline	Methane
% Mass of carbon	0	86	84	75
Molecular weight	2.016	~170	~110	16.043
Octane number	130+	-	86–94	120+
Cetane number	-	40–55	13–17	-
Density at STP (kg/m^3)	0.089	830.0	730–780	0.720
Volumetric energy at STP (MJ/m^3)	1.07×10	3.5×10^4	3.3×10^4	3.3×10
Net lower heating value (MJ/kg)	119.9	42.5	43.9	45.8
Boiling point (K)	20.0	453–633	298–488	111.0
Auto-ignition temperature (K)	853	~523	~623	813
Minimum ignition energy in air at 1 bar and stoichiometry (mJ)	0.020	0.240	0.240	0.290
Stoichiometry air/fuel mass ratio	34.4	14.5	14.7	17.2
Quenching distance at NTP (mm)	0.64	-	~2	2.1
Laminar flame speed in air at NTP (m/s)	1.85	0.37–0.43	0.37–0.43	0.38
Diffusion coefficient in air at STP (m^2/s)	8.5×10^{-6}	-	-	1.9×10^{-6}
Flammability limits in air (% vol)	4–76	0.6–5.5	1–7.6	5.3–15
Adiabatic flame temperature at NTP (K)	2480	~2300	2580	2214

Hydrogen combustion is substantially different from hydrocarbon fuel combustion [107,108]. When compared to hydrocarbon fuels, hydrogen has a few distinct characteristics, the most notable of which is the absence of carbon. Because the fire velocity is so fast, very fast combustion is possible. The flammability limit of hydrogen fluctuates between an equivalency ratio of 0.1 and 7.1, allowing the engine to run with a wide variety of air/fuel ratios [108]. For the hydrogen–air combination to ignite, just 0.02 mJ of energy is required. This allows the hydrogen engine to work effectively on lean fuels and guarantees that its quick ignition. Hydrogen has a density of 0.089 kg/m^3, making it lighter than air and allowing it to diffuse freely into the atmosphere. Hydrogen has the highest energy-to-weight ratio. Hydrogen has a flame speed of 270 cm/s, which might result in a rapid rise in cylinder pressure. Hydrogen has a diffusivity of 0.63 cm^2/s. Because hydrogen's self-ignition temperature is 858 K, compared to 453 K for diesel, it may be employed in internal combustion engines with a higher compression ratio. Compression, on the other hand, is insufficient to ignite hydrogen. To ensure ignition, some sources of ignition must be introduced inside the combustion chamber [109–111].

5.2. Hydrogen Use in Internal Combustion Engines

Spark ignition (SI), compression ignition (CI), and natural gas–hydrogen mixture engines may utilize hydrogen.

5.2.1. Spark Ignition Engines

Hydrogen offers a lot of potential in terms of powering spark-ignition engines and achieving high performance. Some of hydrogen's advantageous qualities, such as quick flame propagation, low ignition energy, and a wide working range enable the combustion process to be optimized and improved. This allows for, among other things, limiting hazardous component emissions to solely NOx [112–115]. Hydrogen can be used in SI engines in one of the following ways.

When hydrogen fuel is combined with air, it produces a flammable combination. With an equivalency ratio below the flammability limit of a gasoline–air combination, it may be burnt in a typical spark ignition engine. Low flame temperatures are produced as a result of ultra-lean combustion. Fewer heat transmission to the walls, improved engine efficiency, and lower NOx emissions are all direct results of this [116]. This is a significant benefit of hydrogen-fueled SI engines [117,118]. In comparison to hydrocarbon-fueled engines, hydrogen-powered engines emit fewer harmful pollutants. NOx and PM (only when H_2 is used as a secondary fuel in a diesel engine) are the primary pollutants in hydrogen engines, according to previous research [119,120]. Because of the greater combustion temperature, NOx emissions from hydrogen-fueled ICEs are higher than those from petrol-fueled ICEs. High NOx emissions arise due to greater combustion temperatures, especially when the engine is working in the stoichiometric fuel-to-air ratio range. The combustion temperature and NOx emissions are reduced when the air–fuel ratio is reduced [121].

