World Electric Vehicle Journal

Review

Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects

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Abstract: Conventional transportation systems are facing many challenges related to reducing fuel consumption, noise, and pollutants to satisfy rising environmental and economic criteria. These requirements have prompted many researchers and manufacturers in the transportation sector to look for cleaner, more efficient, and more sustainable alternatives. Powertrains based on fuel cell systems could partially or completely replace their conventional counterparts used in all modes of transport, starting from small ones, such as scooters, to large mechanisms such as commercial airplanes. Since hydrogen fuel cells (HFCs) emit only water and heat as byproducts and have higher energy conversion efficiency in comparison with other conventional systems, it has become tempting for many scholars to explore their potential for resolving the environmental and economic concerns associated with the transportation sector. This paper thoroughly reviews the principles and applications of fuel cell systems for the main transportation schemes, including scooters, bicycles, motorcycles, cars, buses, trains, and aerial vehicles. The review showed that fuel cells would soon become the powertrain of choice for most modes of transportation. For commercial long-rage airplanes, however, employing fuel cells will be limited due to the replacement of the axillary power unit (APU) in the foreseeable future. Using fuel cells to propel such large airplanes would necessitate redesigning the airplane structure to accommodate the required hydrogen tanks, which could take a bit more time.

Keywords: hydrogen fuel cell; transportation systems; renewable energy; hybrid electric vehicles; clean urban

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Citation: Fakhreddine, O.; Gharbia, Y.; Derakhshandeh, J.F.; Amer, A.M. Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects. *World Electr. Veh. J.* **2023**, *14*, 156. https://doi.org/10.3390/wevj14060156

Academic Editors: Jamie W.G. Turner, Giovanni Vorraro, Hui Liu and Toby Rockstroh

Received: 16 May 2023
Revised: 1 June 2023
Accepted: 7 June 2023
Published: 13 June 2023

1. Introduction

Hydrogen fuel cells (HFCs) are electrical cells that can be continuously fed by fuel. The main products of HFCs are electricity and water once a chemical reaction occurs; as a result, clean energy is generated without any noise and air pollution. With the increasing concern about global warming, it appears to be a natural development that the fuel of the future will be entirely hydrogen [1]. Since fuel cells and batteries are based on the premise that in a chemical reaction, the energy is changed into electricity by electron transfer between the anode and the cathode, they have many characteristics in common. In order to produce low DC voltage, not only fuel cells but also batteries require an external load to carry out useful work. In addition to proton exchange membrane and alkaline fuel cells, phosphoric acid, solid oxide, and molten carbonate fuel cells can be considered the most prevalent forms of fuel cells [2].

Fuel cell electric vehicles (FCEVs) offer advantages over battery electric vehicles (BEVs) such as extended range, short refilling times, and lower carbon footprints in manufacturing. FCEVs filter air and can help clean polluted cities, while also being silent and comfortable [3]. However, FCEVs are currently more expensive to produce and have fewer hydrogen refueling stations available [4]. For trucks, FCEVs have the advantage of a lighter weight, allowing for greater payload [5]. FCEVs outperform BEVs for vehicle ranges over 160 km, with advantages including lower mass and volume, faster refueling, initial greenhouse gas reductions, higher well-to-wheel energy efficiency, and potentially lower life cycle costs [6].

In the context of hydrogen fuel cells in the transportation sector, maintenance considerations related to poisoning due to carbon monoxide (CO) or sulfur, as well as associated costs, are crucial. CO poisoning can occur when CO impurities enter the fuel cell, hindering its performance. To mitigate this, purification techniques and catalysts with higher CO tolerance are employed [7]. Sulfur compounds present in fuels can also cause poisoning, degrading the catalysts. Desulfurization processes and sulfur-tolerant catalysts help address this issue [8]. Regarding costs, initial expenses have decreased due to manufacturing advancements, and efforts to improve durability help reduce maintenance costs. Operational and maintenance costs are generally lower compared to internal combustion engines but should still be considered. Overall, regular maintenance, purification methods, and cost optimization contribute to the viability of hydrogen fuel cells in transportation [9].

Hydrogen fuel cell vehicles utilize electric motors for propulsion, with the specific type of motor varying depending on the vehicle's design and requirements. Two common types of electric motors used in these vehicles are permanent magnet synchronous motors (PMSMs) and induction motors (IMs). PMSMs utilize permanent magnets embedded in the rotor to generate a magnetic field, offering high power density and efficiency. On the other hand, IMs operate through electromagnetic induction and are known for their robustness and cost-effectiveness. Both motor types convert the electrical energy produced by the fuel cell into mechanical power for vehicle propulsion, with the choice between them depending on factors such as power requirements, torque characteristics, efficiency, and cost-effectiveness [10].

In hydrogen fuel cell vehicles, a dualism exists between the slow and constant energy generation of the fuel cell system and the dynamic power demands of road riding, which require high power and rapid acceleration. The fuel cell system generates electricity steadily but may not provide instantaneous power during acceleration. To overcome this, fuel cell vehicles incorporate energy storage systems such as batteries or supercapacitors. These systems store energy to complement the fuel cell's steady output and deliver the extra power required for rapid acceleration. This dualistic approach ensures a balance between constant energy generation and the ability to meet dynamic power needs, allowing for efficient performance in different driving conditions [11].

The aim of the work is to investigate the practical implementation of hydrogen fuel cells (HFCs) across a diverse range of transportation modes from smallest to largest. Specifically, it focuses on examining the utilization of HFCs in motorcycles, scooters, bicycles, passenger cars, buses, trains, trucks, and aerial transportation systems. Each section provides a comprehensive exploration of the unique challenges, corresponding solutions, and potential advantages associated with integrating HFC technology into these specific modes of transportation. By offering an in-depth analysis of a wide spectrum of vehicles and transportation systems, this paper aims to provide a holistic perspective on the current advancements and future prospects of HFCs in achieving sustainable and efficient transportation.

2. Motorcycles, Scooters, and Bicycles

With the increase in traffic jams in major cities around the world, commuting via motorcycles, scooters, and bicycles has become very attractive for many. The manufacturers of these products are competing to make them even more attractive by making them more efficient and more comfortable. Pearl Hydrogen Power Source Technology Co of Shanghai, China, as a pioneer of two-wheeled vehicles powered by hydrogen, demonstrated the first hydrogen bicycle in 2007. Two-wheeled vehicles (TWV), such as bicycles and motorcycles, are common in transportation systems in many places and countries, notably in Asia, with numerous populations. Consequently, HFC two-wheeled vehicles can help meet air quality standards. In addition, they can affect noise pollution reduction [12].

The development of HFC motorcycles is still immature. Many HFC motorcycle and scooter concepts have been proposed [13–17], and many companies have attempted to construct various technologies and motorbike sizes employing a variety of fuel supplies, including HFCs [18]. Compared to gasoline-powered motorcycles, HFC motorcycles are relatively quiet and highly energy-efficient, with zero emissions. The benefits of HFC motorcycles, then, have the potential to minimize the problems associated with a gasoline-powered system and motivate users to acquire and use HFC motorcycle products [19].

The performance and development of electric motorcycles in Singapore and Malaysia were reported by Weigl et al. [14]. The scholars designed, manufactured, and examined an electrical motorcycle sample that used a combination of an HFC system, a lithium polymer battery pack, and an ultra-capacitor module. The interesting results revealed that the motorcycle can travel approximately 2400 km on hilly roads at 77 (km/h), even during heavy rain. The fuel consumption of the sample was 0.51 kg H_2 per 100 km. The results guaranteed that the motorcycle could be built and used for actual road applications [14,20]. Compared to low-carbon transportation systems powered by fossil fuels, HFC sources stand out due to the high-efficiency electrochemical reactions in HFC batteries [21]. The employment of HFCs for evaluating the environmental sustainability of urban delivery systems was applied to different hydrogen vehicles in Italy by Bartolozzi et al. [22]. It was reported that transportation systems powered by HFCs provide a maximum efficiency of 63%, which is much higher than that of conventional fuel consumer engines in Italy.

3. Passenger Cars

In recent years, HFC automobiles have drawn interest as a potential replacement for conventional gasoline-powered systems. Instead of burning gasoline, which produces merely water vapor as a byproduct, HFC automobiles generate energy through a chemical reaction, which occurs between H_2 and O_2. According to an International Energy Agency (IEA) report, fuel cell vehicles (FCVs) could potentially reach 10–15% of all passenger cars, trucks, and buses by 2050, leading to a 19% decline in universal energy-related CO_2 emissions [23]. By the beginning of 2021, there were over 34,000 FCVs on the road globally [24], with the majority in Japan, California, and Germany. While there are still hurdles to overcome in terms of infrastructure and cost, the growing interest in hydrogen fuel cell cars has spurred innovation and investment and provides not only cleaner but also more sustainable transportation for the future than conventional systems.

Despite the efforts made by the automotive industry in the past few years to decrease the effects of ICEs on the environment, they have still not been able to bring emissions to an acceptable level. Burning fossil fuels, such as diesel, in internal combustion engines (ICEs) creates toxic byproducts such as NOX, CO, and CO_2, which are very detrimental to the environment. In 2020, passenger cars were responsible for 41% of the 7.3 billion metric tons of carbon dioxide in global transportation emissions [25]. Therefore, and for the sake of a cleaner and more sustainable environment, the transition to electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) has become inevitable [26]. The early attempts to introduce EVs in the 1990s were not successful because of their costs and low performance in terms of top speed and travel range in comparison with vehicles run on ICEs. With recent advancements in battery and fuel cell technologies, many automotive manufacturers have announced plans to begin serious production within the next two to three years. EV sales will exceed 10% of global vehicle sales in 2022 and are expected to reach 30% by 2030 [27]. Concurrently, the global market share of fuel cell technology is expanding rapidly. In 2022, the fuel cell revenue was estimated at USD 2.9 billion with a projected increase to USD 9.1 billion by 2027 [28]. The combination of EVs with fuel cell technology is predicted to revolutionize the automotive industry soon.

