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Review Article

An overview: Current progress on hydrogen fuel cell vehicles

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HIGHLIGHTS

- PEMFCs are promising in transportation sectors with minimal emissions.
- This study reviews the pros and cons of this technology.
- It also discuss the various type of fuel cells and their applications.
- Recent issues associated with existing fuel cell technology in the automobile sector are aslo reviewed.

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ABSTRACT

The harmful consequences of pollutants emitted by conventional fuel cars have prompted vehicle manufacturers to shift towards alternative energy sources. Currently, fuel cells (FCs) are commonly regarded as highly efficient and non-polluting power sources capable of delivering far greater energy densities and energy efficiency than conventional technologies. Proton exchange membrane fuel cells (PEMFC) are viewed as promising in transportation sectors because of their ability to start at cold temperatures and minimal emissions. PEMFC is an electrochemical device that converts hydrogen and oxidants into electricity, water, and heat at various temperatures. The pros and cons of the technology are discussed in this article. Various fuel cell types and their applications in the portable, automobile, and stationary sectors are discussed. Additionally, recent issues associated with existing fuel cell technology in the automobile sector are reviewed.

Contents

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Introduction

Over the last century, the automotive industry has often relied on fossil fuels and internal combustion engine (ICE) technologies. The energy density of petroleum fuels is high, which is essential for increasing the on-board storage capacity and extending the vehicle driving range. They are also inexpensive to fabricate, simple to handle, and quick to refill; in addition, internal combustion engines (ICEs) are affordable to construct. However, current road vehicles emit a significant amount of CO_2 and other pollutants that decrease air quality. The automotive sector has experienced significant pressure to decrease emissions from automobiles and other vehicles [1]. Automobiles consume up to 40% of all fossil fuels used in the transportation industry [2]. Oil and gas are the most significant contributors to the global balance of primary energy sources, accounting for more than 84% of total global production. Oil contributes to 33% of total energy use, and approximately 65% of that amount is spent on transportation [3].

Greenhouse gases are released by many human activities, including construction projects, which lift them as heat-absorbing clouds into the air. Once this process occurs, the Earth's temperature will increase, and our atmosphere will subsequently be more disturbed [4]. Fossil fuels are being gradually replaced in the energy mix with clean, renewable alternatives. Hydrogen is a future energy source that might replace fossil fuels [5]. Two fundamental challenges are confronting humanity: climate change and the energy issue. Regrettably, a non-renewable source such as oil-based fuels is still the dominant energy source globally, contributing to environmental pollution and climate change [6]. Automobiles are one of the most common products that rely on fossil fuels. As a result, the automotive sector of most countries is progressively using renewable energy instead of fossil fuels to transition to eco-friendly vehicles, resulting in a surge in product development of new renewable energy techniques. In fact, the energy density of FCs is higher than that of conventional energy devices; FCs are well suited for long-distance transportation, and these advantages will encourage FC vehicle development. Table 1 and the Ragone plot shown in Fig. 1 compare the key new energy technologies, such as fuel cells (FCs), batteries, and solar cells.

Vehicles based on fuel cells have the ability to substantially increase fuel economy and might be more powerful than conventional internal combustion engines (ICEs) [7]. Fuel cell-based vehicles are classified as fuel cell-ICE hybrid vehicles (FCIHVs) and fuel cell-battery hybrid vehicles (FCHVs), the former refers to the evolution from the existing ICE-battery hybrid vehicles (IBHVs) to the latter, which is also occasionally known as fuel cell vehicles (FCVs) [8].

Classification of fuel cells

Fuel cells are now largely regarded as efficient and nonpolluting sources of power with significantly higher efficiency and energy density. As a result, fuel cells are viewed as viable technologies for certain sectors, such as transportation, stationary, and portable energy devices [9]. In addition, fuel cells are systems that operate at different temperatures (more than 1000 °C) and produce electricity, water, and heat from a chemical energy source such as oxygen, hydrogen, and natural gas using a catalyst. Additionally, Hermann et al. [9] found that the amount of fuel cell energy mainly relies on the catalytic electrodes and materials employed.

Table 1 – Comparison of various emerging energy devices [7].

Device	Energy density	Life time	Advantage	disadvantage
Fuel Cell	Very high	5000–10,000 (hours)	Modular and compact High efficiency Smooth power output Rapid H_2 refuelling Minimal emission	Slow cold start Expensive Hazards of H_2 Fuel price is high
Battery	High	4–6 (years)	Portable and rechargeable Low cost Established technology	Recharging slowly Lifetime is short Preparing and recycling batteries lead to environmental pollution. Electrolyte flammable
Supercapacitor	Very low	10–20 (years)	Recharging and quick reaction	Short time energy storage High cost
Photovoltaic panel	Medium	15–20 (years)	Eco-friendly	Power output is intermittent. Huge for light transport
Flywheels	High	5–10 (years)	High power output and rating; Eco-friendly	Charging slowly Heavy weight
Superconducting magnetic energy storage system	Low	25–30 (years)	High power output and rating; High efficiency; Eco-friendly; Quick response	Short-term energy storage High cost

Hydrogen energy

Hydrogen production worldwide totals 50 million tonnes. More than 100,000 tonnes are generated each year in the UK via the reformation of fossil fuels. Current global hydrogen production figures indicate that hydrogen is generated from 48% natural gas, 30% oil, 18% coal, and a small amount from renewable sources at 4% [10].

Gielen et al. [11] discovered that the most prevalent element in the world is hydrogen, occurring mainly in water and organic molecules on our planet. It is the lightest and most basic element, consisting of a single electron and a single proton. Najjar et al. [12] claimed that hydrogen must be obtained from a variety of primary sources, including water, biomass, natural gas, and coal. Because hydrogen is nontoxic and considerably lighter than air, when released, it immediately evaporates and thus readily diffuses after a spill compared with; it is also more environmentally friendly than other spilt fuels. Dawood et al. [13] found that the main safety concern is that if a leak goes unnoticed and gas accumulates in a confined location, it might ultimately ignite and create an explosion. Hydrogen is the most energy dense element in terms of mass, yet its energy density is negligible when measured in volume. When hydrogen is stored at high pressure, very low temperatures, or in metal-hydride systems, its volumetric energy density may be increased.

Fuel cell technology

Fuel cell technology is the new, ideal method for replacing combustion engines with lightweight vehicles and produces electricity without energy emissions. In the transportation industry, the fuel cell car is one of the options suggested by vehicle manufacturers and research groups to address energy autonomy issues that plagued battery-electric vehicles a few years ago [14].

Because of their great effectiveness and minimal emissions, fuel cells, which electrochemically transform the chemical energy held in fuels directly to electricity, are commonly becoming a new era of technological development [15]. Several fuel cell types have been developed, and categorization techniques vary. In general, the classification of fuel cells is based on the electrolyte material used through several options for fuel cell design [16]. Proton exchange membrane

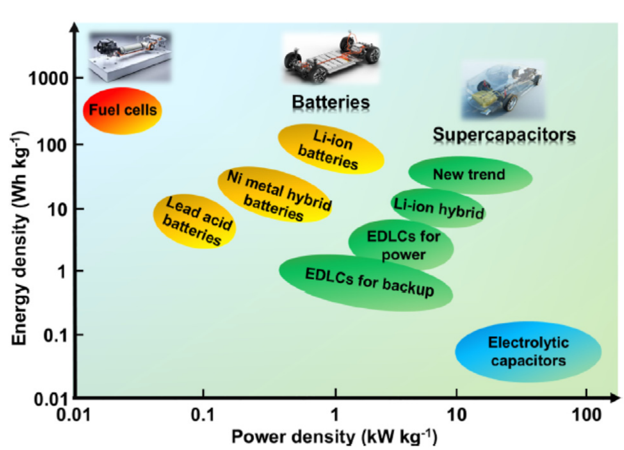


Fig. 1 – Ragone plot of several new energy technologies [1].