Without requiring any modifications, spark ignition engines may run on hydrogen [122]. Higher hydrogen combustion velocity enhances combustion and increases brake thermal efficiency. Hydrocarbon and carbon monoxide emissions are almost non-existent. The evaporation and burning of the lubricating oil coating on engine cylinder walls produces only minimal quantities of these pollutants [123]. The performance of a hydrogen engine is superior to that of a gasoline engine, especially while operating at part load. Hydrogen can also be added to methane or petrol as an additive [124]. This allows very lean mixes with an equivalency factor of 0.1 to be burned. Spark ignition engines, on the other hand, are a poor choice when significant torque is required at low engine speeds. Engines with greater compression ratios, such as diesel, are typically employed in such situations [125].

5.2.2. Compression Ignition Engines

Hydrogen is used as a diesel fuel addition in compression ignition (CI) internal combustion engines for a variety of reasons [126,127]. Small quantities of hydrogen injected into a CI internal combustion engine increase, mixing homogeneity in the diesel spray stream. This is primarily due to hydrogen's strong diffusivity. As a result, the flammable mixture is mixed with air more completely [128–130]. As a result, the creation of hydrocarbons, carbon monoxide, and carbon dioxide may almost be prevented during burning. In the combustion chamber, only the partial combustion of lubricating oil can yield trace quantities of these chemicals [131]. An injector is used in hydrogen-fueled CI engines to inject high-pressure hydrogen into the cylinder. Because the injection nozzle determines how pressurized hydrogen is fed into the combustion chamber, not only the engine construction but also the injector design is critical [132]. Due to the greater auto ignition temperature required by compression ignition engines, hydrogen cannot be used as a solo fuel because the compression temperature is inadequate for commencing combustion [133]. As a result, a spark plug or glow plug is required to burn hydrogen in a CI engine. The primary fuel (hydrogen) is fed into the intake air or carburetor in a dual-fuel engine. The diesel fuel acts as an ignition source, which starts the combustion process. The pilot fuel can make up 10–30% of the overall fuel, with the main fuel providing the remainder of the energy (hydrogen). Nitrogen oxides (NOx) are a severe issue in hydrogen-powered dual-fuel CI engines, just as they are in SI engines. Because of the dilution effect, which lowers the oxygen content in the intake charge, exhaust gas recirculation (EGR) is useful for lowering NOx emissions. However, when EGR rises, volumetric efficiency falls dramatically. There is a 15% reduction in volumetric efficiency when compared to a dual-fuel hydrogen propulsion system without EGR [134]. Furthermore, using EGR in a hydrogen dual-fuel vehicle might increase particle emissions. The smoke levels produced by a bi-fuel engine employing hydrogen and EGR are similar to those produced by a CI ICE. Injecting liquid water into the combustion chamber is another approach to lower NOx emissions. When burning hydrogen, it can help reduce knocking combustion and early ignition. Water has a similar impact to EGR's dilution of exhaust gases, causing the charge to cool and the combustion rate to slow down. Water injection into the intake manifold, on the other hand, reduces the engine's volumetric efficiency [135,136].

5.2.3. Natural Gas–Hydrogen Mixtures Engines

Natural gas is regarded as one of the most advantageous fuels for engines, and natural gas-fueled engines have been developed for both spark-ignition and compression-ignition engines. The natural gas spark ignited engine, on the other hand, suffers from substantial cycle-by-cycle variability and poor lean–burn capacity due to natural gas's sluggish burning velocity and poor lean–burn capability, which reduces the engine power output and increases fuel consumption. [137]. Due to these constraints, combining natural gas with hydrogen for use in an internal combustion engine is an effective way to increase burn velocity, with hydrogen having a laminar burning velocity of 2.9 m/s against 0.38 m/s for methane [138]. Additionally, the inclusion of hydrogen can improve fuel economy and thermal efficiency. The thermal efficiency of hydrogen-enriched natural gas is therefore is discussed.

When it comes to using natural gas–hydrogen as a fuel, there are several obstacles to overcome [139,140]. One of the most difficult aspects is selecting the best hydrogen/natural gas ratio. Unless the spark timing and air–fuel ratio are properly set, anomalous combustion such as preignition, knock, and backfire will occur when the hydrogen fraction rises over a specific level. Because of the smaller quench distance and increased burning velocity of hydrogen, the combustion chamber walls get hotter, causing greater heat loss due to the cooling water.