High power density, the capacity to respond to significant swings in power demand, and employing a low-temperature solid electrolyte providing hydrogen ions are the most essential aspects in selecting the finest fuel cells for passenger cars. For this reason, automobile manufacturers choose to equip new cars with proton exchange membrane (PEM) fuel cells. Due to its abundant availability and strong reactivity, oxygen is used in PEM fuel cells as the oxidant and hydrogen (H+) as the electrolyte [29]. PEM can function at temperatures between 70 °C and 90 °C while maintaining a pressure of 1 to 2 bars. The PEM fuel cell has several benefits in addition to its low operating temperatures, such as being a dry, solid, and non-corrosive electrolyte; tolerance to carbon dioxide content in the surrounding air; high current and voltage; high density of power; and small size and simple design [30]. The energy content of hydrogen is 120 MJ/kg, more than double that of liquefied natural gas, diesel, and gasoline [31].

Though hydrogen fuel cells can offer numerous benefits to vehicles, they have certain drawbacks. These drawbacks include a lengthy startup period, a lack of power output at slower speeds, a delayed response when a quick surge in power is required, and excessive power output during rapid acceleration [32]. These drawbacks can be avoided by integrating a secondary energy storage system that would function in tandem with a fuel cell. If the fuel cell is unable to generate enough energy on its own, this hybrid setup can provide the necessary power. Two groups of these hybridized systems may be distinguished: fuel cell electric vehicles (FCEVs) and fuel cell plug-in hybrid electric vehicles with a longer range (FC-PHEVs).

Similar to a battery electric vehicle (BEV), an FC-PHEV engine with internal combustion burns gasoline and can be used for powering the vehicle when the battery is near depletion, during acceleration, or when intensive heating and cooling loads exist. FC-PHEV increases driving range while cutting down on fuel expenses and hazardous pollutants. FCEVs, on the other hand, rely on the hydrogen that has been stored in tanks to turn chemical energy into electrical energy. FCEV batteries are charged by electricity generated by onboard hydrogen fuel cells or by a regenerative braking technology, which converts kinetic energy gained during braking into electrical power.

The powertrain of an FCEV consists of a number of hydrogen containers, as shown in Figure 1. Fuel cell stacks, a power converter, a rechargeable electric battery used to store energy, and a power distribution unit make up the FCEV configuration. The power needed to drive the vehicle comes from the HFC, which converts the hydrogen energy into electricity and saves it in the battery. The battery charges by the regenerative braking system during barking. The fuel cell does not need to provide any power when the vehicle is in the regenerative braking phase. A power distributor unit (PDU) is used to regulate this shift in power consumption.

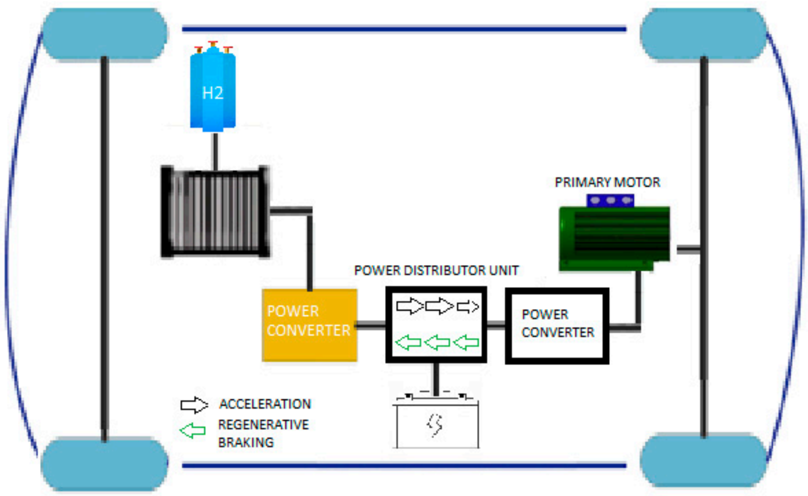

Figure 1. A configuration of fuel cell electric vehicle (FCEV).

Dr. Roger Billings developed the first ever hydrogen-powered fuel cell car in 1991 once he adopted a battery-powered Ford Fiesta model [31]. Later in 1994, Daimler-Benz released the NeCar I (output of 30 kW and a maximum range of 130 km), the first fuel cell-powered car suitable for everyday usage. This was the spark that ignited global innovation in the vehicle fuel cell sector. Due to technological advancement and continual improvement, NeCar II and NeCar III were later introduced with increased storage capacity and driving range (250 km and 400 km, respectively). Among the several fuel cell options, Daimler-Benz chose the PEM fuel cell because it runs at a low temperature of 80 °C and has substantially lower corrosion rates than other fuel cells. The NeCar II was intended to achieve an efficiency of 40–45% by 2003, which is larger than the best diesel automobile engine with an efficiency of 26%. Fuel cells may lower emissions by 90% compared to typical vehicles [33]. Soon after, almost all automobile manufacturers began developing or had concepts for HFC vehicles [31].

General Motors has continuously been a forerunner in the development of electric cars. In 2007, more than 100 HydroGen4 automobiles were built and tested in countries such as Germany and the United States. The automobile could store 4.2 kg of hydrogen, giving it a driving range of 320 km [34]. According to the Society of Automotive Engineers (SAE) J2601 and SAE J2799, once the tanks are empty, they can be replenished in three minutes.

During the 1990s, Honda began the development of HFC vehicles. In 1999, the Honda FCX-V1 was revealed. It was an experimental two-seater vehicle with metal hydride tanks used for storage. FCX-V2 was later developed and included a methanol reformer as well as fuel cell stacks developed by Honda. Using their previous expertise, Honda then developed the FCX-V3. This vehicle stored 250 MPa hydrogen tanks and had a 10 kW power improvement compared to its predecessors.

In 2001, Honda unveiled the FCX-V4. This evolved vehicle had further improvements in terms of storage space as well as a more compact HFC stack. The driving range was further increased to 315 km due to the increase in storage tank pressure to 350 MPa [35]. Figure 2 shows the progress of Honda's HFC vehicles and their corresponding power output.

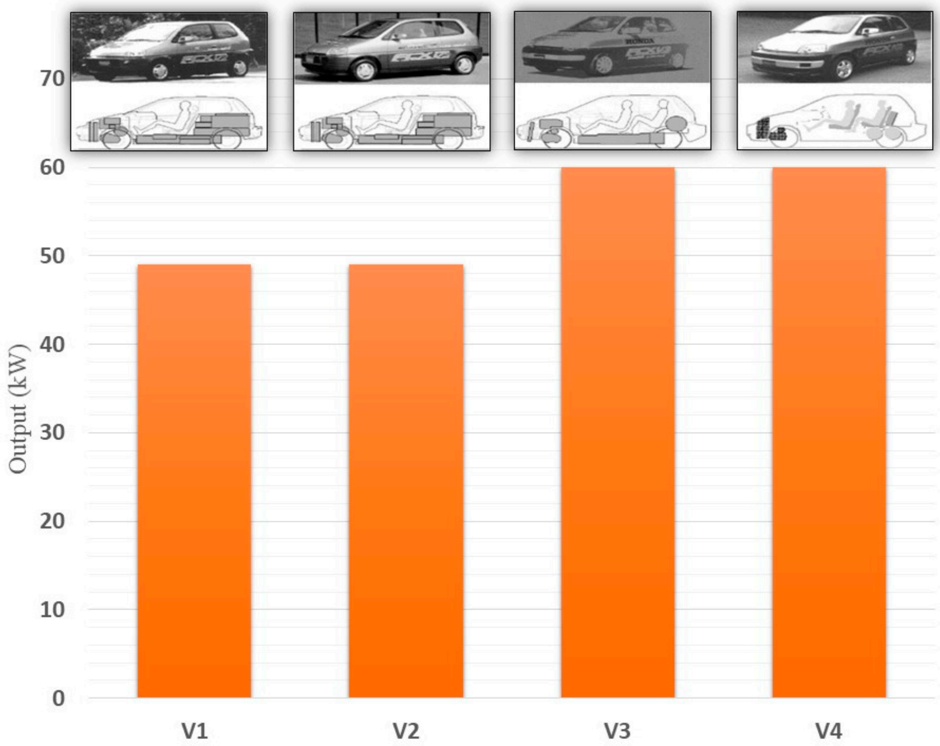

Figure 2. Improvement of Honda HFC vehicles [35].

Table 1 compares the key parameters of the hydrogen fuel cell-powered automobiles that are commercially available on the market. The designs of several cars, including the Honda FCX Clarity, the Hyundai ix35 (a modified version of the existing Hyundai Tucson), the Toyota Mira I, the Honda Clarity FCEV, the Hyundai Nexo, the Mercedes Benz B-class FCEV, the Chevrolet Equinox Fuel Cell, and the Toyota Mirai II, are shown in Figure 3. All listed vehicles are considered midsized automobiles with almost identical attributes and power outputs. It should be noted that none of the vehicles listed are PHEVs because their battery capacities are less than 2 kWh.

Table 1. Comparison of a few features of some HFC automobiles, including power outputs and prices.

Production Year	Vehicle Model	Range (km/Miles)	Power Output (kW/hp)	Hydrogen Tank Weight (kg)/Capacity (L)	Price
2008	Honda FCX Clarity [36]	450/270	100/134	4.1/171	USD 34,995
2013	Hyundai Tucson/ix35 Fuel Cell [37]	415/258	124/-	5.64/140	-
2014	Toyota Mirai I [38]	502/312	114/153	5/122	USD 57,500
2016	Honda Clarity Fuel Cell—FCEV	740/460	105/-	NA	
2018	Hyundai Nexo [37]	609/378	135/-	6.3/156	USD 59,435
2010	Mercedes Benz B-Class F-CELL [30]	400/250	100/136	3.7/-	-
2007	Chevrolet Equinox Fuel Cell [30]	320/200	94/126	4.2/-	-
2020	Toyota Mirai II [39]	650/404	128/182	NA	USD 49,500

Figure 3. Midsized automobiles with less than 2kW battery capacity: (**a**) Honda FCX clarity, (**b**) Hyuandi Tucson/ix35 FC, (**c**) Toyota Mirai I (**d**) Honda clarity FC, (**e**) Hyuandi Nexo, (**f**) Mercedes Benz F-Cell, (**g**) Chevrolet Equinox Fuel Cell, (**h**) Toyota Mirai II.