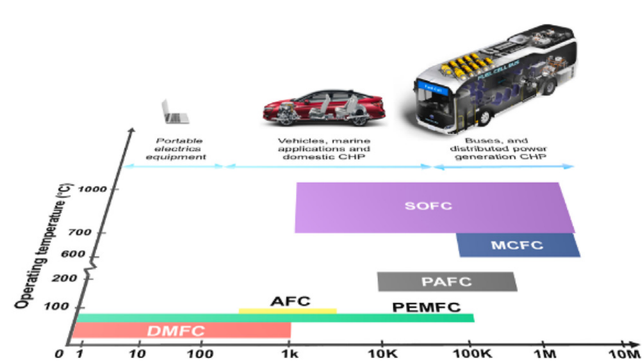


Fig. 2 – FCs operating temperature versus output power [2].

Table 2 – Major type of fuel cell [17].

	PEMFCs	AFCs	PAFCs	MCFCs	SOFCs
Electrolyte	Polymeric membrane	Potassium hydroxide	Phosphoric acid	Molten carbonate	Ceramics
Charge carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Operating temperature	−40–120 °C (150–180 °C in high temp PEMFCs)	50–200 °C	150–220 °C	600–700 °C	500–1000 °C
Electrical efficiency	Up to 65–72%	Up to 70%	Up to 45%	Up to 60%	Up to 65%
Primary fuel	H_2, reformed H_2, methanol in direct methanol fuel cells	H_2 or cracked ammonia	H_2 or reformed H_2	H_2, biogas, or methane	H_2, biogas, or methane
Primary applications	Portable, transportation, and small-scale stationary	Portable and stationary	Stationary	Stationary	Stationary
Shipments in 2019	934.2 MW	0 MW	106.7 MW	10.2 MW	78.1 MW

fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), alkaline fuel cells (AFCs), molten carbonate fuels (MCFCs), and batteries, among others, are examples of fuel cells [17].

AFCs and PEMFCs are classified as low-temperature fuel cells, PAFCs are defined as medium-temperature fuel cells, and MCFCs and SOFCs are classified as high-temperature fuel cells. All of these fuel cells are either employed in the commercial sector or in research and development. Fig. 2 illustrates several fuel cell operating temperatures versus output power.

Table 2 summarizes the primary characteristics and manufacturing status of each type of fuel cell as of 2019. PEM fuel cells, for example, operate at low temperatures between −40 and 120 °C and are now being investigated for portable, automotive, and small-scale stationary applications.

Proton exchange membrane fuel cell

The PEM fuel cell is one of the most widely used fuel cell types since it employs hydrogen as the fuel and oxygen as the oxidant [18]. Hydrogen and oxygen are supplied to the PEMFC by a water electrolysis process in the PEM electrolyser system. Hydrogen loses electrons and transforms into hydrogen ions at the anode of the fuel cell [19]. Electrons, oxygen, and hydrogen ions combine at the cathode of the system and generate heat and water [20].

Protons may travel through a PEMFC and generate electricity. In addition, an electrolyte is composed of a proton exchange membrane that allows charged ions to pass across it. These cells have an operating temperature of 60–80 °C and a high power density [21]. As shown in Fig. 3, a PEMFC is composed of many critical components, including bipolar plates, diffusion layers, electrodes and an electrolyte. The membrane electrode assembly (MEA) is the main core of a PEMFC. It is constructed by sandwiching a proton exchange membrane (PEM) between two electrodes.

PEMFCs have a strong potential for development across a diverse range of energy scales and are capable of producing electricity for some automobiles and stationary and portable applications. The PEMFC feature enabled them to be used in various applications, and this list will continue to increase in the future [22]. Regrettably, the hydrogen storage mechanism used by PEMFCs is the most crucial issue that must be solved with this technology. Bose et al. [23] discovered that PEMFCs are difficult to use as power generators for portable devices because they must contain hydrogen fuel with massive external storage. In addition, when hydrogen fuel is utilized in consumer homes, leakage is similarly hazardous for the following reasons.

Rueda et al. [24] highlighted that Nafion is a widely used proton-conducting polymer membrane in fuel cells because of its capacity to transport protons, excellent thermal and mechanical durability, and selectivity for cations. However, according to Zhang et al. [25], Nafion membranes have disadvantages, including high production costs, lack of environmental friendliness, and hydrogen crossing from the anode to the cathode, which affects fuel cell efficiency and open-circuit voltage (OCV). Additionally, Nafion limits the

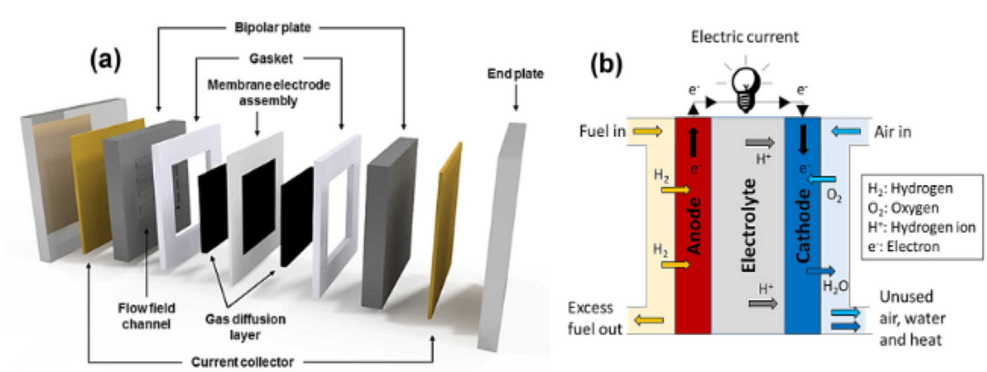


Fig. 3 – (a) Polymer electrolyte membrane fuel cell (PEMFC) main components and (b) the membrane electrode assembly schematic diagram (MEA) [3].

functioning of PEMFCs at low temperatures (80 °C) since it requires hydration and continuous gas humidification to maintain the effective conductivity of protons. When the temperature exceeds 100 °C, the water affinity and mechanical strength of the membrane are reduced. Regarding the disadvantages of Nafion, Adiera et al. [26] investigated and developed novel PEM materials derived from renewable sources with enhanced chemical and thermal stability, water absorption, and mechanical characteristics, which may eventually be used to replace synthetic polymers in fuel cell applications.

Phosphoric acid fuel cell

The electrolyte material in a phosphoric acid fuel cell (PAFC) is concentrated phosphoric acid, which is employed to produce electricity. Electrodes are often constructed of platinum or similar metals, which function as catalysts in the production of electricity. The operating temperature of the cell ranges from 150 to 220 °C [16].

