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Advancements and challenges of fuel cell integration in electric vehicles: A comprehensive analysis☆

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ABSTRACT

Fuel cell technology emerges as a promising green solution, offering mitigation to global warming, air pollution, and energy crises. This eco-friendly approach is witnessing a surge in adoption within the automotive sector, with fuel cell buses, cars, scooters, forklifts, and more, becoming increasingly prevalent. The automobile industry has been rapidly advancing fuel cell technology, inching closer to the commercialization of fuel cell vehicles. As various technical hurdles are surmounted and costs are reduced, fuel cell vehicles are poised to become a competitive force in the automobile market, presenting an excellent solution for environmental sustainability and energy efficiency. This review paper delves into the fundamentals of fuel cells, their characteristics, and their applications in the automotive realm, exploring their prospects in comparison to traditional technologies. Furthermore, it sheds light on the existing research and industrial developments in hydrogen and fuel cell technologies. Additionally, a comprehensive comparison is provided between various fuel cell cars that have already been commercialized, enabling readers to understand the current market landscape. The review also analyses the advantages and challenges associated with fuel cell technology, offering insights into its future development trajectory. Through this comprehensive exploration, readers can gain a deeper understanding of fuel cell technology and its potential in revolutionizing the automotive industry.

1. Introduction

Fuel is a substance which reacts with a lot of oxygen to form products and launch energy. This reaction is called combustion. The energy which is released by this response has been traditionally recognized and harnessed as a power source [1–4]. That is, if the services and products of the combustion are encouraged to generate movement, then the motion might be utilized to execute job [5]. This is the way petrol has been employed in the internal combustion engine from a vast variety of vehicles, from automobiles to buses to ships and trains. The internal combustion engine is made up of cylinder, piston, crankshaft and so forth [6–11]. In the simplest case, each and every cylinder is really a enclosed volume and a piston may travel up and down within the tube. Gas is injected into the cylinder at the top and also the piston is ignited by means of a spark plug [12–20]. The gas reacts with oxygen from the air to produce a growth and this growth forces the piston down. As the bicycle moves, the crankshaft converts the reciprocal motion of the piston into circular movement which may then be used to move the car [21–31]. This is the way gas can be converted from its chemical form into mechanical ac. However, considerable work is demanded by engineers and researchers in various fields in order to master that this transformation and to lessen the damaging by products that are made like CO_2 and NOx [32]. A lot of research and progress was performed in various techniques for this particular conversion and they have started

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to visit fruition, for instance the hybrid and electric vehicles [33–36]. However, all of these processes are based upon the principle of combustion being the overall reason behind the transformation of substance power into kinetic electricity [37]. With this progress in technology, an optional process called a fuel-cell has already been established and can be now being accommodated for distinct applications, for example replacing the inner combustion engine as mentioned before. In actuality, fuel cells work in a similar fashion to the method in which most vehicles produce their energy - burning fossil fuel [38–48]. In a car, gasoline is burned in an internal combustion engine and the created gas and pressure are used to force complex machinery that ultimately turns the wheels. However, unlike internal combustion engines, the hallmark of fuel cell technology is its potential for transforming the energy industry [49–55].

Also, fuel cells can be used where we traditionally use batteries, such as in small electronics or in backup power for traffic signals. Fuel cells can be used in a wide range of applications, including transportation, material handling, and power generation [56–66]. For instance, fuel cells can power the method by which most electricity is produced - burning “clean” hydrogen fuel in a fuel cell produces electricity with only heat and water as byproducts [67]. This is contrasted with traditional ways of producing electricity, like burning coal or natural gas. Also, it works on the same principle as the example illustrated in which hydrogen is reacted with oxygen to produce water and electricity, and the only byproduct is water [68–72]. Emerging fuel cell technology makes it possible to generate power at increasingly high efficiencies and decreasing cost. There is a sharp contrast to the traditional combustion technologies, which are about 25% efficient, and that is simply a factor of the thermodynamics of heat engines and the second law of thermodynamics [73–77]. Fuel cell technology is an important area of research with the potential to revolutionize transportation. However, despite the excitement around the topic, the general public and many consumers know little about fuel cells and their uses. This article provides an overview of the current state of fuel cells as well as some history behind this technology. A fuel cell is an electrochemical device that converts hydrogen and oxygen into water, producing electricity and heat in the process. It is similar to a battery in that the fuel cell generates an electrical current as long as fuel is provided. However, unlike a battery, a fuel cell does not run down or require recharging, as long as the fuel is supplied. A fuel cell consists of two electrodes - a negative electrode or anode and a positive electrode or cathode - and an electrolyte membrane [78–88]. There are different types of fuel cells, depending on the kind of electrolyte used. These include alkaline fuel cells, molten carbonate fuel cells, phosphoric acid fuel cells, proton exchange membrane fuel cells,