Hydrogen Storage System in Passenger Cars

According to the International Energy Agency (IEA), the United States and China had the most fuel cell vehicles on the road in 2019—around 8000 and 6000, respectively. Japan had just 3600 hydrogen cars on the road in 2019, but the country intends to increase that number to over 811,000 by 2030. Onboard hydrogen storage is one of the most challenging problems in implementing hydrogen fuel cells in automobiles [40]. However, hydrogen has the highest efficiency and the lowest energy density as a fuel. This indicates that hydrogen has the highest energy density per kilogram. This property can be regarded as a benefit for hydrogen fuel, but it might cause some issues when storing it onboard. One solution to this challenge is storing hydrogen as a compressed gas at extremely high pressures.

Smith and Aceves [41] analyzed various techniques for hydrogen storage and how each option affected total weight and, consequently, the driving range of the HEV. Typically, hydrogen has the capability to be stored through methods such as pressurization as a gas, cooling to cryogenic temperatures as a liquid, or in the form of solid fuel through a physical or chemical amalgamation involving substances such as metal hydride [42]. The weight, capacity, efficiency, storage safety, and total cost should all be considered when considering hydrogen tank storage. Chalk et al. [43] propose a simplified schematic of the hydrogen storage system, divided into three segments based on the applied pressure levels, driven by a relatively low-power electrical DC motor, as shown in Figure 4.

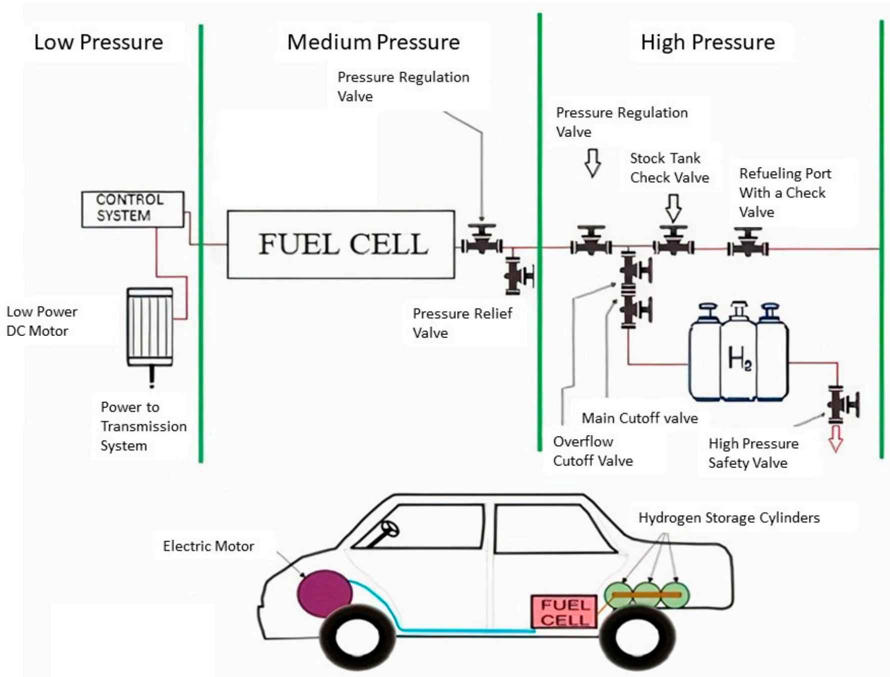

Figure 4. Onboard hydrogen fuel system for fuel cell vehicles [43].

4. Buses

With the objective of diminishing greenhouse gas emissions and enhancing air quality in densely populated urban regions, developed nations have made substantial financial commitments toward the advancement of cutting-edge technologies. Public transportation has recently received significant attention due to its huge environmental impact and tremendous opportunity for improvement. Fuel cell buses are an excellent choice for urban public transit, offering significant environmental and economic benefits compared to conventional buses, such as zero emissions, quiet operations, and reduced maintenance due to fewer moving parts [44].

According to the findings of Eudy and Chandler [45], fuel cell electric buses (FCEBs) have higher fuel economy than diesel buses, as indicated in Figure 5. Despite accounting for a tiny proportion of all vehicles on the road, buses have a considerable environmental impact [46]. Fuel cell buses have zero emissions, making them an appealing choice for decreasing urban air pollution [47]. These buses are significantly quieter than regular diesel buses and require less maintenance and refilling. This is due to the buses' ability to be gathered at a single location for fueling and maintenance under the authority of the fleet operator.

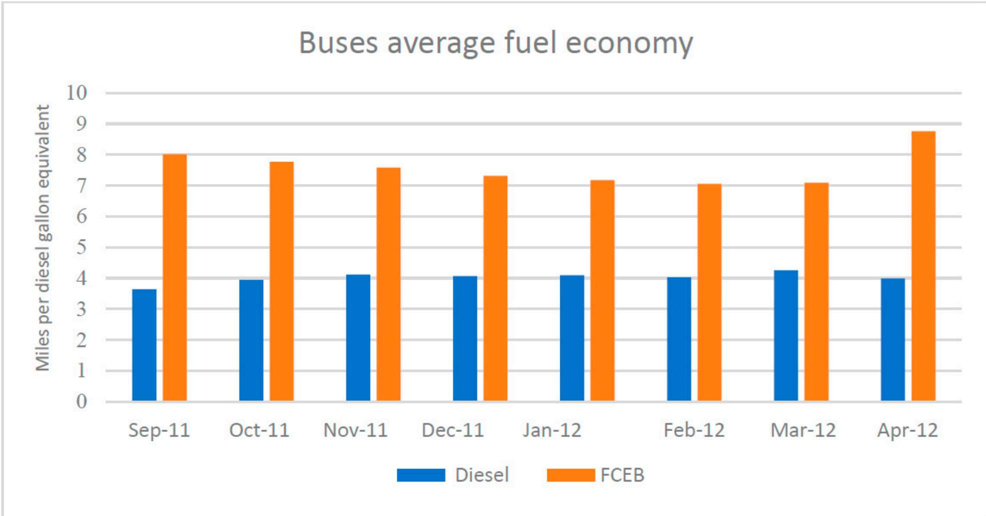

Figure 5. The mean fuel efficiency of fuel cell buses and diesel buses [45].

Buses offer a more advantageous choice for accommodating the fuel cell stack, fuel cell storage system, and battery storage in comparison to conventional vehicles, owing to their diminished weight and capacity restrictions [47]. As a result, various vehicle firms and educational institutions have put several initiatives to the test in the hopes of commercializing HFC bus technology. Common barriers to commercialization include the high initial costs of operating fuel cell buses, the longevity of fuel cell power systems, and the cost of recharging hydrogen gas.

Hydrogen Storage System in Passenger Cars

In order to find the best technology for fuel cell buses, Zamora et al. [48] analyzed two technologies (internal combustion engine and fuel cell-driven electric motor). Both technologies rely on hydrogen for vehicle fuel. The comparison was based on several parameters, including CO_2 emissions, environmental sensitivity, efficiency, dependability, autonomy, useful life, and cost. Based on this study, it was determined that the technology based on fuel cells was a superior option for extracting the potential energy of hydrogen in relation to the criteria discussed previously.

Bubna et al. [47] reported the development of a fuel cell hybrid bus (FCHB). The FCHB consists of hydrogen tanks, nickel–cadmium (NiCd) liquid-cooled batteries, the HFC system, and an inverter. The fuel cell hybrid bus provided an average efficiency of 42% throughout the normal drive cycle, indicating that the bus's performance was highly promising. The FCHB, with its battery-heavy hybrid configuration (which runs mainly in battery-alone mode until the state of recharge), resulted in cheaper costs and improved performance and durability, contributing to this good outcome.

Byung and Tae [49] investigated the development of FCVs by Hyundai-Kia Motors, beginning with their first-generation FCV in 2000. The bus was tested during the 2006 World Cup in Germany. The fuel cell was capable of producing a maximum of 160 kW, with an extra capacitor of 80 kW functioning as a backup when needed. The electric motor on this FC bus has a power capability of 240 kW.

In 2006, the Clean Urban Transport for Europe (CUTE) Project concluded, marking the conclusion of a pioneering initiative that involved the simultaneous deployment of a significant fleet of 27 fuel cell buses across nine cities for testing purposes. Saxe et al. [50] published the HFC bus performance data and examined the drive cycle in five different cities. Their findings suggest that the overall fuel cell system efficiency (between 36% and 41%) is relatively high. However, HFC buses consumed more energy than diesel buses.

The authors stated that more fuel consumption reductions might be achieved by reducing the weight by up to 2 tons, removing reliability measures, and utilizing hybridization with electrical auxiliaries, which can reduce fuel consumption by up to 35–40%.

In order to research the deterioration process of the HFC system, Li et al. [51] designed a plug-in HFC city bus. The 270 total cells in the 18-ton bus, which was constructed in 2015 and featured a 60 kW power stack, demonstrated power stability on continuous journeys. They concluded that an increase in ohmic polarization mostly caused the voltage drop.

In conjunction with Indian Space Research Organization (ISRO), Tata Motors in India was the first company in the area to create a fuel cell bus. The TATA STAR BUS matches Tata Motors' long-term objective of manufacturing more environmentally friendly automotive vehicles. The bus could store four high-pressure (350 bar) hydrogen cylinders with a total capacity of 820 L, which were positioned on the roof of the vehicle. With a Li-ion battery, this revolutionary system has a power capacity of 120 kW. For transitory power needs, the battery assists the fuel cell. Tata Motors has already tested two prototypes and is optimistic about commercializing this potentially transformative technology in public transportation [52].