Phosphoric acid and silicon carbide are employed as electrolyte components in PAFCs. The application of PAFCs is classified into two categories: those with a large size for electric utility use and those with a low capacity for on-site service. Chen et al. [27] revealed that PAFCs were launched with a high-performance pressurized power supply, and the on-site air supply system necessitated minimalism and was easy to handle. The marketing of PAFCs has a lengthy history of development to reach the global market in the future. All parties might cooperate to correct the flaws in the mechanism and seek new and inventive solutions to reduce capital expenditures [28]. However, the limitation that prevents potential PAFC utilization must be removed. PAFCs, for example, have a low power density and a violent electrolyte, which are important limitations that must be overcome. Galbiati et al. [29] noticed that low temperature results in poor ionic conductivity in phosphoric acid and subsequently a strong CO poisoning propensity on the platinum electrocatalyst, which has been observed. Corrosion might occur as a result of the acidic environment created by hydrochloric acid, and the electrolyte cell would degrade. Consequently, Guaitolini et al. [30] discovered that the PAFC efficiency is only approximately 37%, which contributes to the relatively poor quality of power production.

Alkaline fuel cell

All fuel cells operate with fuel interacting at the anode side and the oxidant reacting at the cathode of an electrochemical system, generating electricity and some waste heat. Alkaline fuel cells and PEMFCs have some similarities. Fig. 4 illustrates an alkaline fuel cell (AFC) operation that uses either a liquid or a polymer electrolyte [31]. Where layers 1 and 5 represent the anode/cathode gas diffusion layer (GDL), layers 2 and 4 represent the anode/cathode catalyst layer (CL), and layer 3 represents the liquid electrolyte.

Garche et al. [32] found that AFCs are capable of operating at a broad variety of pressures and temperatures, ranging from 0.22 MPa to 4.5 MPa and 80–230 °C, respectively. Additionally, a concentrated electrolyte is used in high-temperature AFCs where the ion transport mechanism switches from aqueous to molten salt. Cathode oxygen reduction requires water; therefore, water management is a concern that may be addressed by utilizing water-resistant electrodes and retaining the electrolyte's water. Water from the electrolyte is used in the cathode reaction, but water generated by the anode reaction is rejected. Excess water is ejected from the stack and evaporates.

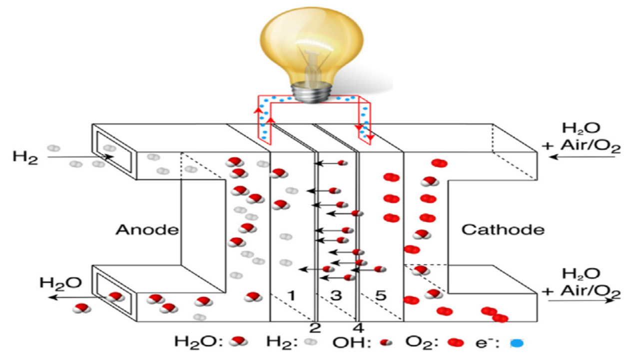


Fig. 4 – The fundamentals of alkaline fuel cells.

Solid oxide fuel cell

A solid oxide fuel cell (SOFC) is a type of stationary power FC that is widely used [33]. A benefit of SOFCs with a high temperature range and efficient transfer of oxidizing ions is that they have the capacity to process a broad variety of fuels [34]. Because fuel reformation occurs spontaneously during cell operation, SOFCs employ a variety of fuels to generate electricity. Thus, due to their potential to produce enormous amounts of electrical power, SOFCs are a prospective large-scale energy source for power plant applications. The high operational working temperature aids in the efficient production of electricity and enables it to be utilized as a heating fuel for the power generation system to produce steam [35].

Aman et al. [36] noticed that in high-temperature operation, this type of fuel cell may be used and maintained for a long length of time. The high working temperatures of SOFCs are one of the primary benefits of this type of fuel cell technology. Due to the simple reformation process, the consumption of different fuels, such as tar and methane, will occur throughout the feeding process. Furthermore, Wu et al. [37] identified that the excess heat generated by SOFCs may be used to enhance the power generation performance. Hossain et al. [38] combined the heat and power (CHP) approach in SOFCs and determined the energy generation efficiency of the fuel may reach 60% fuel conversion and 90% energy generation. However, SOFCs have challenges in terms of material development. In addition, Matthew and Nieh [39] discovered that the small size of the cell production component and issues with material durability and stability prevent easy use of SOFCs in portable device systems.

Proton exchange membrane fuel cell application

PEMFCs are mainly applied in three areas: portable electricity, transportation, and small-scale stationary power production. Typically, portable fuel cells deliver a power output ranging

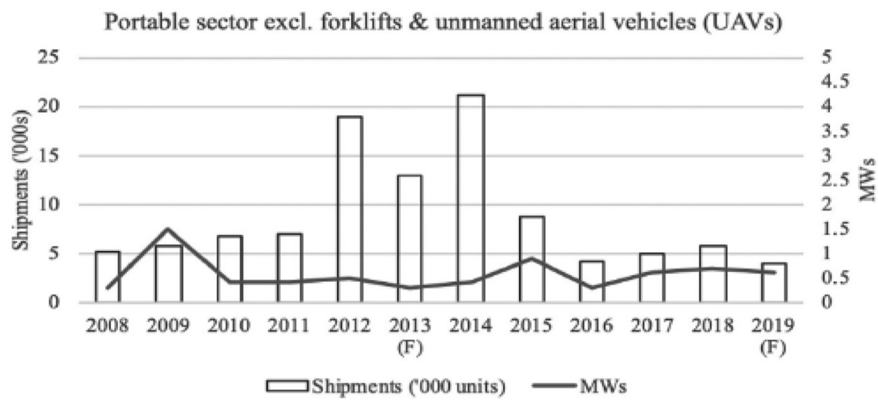


Fig. 5 – Power generation and fuel cell shipment in the portable power sector from 2008 to 2019 [4,5].

from 5 to 50 W. Typical electric vehicle power varies from 20 to 250 kW for lightweight vehicles, buses, and heavy vehicles. Usually, stationary PEMFCs are designed for data centre solutions or power backup from 100 kW to 2 MW. The power output of certain small-scale stationary PEMFCs, such as those used in distant communications and residential applications, ranges from 100 W to 1 kW [40].

Application in portable devices

The growing need for a high-quality, dense, and reliable power supply is the primary driver of the portable power generation market, which is characterized by an increasing number of innovative products, such as disc players, cassettes, phones, and computers. Cacciola et al. [41] identified portable devices that should be lightweight, compact, and affordable, with an expanding number of features. Additionally, Mekhilef et al. [42] found that command technology such as telephones, computers, social media, and the internet has become indispensable to people, necessitating a completely stable electrical supply. Fuel cells are particularly suitable as portable power systems for all of these reasons since they display an excellent energy density, lower cost, durability, and compactness. According to Cacciola et al. [41], as long as fuel is provided to the fuel cell, the gadget will continue to operate, which may be accomplished simply with a tiny and light storage tank.

Indeed, fuel cells may be used to generate electricity in areas where grid connectivity is unavailable. Alaswad et al. [43] mentioned that fuel cells may be used to generate electricity in a camping area without emitting hazardous pollutants, thus preserving the environment and reducing the noise level experienced by other people. According to Sharaf et al. [44], portable battery chargers are another rapidly developing industry in the portable sector, along with small demonstration and instructional remote control cars, toys, kits, and gadgets manufactured by others. Inman et al. [45] described that hydrogen fuel cells are substantially more efficient in terms of energy density. Energy efficiency, power densities, and price must all be carefully analysed to make portable fuel cells cost competitive with rechargeable batteries. Fig. 5 shows the power generation and fuel cell shipment in the portable power sector from 2008 to 2019.