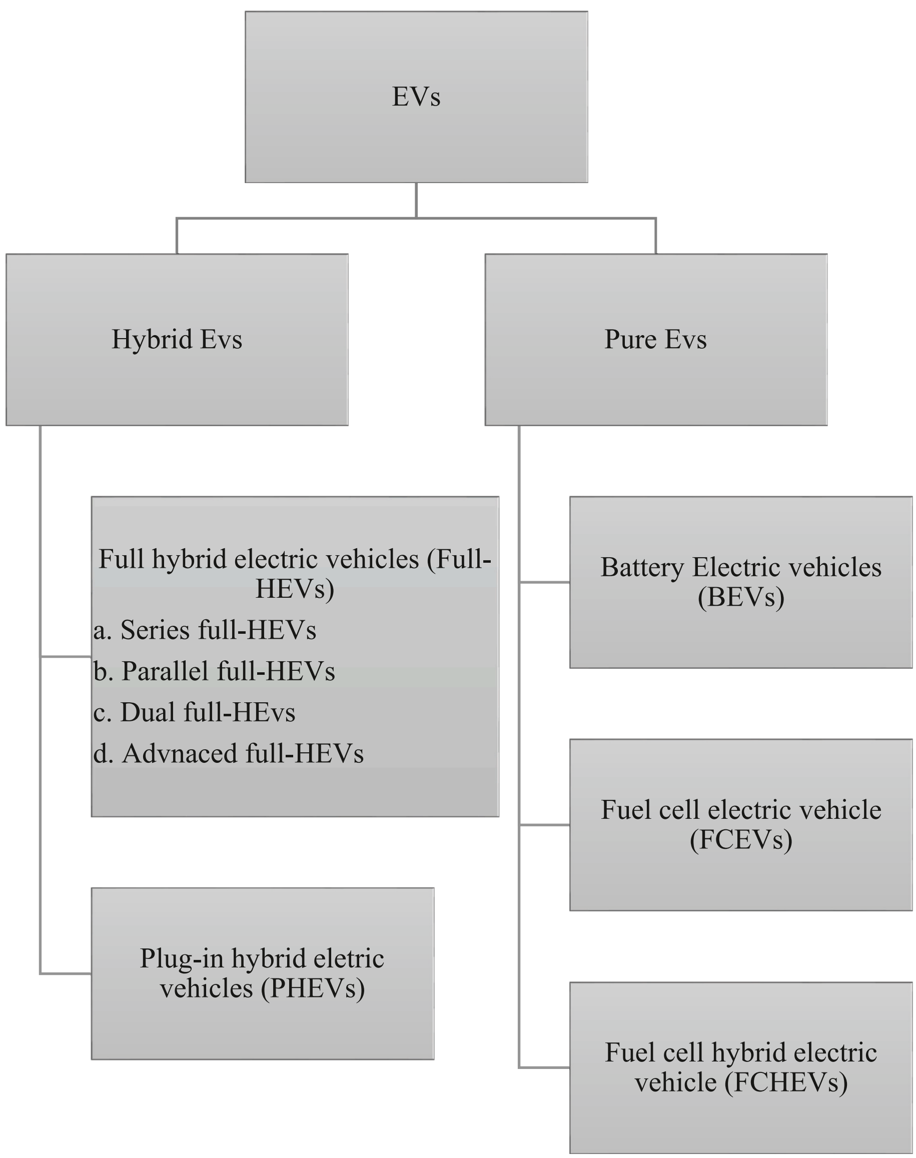

Fig. 1. Various types of electric vehicles (EVs).