Figure 6 displays the active fuel cell hybrid buses in 2014, with the majority deployed in North America and Europe. These buses have accumulated a successful service record of over 3 million miles [53].

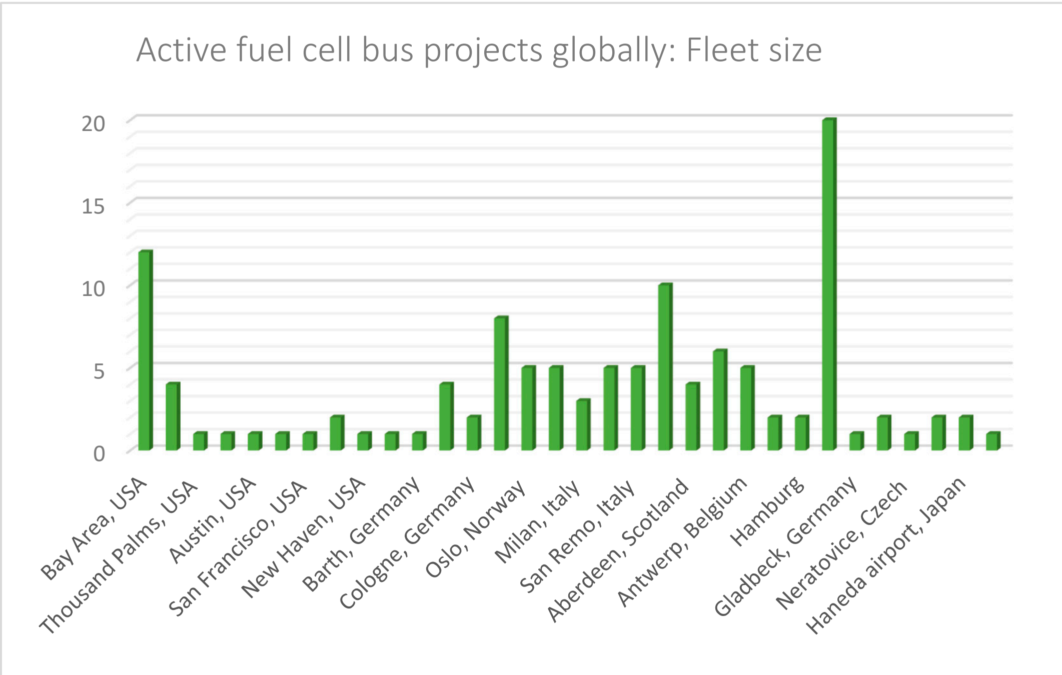

Figure 6. Active fuel cell bus projects globally [53].

Samsun et al. [24] collected data to determine the total number of registered FCVs worldwide. It was found that there were 34,804 fuel cell vehicles by the end of the year 2020, as shown in Figure 7. Only 16.2% of those vehicles were buses. The distribution of vehicle types across the total number of fuel cell vehicles worldwide can be seen in Figure 8. Of those, it was seen that 97% of the buses were operated in Asia, 2% in Europe, and 1% in North America. China contributes to most of Asia's fuel cell buses, with a total of 5290 buses. Passenger cars make up most of the world's fuel cell vehicles, with about 74.5% of total cars.

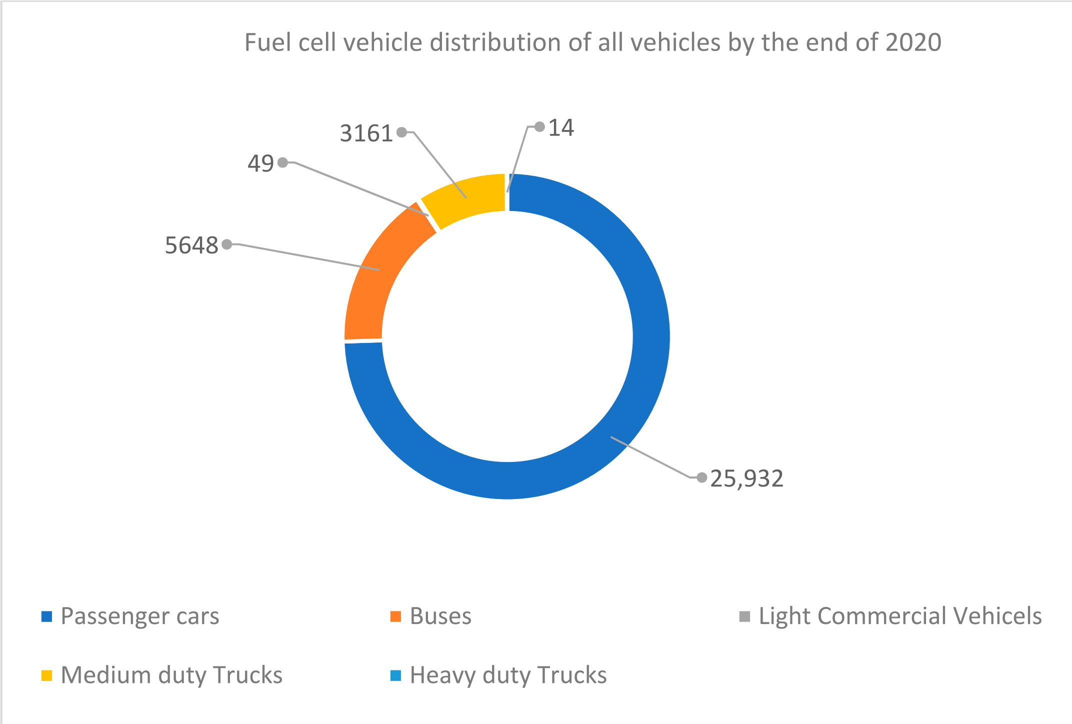

Figure 7. Fuel cell vehicle distribution of all vehicles by the end of 2020 [24].

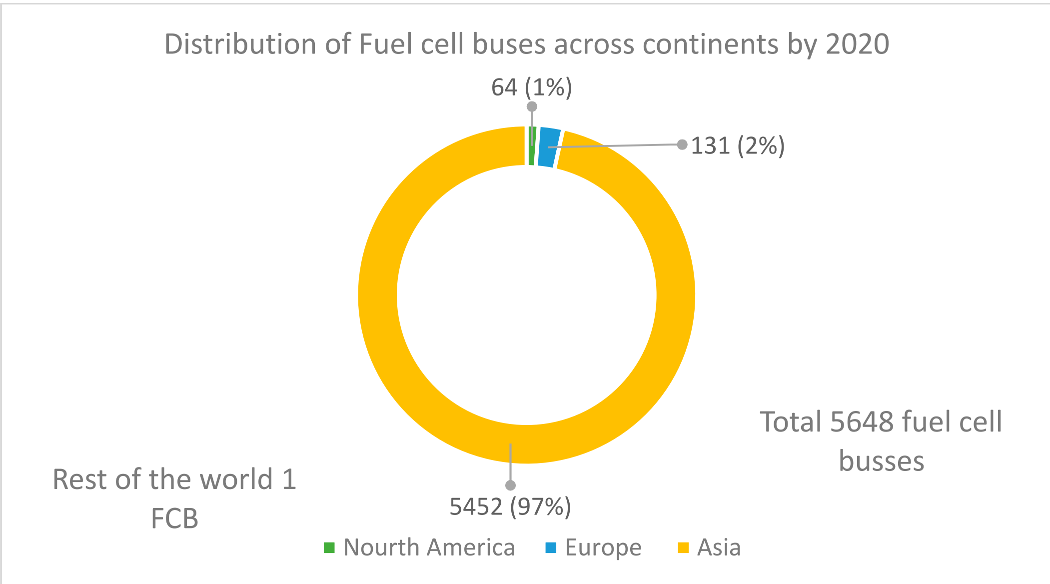

Figure 8. Distribution of fuel cell buses across continents [24].

5. Trains

The energy source for fuel cell-powered trams is hydrogen. A hybrid system combining large-capacity lithium titanate batteries and fuel cells powers the tram. The only pollutants produced by tram operations are heat and water. The tram's hydrogen fuel is stored in high-pressure tanks on the tram's roof. Cutting-edge heat dissipation and storage technology boosts hydrogen capacity and cruising range. This fuel cell tram typically has enough fuel to run for more than 13 h every day. Table 2 shows the specifications of the Fashon city tram which has been employed in China [54].

Table 2. Specifications of the Fashon city tram employed in China [54].

Configuration	Three Coaches and Two Locomotives
Size	35.19 m × 2.65 m × 3.58 m
Mass	55 tons
Max Passenger Capacity	360 people
Max Speed	70 km/h
Max Range	125 km
Daily Operation	13 h
Refueling Events	2–3 times/day
Refueling Time	15 min
Hydrogen Consumption	25–30 kg/100 km

China was one of the pioneers that practically employed a commercial fuel cell-powered tram system in Foshan, a city in Guangdong Province. To take advantage of this chance, the city is developing into a hub for the design and production of hydrogen fuel cell products. It also looks to technology to help the city satisfy its urgent demand for environmentally friendly transportation. Therefore, several hydrogen initiatives have been carried out in Foshan, such as the Foshan Gaoming Modern Hydrogen Tram Demonstration Line, which is perhaps the most well-known of them. In July 2019, the first hydrogen tram was employed in Foshan, and the Foshan Gaoming tram line opened to the general public and began receiving payments in December 2019. During peak hours, the project management team, which is headed by Foshan Metro, expects to operate four trams with departures every 10 min and 115 departures each day. Each tram includes three coach bodies that can accommodate 360 passengers in total, has a top speed of 70 km/h, and has a range of 125 km per refueling [54].

The world's first HFC train, Coradia iLintTM, was powered by hydrogen in 2016 in Berlin with 160 passenger seats. In the European Union (EU), the majority of the passengers commute by electrified railways, which is about 53%; nevertheless, employing such a system in other countries such as North America is not applicable to this capacity as most of the railway lines are non-electrified [55].