Applications in the automotive industry

In the next few decades, fuel cells will grow the most in the passenger car market. Among the primary reasons for this forecast are the modularity of the systems, great efficiency, and increased driving range over older versions. Another important factor contributing to this expectation is an anticipated rise in attention from original equipment manufacturers (OEMs) in the industry [46]. In addition, the rising demand for large commercial vehicles and passenger cars is increasing the market for fuel cells as a better alternative to conventional cells. The automotive industry may be divided into two categories: private (passenger vehicles) and public (buses and trains).

Applications in the private transportation

Fuel cell cars can potentially reduce urban pollution and vehicle reliance on petroleum. Hydrogen fuel cell cars are also essential components of the hydrogen economy, which aims to provide people with clean and sustainable energy in the future. Its fuel flexibility and efficiency are greater than conventional gasoline-fuelled internal combustion engines (ICEs).

Criteria pollutant emissions, such as NO, NO_2, CO, and unburned hydrocarbons, and CO_2 emission problems are some of the principal applications of PEM fuel cell technology in the transportation industry. Automobile PEM fuel cells use hydrogen as their principal fuel, which may be sourced from renewable sources. When running on hydrogen, fuel cell efficiency may be as high as 65%. Furthermore, water is the waste produced during PEM fuel cell operation, resulting in no polluting emissions from exhaust. Practically, most manufacturers have been actively engaged in fuel cell vehicle research and development (R&D) during the last 20–30 years [47]. The proton exchange membrane fuel cell seems to be the best option for automobile applications [48] because of automatic control and optimum operating points [49] and the cold start capability of fuel cells under low-temperature conditions [50].

Hyundai, Toyota, and Honda, some of the prominent automobile manufacturers, announced a high level of FCEV production in 2020. Hyundai Nexo accounted for 63% of total sales in 2019, Toyota Mirai accounted for 32%, and Honda Clarity Fuel Cell accounted for less than 5% [51]. Hyundai Nexo was launched in 2018 and is lighter, more compact, and

Table 3 – PEM fuel cell electric vehicles (FCEVs) [17].

Model of FC vehicle	Max Power Stack	Fuel Economy MPGe (City/Highway/Comb)	Stack Power Density	Fuel Pressure (MPa)	Fuel Tank Capacity (kg) (wt%)	Range (EPA)
Hyundai Nexo	95 kW	65/58/61	3.1 kW/L	70	6.33 (7.18 wt%)	380 miles
Honda FCX Clarity Fuel Cell	103 kW	69/67/68	3.12 kW/L	70	5.46 (6.23 wt%)	366 miles
Toyota FCEV Mirai	114 kW	67/67/67	3.10 kW/L	70	5.0 (5.70 wt%)	312 miles (122.4 L H_2/70 MPa)
Hyundai Tucson Fuel Cell	100 kW	49/51/50	1.65 kW/L	70	5.64 (6.43 wt%)	265 miles
Daimler GLC F-CELL Hybrid SUV Plug-in	~155 kW for car total power output	Combined hydrogen consumption: 0.34 kg/100 km	–	–		~430 km (4.4 kg H_2@700 bar) + 51 km (Battery)
Saic Maxus FCV80	115 kW	–	3.10 kW/L	35	6	312 miles

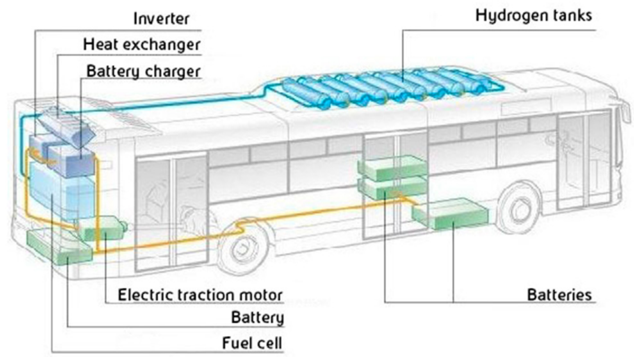


Fig. 6 – The primary schematic of a fuel cell bus [6].

efficient and has a 40% greater range than its predecessor Tucson FCEV of up to 380 miles [52]. Hyundai's 'FCEV Vision 2030′ states that the company aims to build 700,000 fuel cell systems per year by 2030, with 500,000 of those being FCEVs [53]. Since its launch in 2014, the Toyota Mirai has sold over 10,000 units, making it the most popular FCEV. Their fuel cell stack and hydrogen storage designs, driving range, and MPGe are summarized in Table 3.

Applications in the public transportation

The bus is the most promising vehicle type for the large-scale implementation of fuel cell technology in the automotive industry. The primary benefits of buses over vehicles are their power needs, operation schedule, space availability, and accessibility to refuelling stations. Because of the great size of a typical bus, huge amounts of hydrogen may be readily stored onboard, typically on the roof area. The primary schematics of a fuel cell bus are shown in Fig. 6.

The typical PEMFC stack can generate up to 200 kW of electricity and is often used in transit buses that are between 9 and 12 m long [54]. As previously said, the next decade is expected to see a rise in fuel cell usage in various transportation

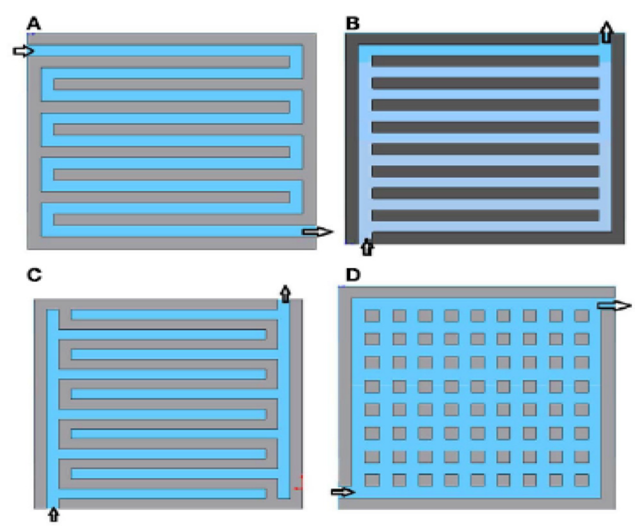
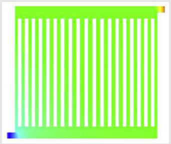
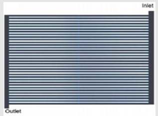
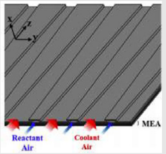
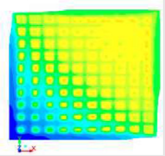
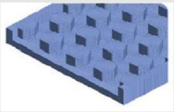
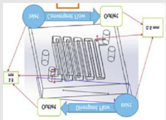
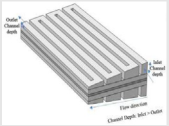
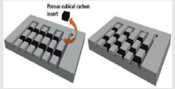


Fig. 7 – Type of flow field design (A) Serpentine; (B) Parallel; (C) Interdigitated; (D) Pin [10].

Table 4 – Flow field designs and their characteristic.