The lean operation limit stretches as the hydrogen addition increases, but the maximum brake torque (MBT) declines, indicating that there are interactions between the hydrogen percentage, ignition time, and MBT [141–143].

6. Comparative Analysis (On-Board Hydrogen Vehicle vs. Hydrogen-Fueled ICEs)

Based on the requirement of environmental safety, hydrogen fuel has been considered as the most environmentally friendly vehicle fuel. However, the way that the hydrogen fuel vehicle utilizes hydrogen has complicated the scenario. Onboard hydrogen generation and its utilization for vehicles require various stages to generate the DC voltage as energy. However, internal combustion engine-based hydrogen fuel vehicles require a hydrogen storage tank which supplies the required fuel for the internal combustion engine [144–146].

Hydrogen, a zero-carbon fuel, may be used to power both internal combustion engines and on-board hydrogen vehicles. Internal combustion engines are most efficient when they are under high load. On-board hydrogen vehicles perform best at lower loads. In highly transitory duty cycles, on-board hydrogen vehicles may also recover energy through regenerative braking, enhancing their overall efficiency. On-board hydrogen vehicles, except for water vapor, create no emissions at all [147]. This is a particularly appealing feature for cars that operate in cramped places or with limited ventilation. Internal combustion hydrogen engines create nitrogen oxides, or NOx, but emit only trace quantities of CO_2 (from ambient air and lubricant oil). As a result, they are not suitable for indoor usage and need exhausting after treatments in order to decrease the NOx emissions. Internal combustion hydrogen engines may frequently run on lower-grade hydrogen. This is useful in some situations as, without the requirement for purification, hydrogen can be used in hydrogen engines [148,149]. However, high-quality hydrogen is required when on board on-board hydrogen vehicles.

Finally, the maturity of hydrogen engines and hydrogen fuel cell technology varies. For decades, internal combustion engines have been widely utilized and backed by large service networks. Rugged engines are available in a variety of sizes and configurations, and may function in dusty settings or be subjected to high vibrations. Switching to hydrogen engine drive trains requires common parts and technology for car makers and fleet operators. The tried-and-true, dependable character of internal combustion engines will provide reassurance to risk-averse end-users [150–152].

As a result, on-board hydrogen vehicles and hydrogen ICEs are not in direct competition with one another. On the contrary, because both drive the development of shared hydrogen production, transportation, and distribution infrastructure, the growth of one aids the development of the other. They are complementary technologies that are part of the current effort to reduce the automotive and transportation emissions to zero.

Most customers are unfamiliar with the on-board hydrogen propulsion technology, which is fundamentally different from internal combustion engine automobiles. However, the fuel cell stack and hydrogen storage systems are distinctive and costly, and other components in on-board hydrogen generation require considerable cost reductions as well [153,154]. The module that controls the operation of the fuel cell stack and the entering air, hydrogen streams, electric drive motors and controls that drive the vehicle, and high voltage batteries that store regenerative braking energy while also assisting in fuel cell operation are all examples of these.

On-board hydrogen generation subsystems must compete in terms of performance, cost, and longevity with what automotive makers and consumers have grown to expect in modern cars [155]. Automotive manufacturers and purchasers will not be willing to invest in fuel cell technology until the technologies that make up the different components of a fuel cell car have evolved to acceptable levels of cost, performance, dependability, durability, and safety. Above all, tremendous progress must be made in the fuel cell stack.

7. Conclusions

This paper presents a review of hydrogen fuel for mobility in various transportation sectors. This clean energy has zero environmental impact, which attracts the automobile industries for hydrogen vehicle development. Hydrogen offers several advantages in terms of combustive qualities in internal combustion engines, but it requires careful engine design to avoid anomalous combustion, which is a key issue with hydrogen engines. As a consequence, engine efficiency, power production, and NOx emissions may all be improved. The cost and efficiency of a hydrogen plant are determined by hydrogen production sources. Costs may be reduced if the plant is close to its natural resources, and therefore, the locations of its sources should be considered while developing a hydrogen plant. People will adopt hydrogen technology if they are aware of the benefits it provides to the environment and human life. Educating residents about hydrogen technology is critical in gaining public support for the technology's growth.

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