Hsiao et al. [56] developed a hybrid system incorporating a proton exchange membrane fuel cell (PEMFC) into a mini-train capable of accommodating 9–12 passengers. The fuel cell power system employed in this research encompassed a 200-watt PEMFC, four metal hydrogen storage tanks interconnected with a group of low-pressure lead acid batteries, and an intelligent electronic energy control system. Power provision was achieved by means of a parallel connection of fuel cells and lead acid batteries. The mini-train operated outdoors on a track measuring 18.4 cm in width and 212 m in length at the National Science and Technology Museum. Following a two-year implementation period, noteworthy findings were obtained. The small train logged over 2000 h of service and carried over 70,000 passengers during that period [56]. The research illustrated that connecting lead acid batteries and fuel cells in parallel may resist Taiwan's high heat and humidity while providing stable electricity. This fuel cell power system was capable of providing the same amount of power to the mini-train as lead acid batteries.

Despite the early stage and incomplete development of hydrogen fuel cell (HFC) technology for trains, available literature highlights that hydrogen-powered trains demonstrate a range roughly ten times greater than that of battery-powered electric trains. These trains can achieve top speeds ranging from 125 to 140 km/h and cover distances of up to 1000 km before requiring refueling. Furthermore, the refueling process for these trains takes less than 20 min, signifying a notably rapid procedure.

6. Trucks

HFC technology in medium-duty (MD) and heavy-duty (HD) vehicles has high potency in reducing greenhouse emissions and energy consumption. Globally, heavy-duty trucks produce approximately 36% of nitrogen oxide emissions [57] and 25% of the US transportation sector's greenhouse gases [58]. Studies conducted by the US Energy Information Administration predict a spike of up to 80% in total miles driven by trucks between 2010–2050 [59]. For this reason, trucks have been a vital parameter to consider when reducing emissions from powertrains. Despite the widespread use of fuel cell technology in cars and buses, its application in trucks is still relatively limited. HFCs have been put forward as a feasible substitute for diesel engines with the aim of reducing pollutant emissions [60]. However, their driving range and performance are still in question. Although the number of hydrogen fuel cell electric trucks, vans, and buses on the road today is limited, several studies have shown that HFC vehicles are crucial for minimizing the effect of climate change by the year 2050 [61].

Integrating the fuel cell system into medium-duty and heavy-duty trucks can be complex due to the effects of the components on the weight and aerodynamics of the trucks. Trucks are classified into several categories. Whether MD or HD vehicles, they are classified based on their designated vocational applications and corresponding weight classes.

Table 3 demonstrates the estimated vehicle population in 2014 [62]. According to Oak Ridge National Laboratory [63], around 10.9 million registered class 3 to 8 vehicles exist. In total, they make up about 5% of on-road vehicles. The most significant number of trucks is the class 8 tractor (60,000 lb. or more), which counts 2.67 million vehicles.

To the best of our knowledge, we compiled a list of the hydrogen-powered trucks that are in operation and expected to be produced in the coming years, as shown in Table 4.

Because of the additional design space, customizability, and weight, utilizing an HFC system in trucks appears to be a potential option, resulting in better scaling and, hence, commercialization. Several studies exist in the literature that discuss the chance of introducing HFC technology and other alternatives to the market, their overall effect on the environment, and their economic impact [65]. Çabukoglu et al. [66] presented a study to determine whether it is possible to decarbonize heavy-duty transport across the entire Swiss national fleet. The scholars also studied the feasibility of day-to-day operations for every vehicle class. A study conducted by Lewis et al. [67] used GPS data to determine the optimal powertrain for given routes and duty cycles. They concluded that a hybrid mechanism comprising a 32 kW HFC, a 49 kWh battery, and a 15 kg hydrogen storage tank should yield an optimal option.

Kast et al. [62] analyzed the design of hydrogen fuel cell trucks in detail and discussed the possibility of onboard storage and the vehicle's performance under different drive cycles. Storing the hydrogen tanks in the most appropriate location is essential, as this will significantly impact the vehicle's air resistance due to its shape. There are various places for storing hydrogen tanks on a truck, which vary based on the vocation and truck size [62]. These storages can be categorized as follows:

1. Side-rail tanks: This is the most convenient model, as most MD and HD trucks already have this space available.
2. Back-of-cab storage: This is an option for larger trucks, typically classes 4 to 8.
3. Under the chassis: This is suitable for smaller-class vehicles (e.g., class 3 and below). This configuration can only work for particular trucks because of chassis design constraints, i.e., the tanks do not interfere with the beams.
4. On top of vehicle: This type can only be used on certain trucks and results in a higher center of gravity.

Multiple storage tank locations can be utilized to optimize the trucks' driving range.

Figure 9 shows an estimated driving range for several vehicles based on optimizing storage tank locations onboard [62]. The payload and hydrogen storage capacity significantly influence the driving range of a high-capacity (HD) vehicle. A completely fueled HD truck, equipped with two storage tanks containing 40–60 kg of hydrogen each at a pressure of 350 bars, generally covers a distance of approximately 500 to 1000 miles before requiring refueling [68].

Table 3. Estimated vehicle population in 2014; the heat map shows the relative market share per vehicle category of MHDVs [62].

	Class	8	8	8	8	7	6	5	4	3	Total
	Weight (lbs. 10^3)	**60 +**	**50–60**	**40–50**	**33–40**	**26–33**	**19.5–26**	**16–19.5**	**14–16**	**10–14**	
Vans	Step	2	1	1	2	5	127	101	98	234	572
Vans	Enclosed	4	4	14	18	87	294	178	80	256	933
Vans	Insulated	2	3	4	6	40	60	23	7	21	167
Vans	Open top	6	22	69	38	78	89	19	12	11	345
Vans	Other	1	1	2	1	4	20	7	1	43	90
Work Vehicles	Flatbed	33	41	81	100	203	475	157	185	341	1617
Work Vehicles	Dump	203	160	187	101	181	315	80	114	204	1546
Work Vehicles	Concrete	122	49	17	2	0	0	0	2	0	193
Work Vehicles	Tow	2	4	7	11	16	78	31	36	65	249
Work Vehicles	Utility	2	7	11	31	73	106	70	46	117	465
Work Vehicles	Garbage	32	73	49	26	20	14	6	2	5	229
Freight	Tank	19	28	51	41	130	96	14	13	13	405
Freight	Beverage	0	0	2	8	46	32	5	3	4	100
Freight	Tractor	2670	314	279	131	64	31	0	0	0	3489
Other		29	21	24	15	40	104	49	69	151	502

Table 4. The characteristics of different hydrogen-powered trucks employed in Europe [64].

Manufacturer	Range (km)	Max Gross Weight	Type of Truck	Fuel Cell Capacity	H2 Storage	Operation Status	Number of Trucks
VDL	400	27 tons	Truck trailer	88 kw	30 kg @ 350 bar	In operation since 2020	1
Scania/Asko	400–500	27 tons	Truck trailer	90 kw	33 kg @ 350 bar	In operation since 2020	4
E-trucks Europe	400	26 tons	Refuse truck	40 kw	-	-	1
SYMBIO: Renault Maxity H2	200	4.5 tons		20 kw	Two tanks with 75 L, each one can store 4 kg of hydrogen with 350 bar	In operation	1
ESORO	375–400	34 tons combined with trailer	Heavy duty truck	100 kw	31 kg @ 350 bar	Started 2017. Not operational anymore	1
Nikola Motors	805–1200	36 tons	Class 8—sleeper cab semi-truck	-	-	Concept—expected operation in 2022–2023	1
LOOP Energy	-	-	Yard truck (off-road heavy duty)	56 kw	-	In operation	1
DONGFENG	330	7.5 tons	Box van truck	30 kw	-	In operation since 2018	500
SCANIA/Renova	-	-	Refuse truck	-	-	Concept	1
Kenworth	320	36 tons	Class 8—truck trailer	85 kw	-	In operation	1
UPS	200	12 tons	Class 6—Delivery truck	31 kw	2 × 5 kg, high-pressure tanks	In operation	17
PLUGPOWER	430	-	Off-road truck	20 kw	-	In operation	15
TOYOTA/HINO	600	25 tons	Class 8—heavy duty	-	Developing a new large-capacity, high-pressure (70 MPa) hydrogen tank	Concept	-
MITSUBISHI FUSO	270–300	7.5 tons	Rigid truck—light duty	75 kw	5–10 kg @ 700 bar	In operation	150

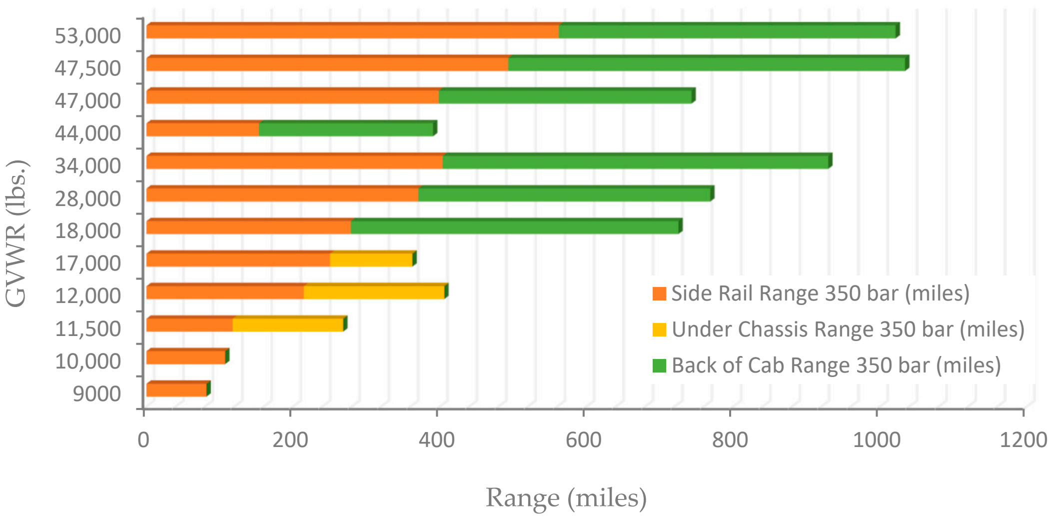

Figure 9. The range of the vehicle determined by the placement of the compressed hydrogen storage tank at a pressure of 350 bar [62].