Ref.	Flow Field Design	Objective	Design Approach	Advantages	Disadvantages	Illustrative pictures
[66]	Parallel-type flow field	Achieving more uniform reactant velocity and pressure distribution over flow field	Changing width and depth of distributor, collector and channels. For best result wider distributors used with narrow channels	More uniform pressure and velocity field along channels and balanced flow especially in the vicinity of inlet and outlet manifolds	Possibility of hindered reactant flows along wider and deeper channels by condensed water due to decelerated flow velocity and lower average pressure along the flow field	
[67]	Parallel-type flow field	Achieving uniform reactant distribution between channels	Feeding parallel channel groups with a wider distributor and collectors which are starting wider at the inlet and finishing narrow or vice versa	Uniform reactant distribution between channels	Significant velocity and pressure loss along flow length and the possibility of water accumulation in channels starting wider distributor and finishing narrow collector	
[68]	Parallel flow field	Elevating water retention to keep membrane hydrated in case of dry reactant supply besides increasing cooling capacity in a passive aircooled PEM fuel cell	Generating diverging reactant channels to slow down reactant air, on the other hand, converging cooling air channels which are adjacent to reactant channels	Membrane dehydration in open cathode passive cooling fuel cells is aimed to be prevented with diverging reactant channels slow down air to increase water retention by the new design. On the other hand, converging cooling channel enabled increasing heat discharge from the cell with faster flowing air	The design should be considered as a concentrated load due to misaligned ribs in stack array packing of the cell	
[69]	Pin-type flow field	optimize the pin-type flow field configuration.	Three-dimensional numerical simulations of PEM fuel cells were used to test the proposed optimization model and compare the performance of the fuel cells.	low-pressure drop	stalled zones and unbalanced flow distribution	
[70]	Pin-type flow field	Improving uniformity of variables like reactant pressure, velocities, oxygen mass fraction besides less pressure drop capability	Honeycomb-shaped pins are positioned in a staggered the array on the flow passage	The new design serves homogenous velocity, pressure, concentration distribution with less pressure drop in reactant gasses	Recirculation zones are still prone to come up behind pins concerning flow direction. On the other hand, unbalanced force distribution on both plate and MEA is prone to be come up in clamping of the cell stack	

[71]	Serpentine flow field	Keeping partial pressure of reactant constant from inlet to outlet. Obtaining enhanced liquid water disposal	Converging and diverging channel depth	Enhanced reactant concentration along reaction site and better water disposal	An optimum channel depth should be defined for every cell. An effective optimization correlation between channel depth and other PEMFC parameters should be derivated	
[72]	Serpentine flow field	Creating a higher driving force for excessive water and maintaining constant reactant pressure along	Converging channel depth from inlet to outlet	Strengthened water discharge and higher reactant concentration	Plate strength and mechanical behaviour should be considered to achieve a stable plate that has different plate thickness due to varying channel depth under high clamping force	
[73]	Serpentine flow field	Mitigating condensed water away from GDL and active area	Porous carbon and porous sponge open pore material made inserts positioned in stagger and aligned array in ribs which separates channels	Active water removal via porous materials from the GDL, thus serving higher performance, especially at high current densities	The new design should be tested for extreme conditions of water-logged porous insert in case absorbed water has not been carried out by reactant gasses	
[74]	Bioinspired flow field and interdigitated flow field	Under rib convection enhancement and partial reactant pressure stabilization	Bifurcating channel design with narrowing channel with respect to Murray's law for less pressure drop	Increased reactant concentration and higher reactant partial pressure on the active surface	Stagnant point formation, especially in the region close to the outlet port and in the non-interdigitated constant channel width flow field	

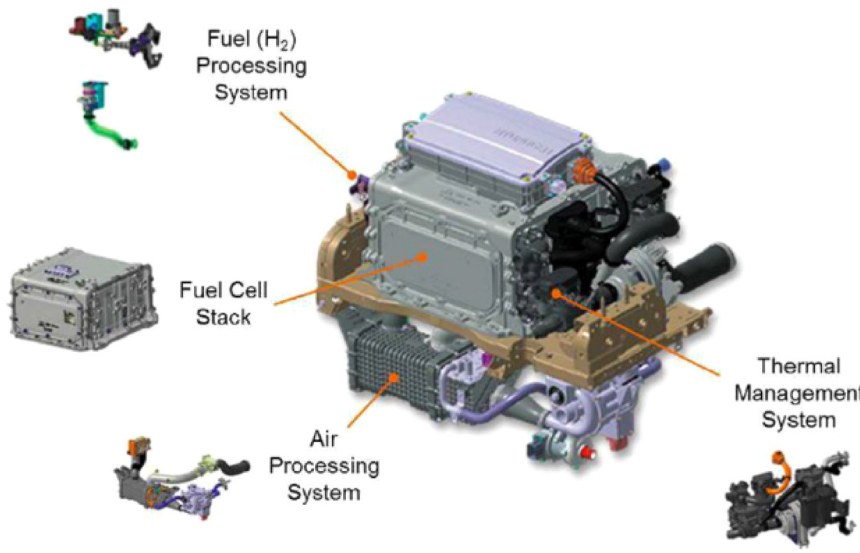


Fig. 8 – BOP components of Hyundai Nexo FCEV [7].

modes, especially in public transportation including buses, trucks, trains, and aeroplanes [55,56].

Application in stationary devices

The use of fuel cells may assist in the transition from large-scale centralized energy production to decentralized distributed energy production. Fuel cells might be utilized for domestic power generation or combined heat and power (CHP) distributed production on a home or larger residential block basis because of their natural source, minimal pollution, remarkable load-following, and very efficiency [57]. For CHP applications, PEMFCs and PAFCs are often utilized, particularly for domestic CHP generation. Compared to the three primary sectors, stationary fuel cells grew the most. The stationary industry now encompasses the main share of fuel cell applications. Fuel cells for stationary devices are typically applied in a variety of sizes, ranging from smaller grid-connected micro combined heat and power units for domestic uses to off-grid backup power systems for essential infrastructure and main supply for premises and up to megawatt-scale grid-connected power plants [58].

Wang et al. [15] discovered that PEMFCs are often utilized in stationary applications as the main power source, backup power source, and combined heat and power source. Stationary PEMFCs provide main power as a backup to the grid

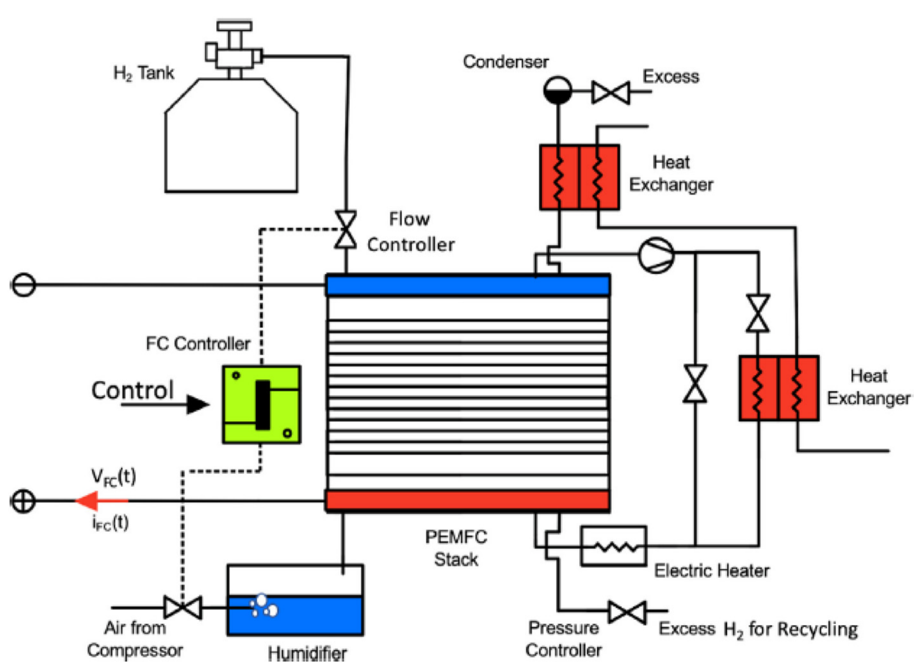


Fig. 9 – The Schematic diagram of BOP and PEMFC stack [8].

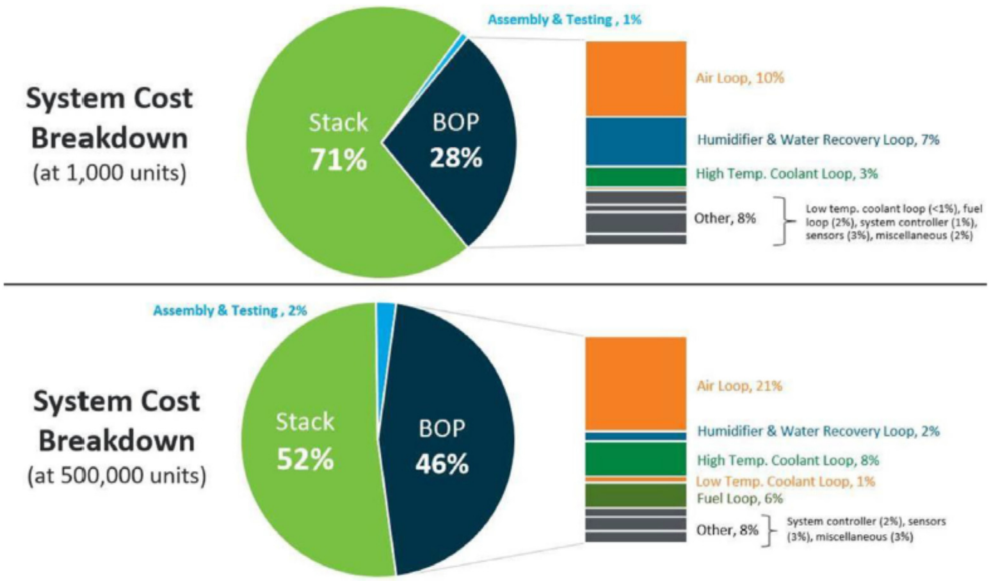


Fig. 10 – A fuel cell system's cost breakdown based on a manufacturing capacity [8].

and as a dispersed power source even when the grid system is down. Wang et al. [59] found that the efficiency of traditional ICE-based power plants ranges from 30% to 40%, but the maximum efficiency of the PEMFC is approximately 65%. Fuel cells have now progressed to the point where they may have prospective markets in which power must be generated with great efficiency and minimal effects on the environment.

Application in military

Fuel cell technology is essentially noisily, and the hot water they produce as a by-product can be used to heat other things. The infrared signal of fuel cells is a big draw for submarines used for military purposes. According to T. Hibino et al. [60], many prototype systems have been successfully tested in the last several years.

Submarines are the military's primary use for fuel cells since fuel cells provide significant benefits in undersea warfare, stealth, and autonomy. Indeed T. Wilberforce [61] discovered that combined with Air Independent Propulsion (AIP) an anaerobic engine technology enables submarines to remain below for longer. They may become nearly quiet compared to diesel-powered boats and even nuclear-powered submarines.

In addition to transportation and automotive applications, fuel cells may be used to power static or mobile military equipment. The United States uses fuel cells to power some military equipment via the Corps of Engineers Research and Development Centre Constructability Engineering Research Laboratory (ERDC-CERL). For example, they created the Silent Camp concept system, which combines diesel generators with fuel cells and hydrogen storage. The purpose is to reduce and improve fuel usage and noise, heat, and chemical pollution. Various fuel cell technologies might contribute significantly to the energy security of operating settings with additional technical breakthroughs [62].

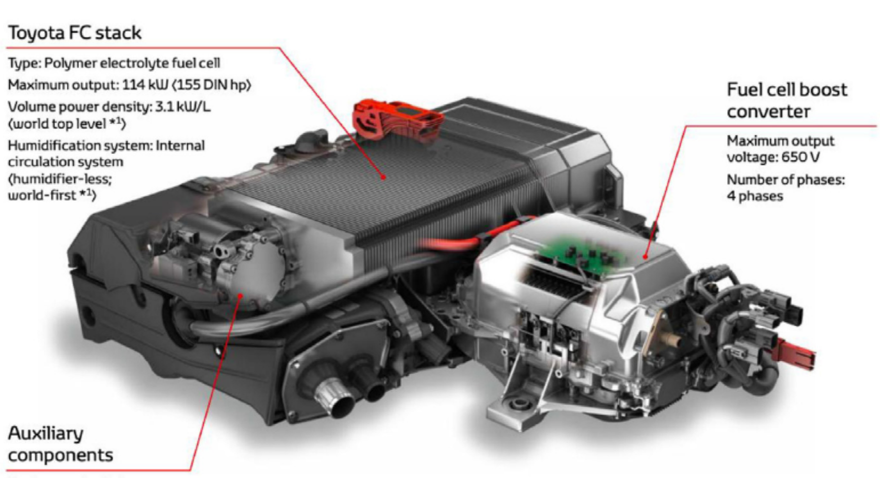


Fig. 11 – Toyota Mirai fuel cell stack [9].

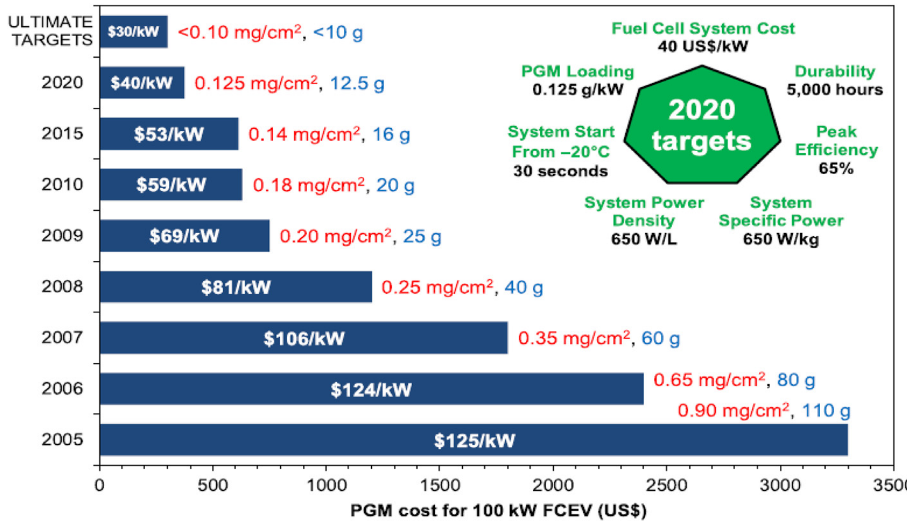


Fig. 12 – The cost and loading of platinum group metals (PGM) for a 100kW FCEV from 2005 to 2020.

Moreover, drones look to be an exciting area for the development of fuel cells. They would allow military drones to be more stealthy and obtain greater range capacity than drones powered by batteries. Lightweight and wearable power systems such as those used by troops in the field to power their GPS, radios, laptops, medical equipment, and lighting systems may also benefit from fuel cells. Comparing portable fuel cells to batteries including Li-Ion, they provide greater energy for less weight. Additionally, they can be refuelled more quickly than batteries.

Type of PEMFC gas flow field design

The flow field in the PEMFC is formed by channels on the bipolar plate, which convey substances to the reaction area while also removing water from the fuel cell stack [63]. Straight parallel type, serpentine, pin-type, and interdigitated-type flow fields are the most prevalent designs used in PEMFCs, as illustrated in Fig. 7.