Kast et al. [62] achieved impressive outcomes in terms of power-to-weight ratio, fuel economy, hydrogen storage, and vehicle range.

Figure 10 displays the calculation of the required hydrogen storage for different trucks to attain a specific driving range, using data extracted from the literature [62]. It can be seen that the trend follows a quadratic fit as the gross vehicle weight rating (GVWR) increases.

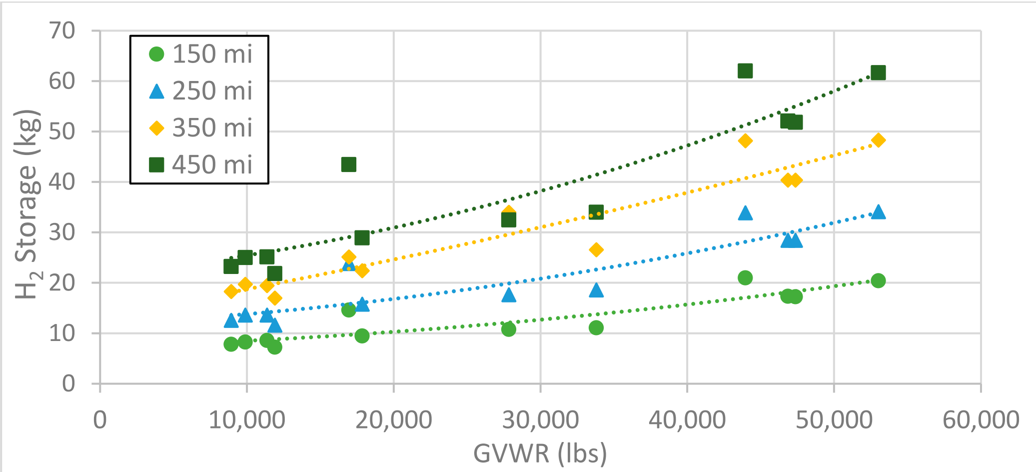

Figure 10. The required quantity of hydrogen storage necessary to attain a specific range for each representative truck is estimated based on the gross vehicle weight rating (GVWR) [62].

The improvement of HFC-powered trucks has grown in interest among manufacturers in the past couple of years. According to Çabukoglu et al. [66], developing hydrogen-powered fuel cell trucks does not only mean building new trucks but also converting them into FCEVs. Converting heavy-duty vehicles is less complex than lighter vehicles, and that is because lighter-duty vehicles (less than 18 tons) have less space to store the hydrogen tanks. More work is needed in terms of infrastructure and the installation and production of hydrogen refueling stations. Fuel congestion and refueling rates are also issues to consider before commercialization. Such a project's feasibility and cost analysis also need to be studied to prove its sustainability. The aim is to develop sustainable MD/HD trucks that meet the performance requirements while generating zero greenhouse emissions. Assuming that the infrastructure is ready and the feasibility study proves suitable, fuel cell trucks are likely to become the leading form of truck transport due to their zero emissions and extended driving range.

7. Aerial Transportation Systems

The adverse impact of the emissions resulting from burning fossil fuels on the climate is becoming apparent. The aviation industry contributes about 2.1% of global CO_2 emissions, and when other pollutants and greenhouse gases are factored in, this figure approaches 5%, making the industry one of the top ten emitters [69]. Noise pollution is another nuisance, especially for communities neighboring major airports around the globe. To tackle these problems, the European Commission, for instance, has set a few environmental targets aiming to reduce CO_2 emissions by 75%, NO_x gases by 90%, and perceived noise by 65% produced by a typical aircraft compared to the year 2000 levels by the year 2050 [70,71]. Similarly, the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO), among other influential entities in the aviation sector, have set a target of attaining a 50% decrease in CO_2 emissions by 2050. Such ambitious goals would require a drastic paradigm shift in the aviation industry that cannot be merely achieved by reducing fuel consumption through improvements in aircraft aerodynamics or by designing more efficient engines.

According to a report conducted by McKinsey in 2020 [72], fuel cell technology has the potential to reduce the climate impact of the aviation industry by approximately 75% to

90%. This reduction could take place with a minimal increase in the cost of about USD 5–10 per passenger (PAX) for commuter and regional aircraft, 20–30% per PAX for short-range aircraft, 30–40% per PAX for medium-range aircraft, and 40–50% per PAX for long-range aircraft in comparison with conventional aircraft of the same category. Table 5 presents the definition and classification of the different types of aerial vehicles.

Table 5. Aerial vehicle (AV) categories and definitions.

Type of the AV	Definition	Number of Passengers	Conventional Propulsion Type
UAV	A drone, also referred to as an unmanned aerial vehicle (UAV), is an aircraft operated remotely.	0	Battery Reciprocating engine
Sport Aircraft [73]	It is an aircraft other than a helicopter or powered lift with a maximum gross weight of 650 kg (300 lbs) unpressurized cabin.	Max 2	Single reciprocating engine
Commuter Aircraft [74]	A commuter aircraft is primarily used by businesspeople for short-distance travel and has a maximum take-off mass of 8620 kg.	Max 19	Multiple jet engines
Transport aircraft [75]	A transport aircraft refers to an airplane with multiple engines that has a seating capacity exceeding 19 or a maximum take-off weight surpassing 8620 kg (19,000). The category includes: • Short-range aircraft (<3 flight h); • Medium-range aircraft (3–6 flight h); • Long-range aircraft (6–16 flight h); • Ultra-long haul (>16 flight h). Regional aircraft fit under the short- to medium-range category. Regional aircraft are typically jet and turboprop aircraft, with a seating capacity ranging from 19 to 130 seats, operating on short- to medium-haul routes.	More than 19	Multiple jet engines Turboprop engines

Many researchers have recently been engaged in finding alternative sources of energy, such as lithium ion batteries, fuel cells, or other hybrid architectures, to power aircraft. Zunum, Airbus, Aero, and Eviation are notable companies endeavoring to create short-range passenger aircraft powered solely by electric batteries. These batteries hit the market in 2021 [76]. The limited energy storage density of batteries, which stands at 0.35 $kWh \cdot kg^{-1}$, severely constrains the payload and range of all-electric aircraft, although they have the potential to eliminate greenhouse gas emissions caused by air travel [76]. In contrast, fuel cell-based systems offer enhanced performance with regard to range and endurance. The two pivotal factors for aircraft electrification are energy density in Wh/kg and power density in W/kg. The former determines the aircraft's potential range and passenger-carrying capacity, while the latter plays a crucial role in takeoff and climbing procedures. Figure 11 shows the energy and power densities of various electromechanical energy storage methods.

Small and medium-sized aircraft in the aviation industry are garnering growing attention for the implementation of hydrogen fuel cells, mainly because of their energy efficiency, high energy density, and minimal environmental footprint.

The relationship between HFC technology and the aviation industry is not a recent development. Back in 1932, the English engineer Francis Thomas Bacon created the initial hydrogen–oxygen fuel cell, which marked a significant milestone. This groundbreaking invention proved to be highly effective, leading to its utilization in the space sector to energize satellites and rockets for space exploration initiatives such as Apollo 11 from the 1960s onward [78,79] Recently, leading airplane manufacturers, such as Airbus and Boeing, have been considering using hydrogen fuel cells to replace their aircraft's traditional auxiliary power units (APUs). An APU is a compact turbine engine that is typically situated in the tail cone of an aircraft or, in certain instances, within an engine nacelle or the wheel well. An APU is present in the majority of contemporary turbojet-powered planes, encompassing smaller regional jets as well as a handful of turboprop aircraft. By propelling the electrical generator, the APU enables the aircraft to function independently without the need for ground support equipment. Consequently, it empowers the aircraft to operate autonomously. With more advances in the technology related to hydrogen fuel cells, such as hydrogen production, storage, and refueling, large commercial airplanes partially propelled by hydrogen fuel cells could become a reality in one or two decades [80].

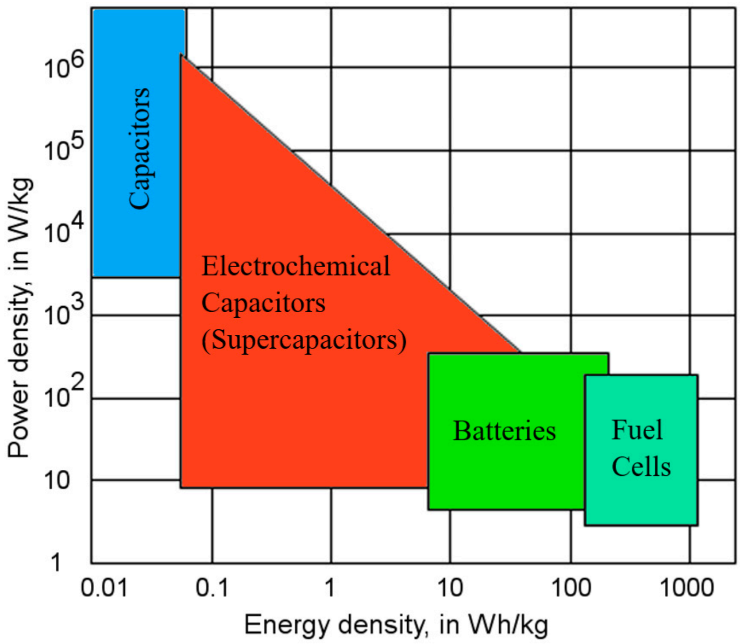

Figure 11. Comparison between various electromechanical storage structures according to the power and energy densities [77].