The flow field of the PEM fuel cell performs a variety of functions, including isolating the reactant gases, spreading to the catalyst layer, and transferring current to the external circuits [64]. Manso et al. [64] thoroughly evaluated studies that examined the most common forms of flow fields and geometric characteristics, such as the channel width and rib width.

Fahim et al. [65] performed a further assessment of the various flow field designs and the characteristics that affect them in the PEMFC, such as pressure loss and no uniform current density distribution. Liu et al. [66] conducted experiments with different types of flow field designs. Their findings indicated that a single cell with a single serpentine flow field outperforms all other configurations. Aside from water and heat control, the flow field design of the BPP influences efficient reactant dispersion. According to Yang et al. [67], flow fields influence the voltage stability of cells, depending on their working style, since flow field design is a well-researched issue in the PEMFC field.

The most popular flow field designs and design methodologies were explored here using scientific and patent sources. The advantages and disadvantages of basic flow field designs have been examined and are presented in Table 4.

Performance of PEMFCs in fuel cell vehicles

In addition to increasing the performance of PEM fuel cell vehicles (FCVs), the total energy management, including the energy storage components, must be optimized and the operation of the PEMFC system must be improved. Numerous papers in this research field address the optimum power management of various types of PEMFC cars.

The stack behaviour of the PEMFC significantly enhances overall performance of the FCV system. In mobile applications, such as an FCV, PEMFCs must be operated under various time-varying drive cycle situations, such as load changes, high power circumstances, idling, and startup and shutdown cycles [17]. When an external load is introduced to the system, the current output of the stack is modified correspondingly, while the stack voltage is inverted. Operational current levels significantly affect the frequency and length of purging operations at a steady load. Transience is characterized by overshoot and undershoot behaviours, as well as varying peak magnitudes at various current levels. Furthermore, the performance of the PEMFC stack is also affected by operational issues, such as ambient temperature, reactant flow rate, and relative humidity.

Optimal operating conditions are required to ensure that limiting factors such as reactant deficits, membrane dehydration, and water flooding may be avoided or minimized and to achieve high performance of the PEMFC stack. Studies of the dynamics and performance of the stack are needed to understand the behaviour of the stack for the FCV power train. Furthermore, the major issues in PEMFC stack units are thermal, water, and power control. Hwang et al. [68] identified that the temperature of the stack influences the electrochemical kinetics of the electrodes and the capacity of reactant gases to move through porous media. On the other hand, Colpan et al. [69] discovered that electrolytes are affected by their water content in terms of proton conductivity, and a sufficient water content is required to avoid membrane dehydration.

The power management specification components for the integration units should include their design, size, and smart loop system. Furthermore, since the operation of the FCV system depends on ambient temperature and humidity, it must be built to function under a variety of conditions. Thus, Sohn et al. [70] identified that effective water and heat management are critical for a fuel cell's capacity to adapt to a particular environment. According to Zhang et al. [71], PEMFC BOPs are utilized in thermal and water management systems, such as humidifiers, air condensers, pumps, and valves, increasing the cost and size of the fuel cell. Narayan et al. [72] concluded that reducing the BOP, water, and heat management of the PEMFC may enhance its physical properties and mobility. In addition, the BOP for water and thermal control must be light, small, and operate effectively. Furthermore, PEMFC heat and water transfer must be thoroughly studied before choosing management system designs for portable development.

Appropriate, practical, and efficient complex integration systems are needed for improved thermal and water management, control loop system integration, and integration of the auxiliary system for this FCV system. In terms of FCV operation, the PEMFC performance decreases substantially when subjected to repeated startup and shutdown cycles while driving [73]. The durability of PEMFCs in FCVs is therefore not reliant on the choice of membrane material and structure, catalyst, catalyst layer material and structure, gas diffusion layer material structure [74] and operating conditions during the driving cycles [73]. System operation strategies can be used to enhance the durability of PEMFCs under startup and shutdown cycles [75]. The durability of PEMFCs might be improved by acquiring a detailed understanding of the failure modes and degradation mechanisms [74].

Fuel cell vehicle system

Balance of plant (BOP)

Fuel cell stack functioning necessitates auxiliary components and systems, collectively known as the balance of plant (BOP) systems, such as fuel process, fuel circulation, humidification, thermal management, and power management systems [59]. Figs. 8 and 9 illustrate the BOP of the Hyundai Nexo FCEV and the BOP schematic diagram.

BOPs are severely hampered in vehicle applications because of the limited amount of space. Thus, the need for the BOP and its associated expense must be decreased in vehicle fuel cells [76]. Fig. 10 shows that the BOP contributes between 40 and 50% to the overall fuel cell cost.

The purpose of thermal management at the FCEV level is to eliminate unwanted heat generated by the FC stack and reduce the temperature of the vehicle to that of the surrounding environment. Chen et al. [77] found that the previous technology is significantly more difficult because fuel cells operate at a far lower temperature than ICEs. As ambient air is accessible for usage, the air supply system is substantially simpler. Liu et al. [78] discovered that the air supply system accounts for approximately 10–21% of the total cost of a fuel cell system, and the air pressure must be increased to the PEM fuel cell working pressure, commonly 1.5–2 atm, which necessitates the use of an air compressor to reduce polarisation in bulk transit. Furthermore, Rojas et al. [79] found that air quality may affect fuel cell efficiency. Contaminants or dust may accumulate within a fuel cell, affecting the CL and membrane.

Hydration and ionic conductivity of the PEM are ensured by humidifiers, which provide water to dry reactants. Approximately 2–7% of the fuel cell system cost is attributed to the humidifier BOP. Even if the FC creates water during operation, the PEM near the intake may experience dry operation because the ambient air is dry at high temperatures (e.g., 80 °C). Because of the restricted amount of space available for transporting water for humidification, installing a humidifier in passenger cars may be essential. Internal or exterior water recirculation is necessary to minimize the amount of water needed for humidification, which is used in the Toyota Mirai [80]. Moreover, employing thinner PEMs, which have a lower ohmic loss, helps reduce humidification.

Fuel cell stack

The amount of voltage a single cell can generate is limited; it only reaches approximately 0.9 V. A stack of fuel cells may be constructed to produce greater power and high voltage using manifolds to share one or more inlets and outputs [76]. As shown in the study by Devrim et al. [81], water, heat control, and fuel intake become significantly more difficult at the stack level due to interactions among component cells. Numerous connections inside stacks, including current flow, heat exchange, and coolant and reactant gas flow fields, allow individual fuel cells to interact. The local resistance of one cell may substantially alter the performance of the whole stack since the current travels through all the cells linked in series. Bürkle and Yang [82,83] reported a FC stack that shares a single inlet or outlet manifold, and a fuel cell with a high flow resistance received fewer reactants, resulting in local reactant deficits, decreased cell performance, and potential material degradation over time. The same limitations have been observed for the flow field of coolant [84]. Fig. 11 represents the fuel cell stack system used in the Toyota Mirai vehicle prior to 2020.

Hydrogen storage

For FCEVs to succeed in the market, hydrogen storage aboard the vehicle is essential. Hydrogen fuel cell cars should have a comparable driving range as ICE vehicles to compete. Due to the low volumetric energy density of hydrogen, maintaining a sufficient hydrogen supply onboard remains a concern in terms of weight, volume, kinetics, safety, and cost. Various techniques for hydrogen storage have been developed [10], as described below.

- Liquid hydrogen – Hydrogen in the liquid form has a high energy density, but it should be maintained at −253 °C at atmospheric pressure to be stored as a liquid. As a result, a well-insulated liquid hydrogen tank is needed. Additionally, the liquefaction process consumes approximately one-quarter of the chemical energy contained in hydrogen.

- Compressed hydrogen - Major electric vehicle (EV) manufacturers choose to use this method. A pressure of 350 bar is used by Honda and Nissan, whereas Toyota uses 700 bar. Compression uses a large amount of energy because of the low energy density.
- Metal hydride - This technique is the safest approach, but it is also the heaviest storage device; in addition, storing hydrogen requires a long period (such as a lengthy refuelling period). It also has a low rate of release.
- Hydrogen absorbed onto metal organic frameworks (MOFs) and carbon nanotubes (CNTs) is still in the early stages of research.

In automobiles, the fuel system must receive more attention since oxygen may be utilized to generate electricity. FCEVs currently store hydrogen in the form of a highly compressed gas to maximize the energy density. Compressed hydrogen, on the other hand, creates major safety and consumer acceptability difficulties. Currently, Sheffield et al. [85] reported that most FCEVs operate at a hydrogen pressure of approximately 70 MPa, resulting in a hydrogen density of 38 kg/m^3 compared to 23 kg/m^3 at 35 MPa. Compressed hydrogen storage devices contain 5 kg of hydrogen, providing a driving range equivalent to that of conventional vehicles, with a capacity that is approximately 75% greater than ordinary petrol tanks (typically approximately 20 gallons). For example, Toyota Mirai and Hyundai NEXO build in a hydrogen tank capacity of 5 and 6.33 kg, respectively, with a range of 312–380 miles [15].

Jiang et al. [86] explored hydrogen storage tanks, and FC stacks typically function at a stoichiometric ratio of approximately 1.2 at the anode, necessitating the recirculation of wasted hydrogen fuel for fuel cell usage. Furthermore, liquid fuels may be used in car fuel cells to reduce the need for onboard pressurized tanks. Using a the fuel reformation subsystem of a chemical reactor, a mixture rich in hydrogen gas is generated for use in fuel cells. Pérez et al. [87] described that CO in the reformate mixture may cause Pt catalyst poisoning at the anode of PEM fuel cells that operate at low temperatures, reducing fuel cell performance. Al-Tememy and Lei [88,89] discovered that Pt poisoning can be mitigated by adding air to the mixture to decrease the CO concentration or by running fuel cells at high temperatures.

Challenges and disadvantages of fuel cell vehicles

Several reasons why PEMFCs are worth considering in fuel cell vehicle development are described below. They may completely replace conventional technologies such as ICE in the automobile industry. PEMFCs run on hydrogen, which has one of the greatest specific energy values that is three times that of gasoline; their sole waste is water, and thus they never pollute the air; and they have fundamentally greater efficiency than a conventional vehicle. In addition, they are small, quick, and have a wide range of operating power capabilities.

The application of fuel cells as renewable energy sources may lead to issues related to efficiency, cost, and restrictions. The efficiency of a system is determined by its configuration, design, and component selection. Furthermore, the cost of a system is mainly influenced by its efficiency [2]. In addition to kinetic energy, most FCEVs produce thermal energy and water and emit low pollutant concentrations [90,91]. Furthermore, compared to regular cars, FCEVs contribute to a cleaner environment and reduce fuel costs [92].

Faster refuelling (less than 5 min), freedom from “range anxiety” (up to 600 km between refills), longer life expectancy (>200,000 km), better driving experience, and improved safety are all benefits of FCEVs over BEVs [93]. A longer range is obtained more readily and economically in FCEVs, which merely require greater hydrogen tank capacities, especially for heavy-duty transportation [76].

Fuel cells, despite their many benefits, have yet to be widely used. The disadvantage is that fuel cell technology is still prohibitively costly. However, compared to the infrastructure of other market rivals, such as pure electric cars or gas vehicles, hydrogen infrastructure remains negligible [94]. The high expense of FCEVs is mainly attributable to the usage of platinum (Pt) catalysts and the current low manufacturing quantities. However, precious metal loading has decreased considerably in the recent decade [93]. As shown in Fig. 12, it is still a major concern. Daimler, for example, has reduced the amount of platinum in its FCEVs (Mercedes GLC F-Cell vs. B-Class F-Cell) by 90% since 2009, while Toyota is aiming for a 50% decrease from the current levels. FCEVs might become cost-competitive with BEVs by 2030 if ultralow loading Pt or nonprecious metal catalysts are used and FCEV manufacturing capacity is increased [95].

The major disadvantage of PEM fuel cells is require an expensive catalyst, platinum, which adds to the overall unit cost. P. Chandran et al. [96] mentioned The catalyst used in PEMFC is the highest contributor to the overall cost of a fuel cell. The commonly used catalyst in PEMFC is platinum (Pt) due to its good catalytic activity, stability to withstand the operating environment and resistance to corrosion. However, the less abundance and high cost of Pt made researchers put tremendous effort into finding an alternative for Pt without compromising the catalytic performance [97].

As noted, PEMFCs normally operate at low temperatures between 60 °C and 100 °C. The advantages of low-temperature operation of PEMFCs are that it is a lightweight packed system and has a quick start-up process. One of the major problems associated with low-temperature PEMFCs is the contamination of catalyst by CO in the reformate gas, which hinders its activity [98].

Staffell et al. [95] mentioned that the capital and operational expenses of FCEVs are still greater than those of BEVs, with current models costing approximately twice as much. Higher temperature operation is required to dissipate excess waste heat from a local fuel cell with a higher thermal resistance or one that is not as well cooled as nearby fuel cells. The design of the stack mainly relies on numerical simulation [99,100]. Adding a stack of fuel cells to a single-cell model is simple since it does not require any additional physics. Zhang et al. [101] investigated a three-dimensional (3-D) cell-level model that is computationally expensive to simulate stacks because of the enormous number of grid points that must be computed. Additionally, Wang et al. [102] identified the difficulty of replicating the flow field communication between the component fuel cells, especially when two-phase flow in GFCs is considered.

Conclusions

The current status of fuel cell electric vehicles (FCEVs) is reviewed in this study along with the principles of PEM fuel cell technology and technical problems in automotive applications. PEMFCs are the most common and well-established FC technology for automobiles. Numerous fuel cells and their uses, specifically fuel cells in automobiles, were investigated. Consequently, PEMFC utilizes hydrogen as a fuel and only creates pure water as a final product, achieving 65% efficiency, which is higher than that of conventional vehicles. Furthermore, hydrogen fuelling can be completed in less than 5 min, making it more efficient than the current battery-based electric cars, which need more time to charge.

Cost continues to be a large barrier to fuel cell vehicles competing with internal combustion engines. Under high-volume production, the electrocatalyst, which is commonly generated from platinum group metals (PGM), accounts for approximately 40% of the cost of a fuel cell stack. More R&D is needed to advance FCEV technology and development. PEMs and catalyst materials are still active research fields for high-temperature PEMs and low-cost catalyst layers (CLs), such as low Pt loading. The total power density and reliability may be increased by reducing the BOPs.

In conclusion, FCEVs have several significant limitations and challenges, and the future development of FCEVs requires the cooperation of academic institutions, businesses, and governments to overcome them. After addressing these issues, FCEVs are expected to grow rapidly and be widely embraced by consumers. The use of hydrogen fuel cells will soon have a large effect on the transportation industry, and producing fuel cells in large numbers and selling them commercially will soon be cheaper. A reasonable assumption is that fuel cell-based vehicles, power plants, and energy producers will increase in prominence in the next few decades.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.10.156.

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