In general, fuel cell applications in the aviation industry can be classified into propulsive and non-propulsive (i.e., for electric power generation) applications. There are currently many studies and attempts by researchers and aircraft manufacturers to use fuel cells for propulsive and non-propulsive functions in small and medium-sized aircraft as well as UAVs. For large commercial airplanes, however, the current volume of work is focused on using fuel cells for non-propulsive functions.

The next section represents a review of fuel cell applications in propulsive and non-propulsive applications in the aviation industry.

7.1. Fuel Cells for Non-Propulsive Applications (Electric Power Generation)

Most aerial vehicles need electric energy to power their various systems, such as the cabin pressurization unit, lighting, cockpit avionics, the environmental packs used for heating and cooling, etc. This electrical power is generated via a generator, which is driven either by the main engine or by an auxiliary power unit (APU). The main engine and APU mainly rely on fossil fuels as a source of energy.

The increasing pressure on the aircraft manufacturer to reduce emissions, noise, and cost prompted the transition to more electrical aircraft (MEA) options [81–83]. This shift meant replacing the main engine/APU-driven generator with direct electric power generation systems, such as batteries, fuel cells, and supercapacitors, as standalone systems or in hybrid combinations. Many researchers regard fuel cell systems as a significant contender for achieving MEAs [83–89], due to their numerous benefits, which include but are not limited to high efficiency, minimal to no emissions, distributed power generation, and the possibility of water reclamation [90,91]. Several fuel cell forms exist, varying in terms of their operating temperature range and electrolyte composition. These include the solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), molten direct methanol fuel cell (MDMFC), and proton exchange membrane fuel cell (PEMFC). Among these, SOFC and PEMFC have attracted the most attention for applications related to the aviation industry. Table 6 and Figure 12 show the two types' specs and schematics [92].

Table 6. Characteristics of PEMFC and SOFC [92].

Parameter	PEMFC	SOFC
Electrolyte	Proton exchange membranes	Ceramic
Operating temp.	80–100 °C	600–1000 °C
Charge carrier	H^+	O^{2-}
Reforming process for HC fuels	External	Partial external pre-reforming, partial stack-internal
Prime cell components	Carbon-based	Ceramic based
Catalyst	Platinum	Perovskites/nickel
Robustness against poisoning	Highly sensitive to CO, UHC, S	Sensitive to S
Product H_2O management	Evaporative	Gaseous product
Product heat management	Process gas + independent cooling medium	Internal reforming + process gas
H_2O effluent location	Air side	Fuel side
System efficiency	>40%	>75% (hybrid SOFC)
Response to load change	Quick, dynamic system behavior	Slow, static system behavior
Maturity	First operational test series in automotive industry	Breadboard units for mobile application

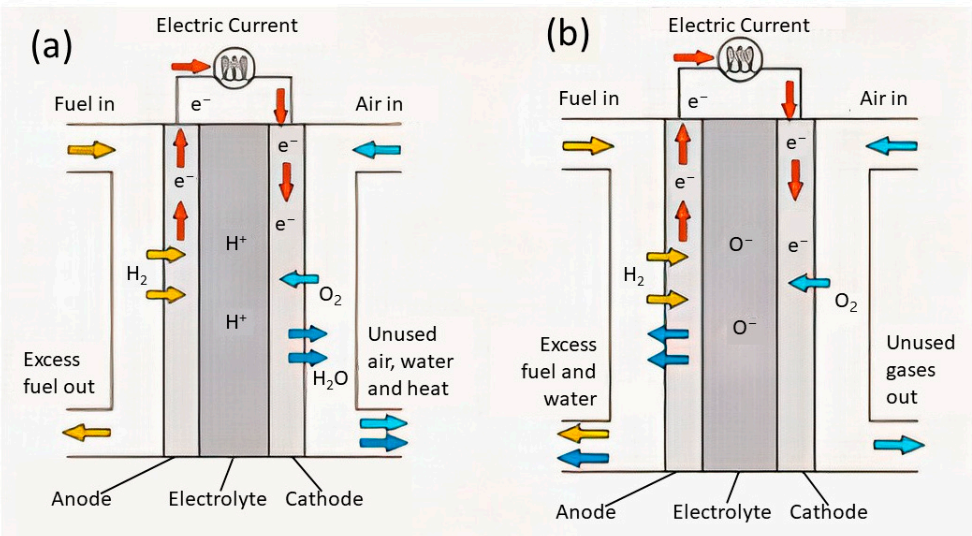

Figure 12. Schematics of (**a**) PEMFC, (**b**) SOFC [93].

Shanshan et al. [92] conducted a comparison between solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs) in terms of their performance for generating electrical power onboard an MEA. Based on the presented configurations, the authors concluded that SOFC performs better than PEMFC. Whyatt G. et al. [94] investigated the potential of using SOFC for generating electricity on Boeing 787 as a case study. Elamn et al. [90] compared the performance of SOFC-GT and PEMFC-GT hybrid configurations against the conventional gas turbine (GT)-APU. According to the study, the findings indicate that concepts incorporating solid oxide fuel cells (SOFCs) demonstrate significantly higher system efficiencies, suggesting a greater potential to replace conventional auxiliary power unit (APU) systems. Similar work was conducted by

Daggett [95] in which SOFC-GT was proposed as a hybrid system on Boeing 777 as a case study. He predicted that the SOFC-GT APU would be 60% efficient at sea level. Rajashekara et al. [85] modeled different hybrid architectures of FC-GT APU in an attempt to find the optimal configuration for generating electrical power on board the 305-seat Boeing 777. The authors concluded that the hybrid SOFC-GT combination is highly attractive. It was predicted to have a fuel efficiency of 73.7% at high altitude and 60.6% at sea level.

In a similar vein, the research conducted by Gummalla et al. [96] examined the performance of the solid oxide fuel cell–gas turbine (SOFC-GT) auxiliary power unit (APU) concept for a 162-passenger, more electric, short-range aircraft with a range of 1000 nautical miles and a peak load of 360 kW. The study estimated that the system could achieve fuel savings of 6.7% compared to the baseline GT APU system. Furthermore, Collins F. et al. [76] investigated the utilization of a hybrid configuration combining SOFC-GT and battery systems for onboard electric power generation in four different aircraft: the Fokker F70, Boeing 787-8, and Airbus models A300 and A380. The hybrid system, comprising the SOFC-GT–battery setup, was optimized to maximize passenger payload when compared to existing turbine technology operating on jet fuel, as well as next-generation turbine technology utilizing liquid hydrogen. The energy and power analysis conducted suggests that the SOFC-GT–battery hybrid configuration could have a significant role to play in future commercial aircraft.

7.2. Fuel Cells for Propulsive Applications

Presently, most large civil aircraft use turbofan engines as their primary power source. Smaller aircraft, such as sport aircraft, commuter aircraft, or AUVs, prefer to use a motor or turbo-propeller engine. The required power for large commercial aircraft is generally above 400 kW, whereas the required power for smaller aircraft is typically in the range of 5–240 kW [84,97–99]. For a small electrical UAV to achieve flight, it generally requires a power-to-weight ratio ranging from 20 to 200 watts per kilogram. To provide an example, a UAV with a take-off weight of 4.5 kg and a wingspan of 5 m would necessitate approximately 100 W of power. In contrast, larger UAVs capable of carrying a load of 300 kg might require around 1.5 kW of power. For high-altitude and long-endurance (HALE) UAVs, the power requirement could be in the tens of kWs [100]. Many researchers have presented analytical studies proposing fuel cell technology to provide a propulsive function to different types of aircraft.

Suewatanakul et al. [101] introduced a hybrid mechanism consisting of a proton exchange membrane fuel cell (PEMFC) and a battery for an autonomous underwater vehicle (AUV) aircraft. The UAV in question has a wingspan of 4 m and a maximum take-off weight of 25 kg. Their research findings revealed that by utilizing a 650 W fuel cell in combination with a 100 Wh battery pack and an 80 g compressed hydrogen fuel supply, the aircraft was capable of completing a 2 h journey. Similarly, Farajollahi et al. [102] explored a hybrid propulsion system that incorporates a PEMFC and a battery for a small unmanned aerial vehicle (UAV). Similar work was conducted by Wang et al. [103] in which they investigated the performance of hybrid UAV systems comprising a battery pack and three different types of fuel cells: PEMFC, DMFC, and SOFC.

Qin et al. [104,105] have proposed a SOFC turbine-less jet engine to provide electric propulsion for long-endurance AUVs. In their proposal, the compressor is driven by the SOFC instead of a turbine. Figure 13 shows a schematic of the proposed propulsion system. Different jet fuels were studied to produce the needed hydrogen through a reformer for the SOFC. The following fuels were used: methane, methanol, decane, and propane. The researchers reached the conclusion that the efficiency and specific power of the SOFC jet engine surpass those of combustion engines.

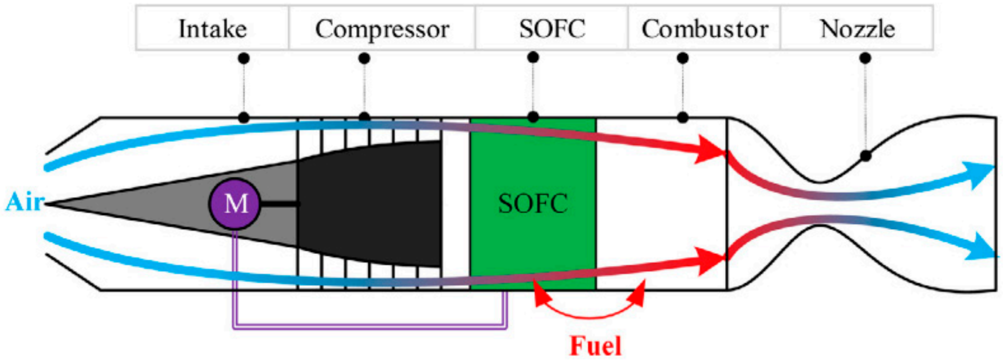

Figure 13. Schematic of SOFC turbine-less jet engine as proposed by [104].

Gonzalez-Espasandin et al. [106] proposed PEMFC and DMFC hybridization concepts with electric batteries for UAVs. The batteries were used to overcome the fuel cells' lower power density. Marinaro et al. [107] presented a numerical analysis of the propulsion system based on PEMFC as the primary power source as well as a battery backup and ultra-capacitor for a secondary energy source. The PEMFC unit was designed to meet continuous electrical loads during the cruising segment of the flight, and the battery pack was designed to provide an extra energy boost during take-off and climbing. The ultra-capacitor was sized to avoid a high discharge rate of the battery pack and to contribute to the power mix during the maximum power demand. The power management strategy used is shown in Figure 14. The system was designed to generate at least 30 kW. Two power architectures were analyzed: one comprising the battery pack alone and the other made up of the PEMFC and battery pack working in synergy. According to their findings, the hybrid architecture, which consists of PEMFC and a battery pack, provides greater energy density onboard the aircraft.

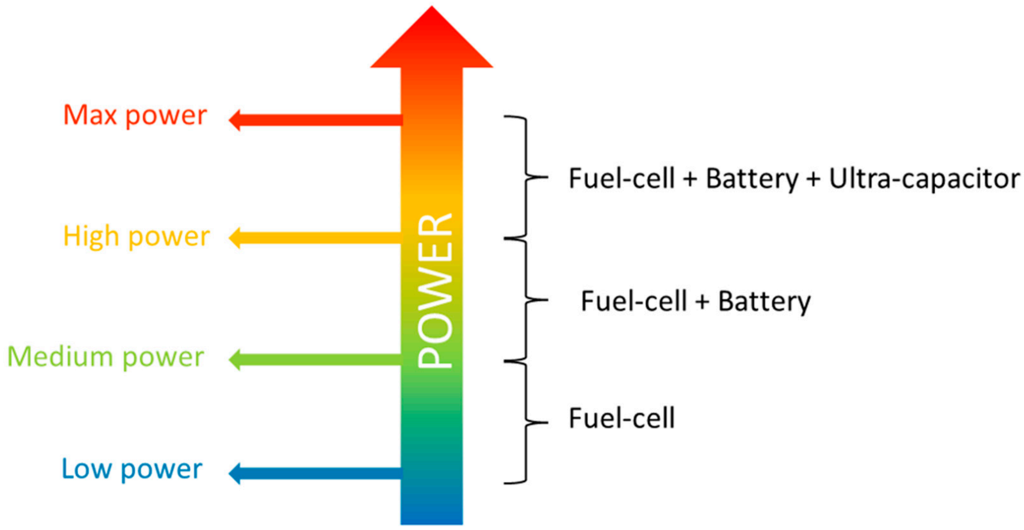

Figure 14. Schematic of the power management strategy used by [107].

In conclusion, when it comes to using fuel cells to replace the conventional APUs onboard aircraft, the most promising architecture is the SOFC-GT hybrid system [92,108]. The literature survey showed that SOFC-GT hybrid systems could achieve efficiencies as high as 75%, much higher than the non-hybrid option (maximum of 38%) [108]. Other hybridizations of GT with PEMPC and batteries seem to be less likely. Although PEMFCs' technology is more mature than SOFCs, SOFCs have some qualities that make them the preferred option for replacing the conventional APU on aircraft. Among these qualities are (i) the possibility of internal fuel reforming for short-chain hydrocarbon fuels such as methane, ethanol, methanol, and natural gas [109], (ii) higher power density, and

(iii) greater efficiency [108]. An external reformer would be needed for long-chain hydrocarbon fuels such as gasoline and kerosene [110–112]. Reforming fuels requires high temperatures (700–800 °C), which are compatible with the operating temperature of SOFCs (600–1000 °C) but not in the case of PEMFCs (80–100 °C). Furthermore, because SOFCs operate at high temperatures, their hybridization with gas turbine power plants results in high cycle efficiencies [84,85]. Furthermore, it has been reported that, for similar stack power densities, PEMFC is about 50% heavier than SOFC due to the larger PEMFC size, which results in lower system efficiency [90].

Dong et al. [113] conducted a synthesis analysis to implement electric propulsion in large civil aircraft. Seitz et al. [114] proposed a SOFC-GT hybrid concept for the propulsion system of commercial aircraft whereby the byproduct water of SOFCs is injected into the gas turbine to increase its efficiency. The water is converted into superheated steam and injected into the combustion chamber to increase thermodynamic efficiency, as shown in Figure 15.

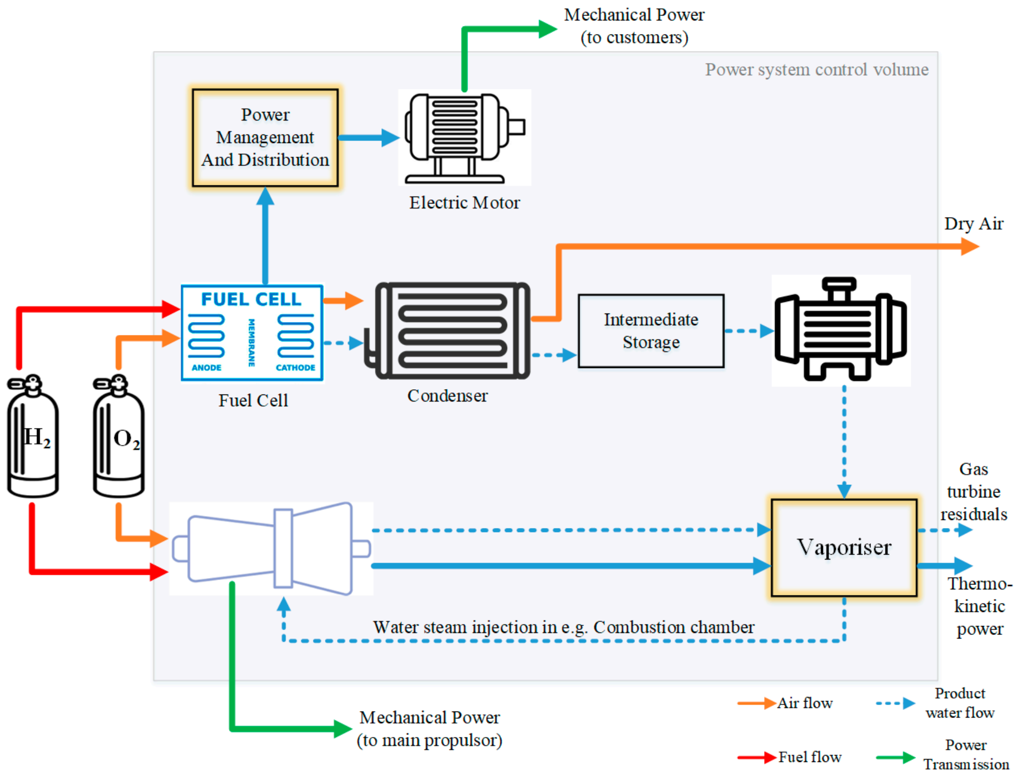

Figure 15. Schematic of SOFC-GT architecture studied by [115].

It is worth mentioning here, however, that the deployment of fuel cells for propulsive applications in the foreseeable future is most likely to take place in UAVs, sport aircraft, commuter aircraft, and regional aircraft. To accommodate the size of the liquid hydrogen (LH2) tanks on medium- and long-range aircraft, the fuselage must be significantly extended. Increasing the size of the fuselage would lead to an increase in fuel consumption of about 25% compared to a conventional aircraft. Therefore, the implementation of fuel cell technology for propulsive function in medium and large aircraft may have to wait until new aircraft designs are made. Such development could be 20 years away. Meanwhile, the use of synthetic fuel (synfuel) is likely to be a more cost-effective solution for reducing emissions [72,115].

8. Conclusions

This article presents a comprehensive examination of the application of hydrogen fuel cell (HFC) technology within the transportation sector, encompassing a wide range of vehicles from bicycles and scooters to commercial airplanes. The analysis provides compelling evidence of the considerable potential for HFC technology to secure a significant portion of the market in this industry by the end of the present decade. The distinct advantages inherent in HFCs, namely zero emissions, compactness, durability, and high efficiency, far outweigh those offered by most alternative energy sources. Conversely, HFCs do encounter several limitations, such as the costliness of catalysts and the relatively low power density, in addition to the challenges associated with hydrogen itself, such as production, storage, and distribution infrastructure.

Among the different types of HFCs, two types were noticed to be the most prevalent: PEMFCs and SOFCs. Due to the similarity of their operating temperatures, PEMFCs are most commonly used in two-wheeled vehicles, cars, drones, and small aircraft, whereas SOFCs are primarily used in large and medium-sized airplanes in hybridization with gas turbines.

The penetration of HFC for propulsion functions in large commercial airplanes would require redesigning the airplanes in order to accommodate the large size of hydrogen tanks needed. Hence, the use of HFCs in large airplanes will be limited to electric power generation in the foreseeable future. To overcome the drawbacks of low power density and the slow response of HFCs, hybridization with ICEs, batteries, and/or supercapacitors is sometimes used.

In conclusion, this study has shed light on the challenges and solutions associated with hydrogen fuel cells in transportation systems. To further guide researchers in this field, it is essential to identify the research gaps and highlight the challenges that need to be addressed. Key areas of focus include understanding the long-term durability and performance of fuel cell systems, evaluating the impact of environmental conditions on efficiency, exploring the economic feasibility and scalability of hydrogen infrastructure, and investigating advanced materials and catalysts. Additionally, challenges such as enhancing onboard hydrogen storage, developing cost-effective production and distribution methods, addressing safety concerns, and integrating fuel cell systems with renewable energy sources have been identified.

Author Contributions: All authors contributed substantially and equally to writing and original draft preparation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no extra external funding.

Data Availability Statement: As this paper is a review paper, no new data were created in this study.

Conflicts of Interest: The authors declare no conflict of interest.

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