and solid oxide fuel cells. Fuel cells have been around since the 1830s and have powered spacecraft and other applications for many years [89–99]. NASA has used alkaline fuel cells since the 1960s to produce electrical energy and drinking water for astronauts. In the 21st century, fuel cells were first used for automobile applications, primarily because of a push to develop renewable energy sources. As developed and developing countries become increasingly dependent on oil, alternative energy sources such as fuel cells represent a different path in future energy security and independence. With the advancement of science, fuel cell technology will continue to improve and ultimately, fuel cells will be a competitive form of energy production [56–58]. In a global scale, fuel cells are seen as a reliable and clean source of energy, especially for the future. Fig. 1 depicts the distribution of fuel cell electric vehicles (FCEVs) among industrialized nations as of 2020 shows South Korea leading the way, followed by China, the USA, Japan, and Europe. Kim et al. research focuses on South Korea's national hydrogen refueling station deployment strategy for 2022–2040 [45–49] (see Fig. 2). Rose concentrates on developing a potential heavy-duty hydrogen refueling station setup for Germany in 2050. Various control strategies like proportional-integral-derivative (PID) controllers, rule-based fuzzy logic controls, model predictive control, predictive control strategies, and equivalent consumption minimization controls (ECMS) have been implemented for controlling fuel cell hybrid electric vehicles (HEVs). Analysis of energy management strategies (EMSs) including rule-based, optimization-based, and advanced learning-based approaches is utilized to ensure efficient, steady and reliable operation of various energy sources in FCHEVs.

A hybrid energy storage system with a combined architecture and power management technique is proposed for fuel cell hybrid electric vehicles. The various types of electric vehicles (EVs) are depicted in Fig. 1. The most basic form is the battery electric vehicle (BEV), which relies solely on batteries for power. However, there are several models that can utilize multiple power sources. Hybrid electric vehicles (HEVs) employ a dual or complementary energy system, where at least one component generates electricity [100,101]. HEVs combine an electric motor with a combustion engine. Ultracapacitor-based electric vehicles (UCEVs) pair batteries with capacitors for energy storage. Fuel cell electric vehicles (FCEVs) integrate batteries and fuel cells [100,102, 103].

The different EV categories shown in Fig. 1. BEVs, which are fully electric and battery-powered; HEVs, which have both an electric motor and a gasoline engine; plug-in hybrid electric vehicles (PHEVs), which can be charged from external sources and use both electric and gasoline power; and FCEVs, which generate electricity from hydrogen fuel cells to power the electric motor. Electric vehicles (EVs) can be broadly categorized into two main types based on their primary power source, energy storage system, and fuel delivery method: hybrid electric vehicles and pure electric vehicles.

Hybrid EVs combine a technology. They can be mild hybrids, full hybrids internal combustion engine (ICE) with electric motor (EM), or plug-in hybrids. Advanced full hybrid EVs are being developed by integrating internet of things (IoT) connectivity, artificial intelligence, wireless charging capabilities [104], and cloud computing to achieve zero emissions goals. Pure electric vehicles, on the other hand, rely solely on electric power and are independent of ICE technology, enabling true zero emissions from the tailpipe. Fuel cell technology offers a cutting-edge solution to overcome the limited driving range of battery electric vehicles and reduce dependence on the grid. Fuel cell electric vehicles are becoming increasingly attractive for meeting sustainability targets as future vehicles.

They benefit from the integration of hybrid energy storage systems and smart vehicular technologies, making them more adaptable and versatile. Internal combustion engines (ICEs) have been the predominant technology in the transportation sector due to their high efficiency and reliability. However, they contribute significantly to environmental pollution through air emissions, water contamination, and land degradation. Hybrid electric vehicles (HEVs), which combine an ICE with an electric motor, offer reduced emissions compared to conventional vehicles, but they have more complex and bulkier systems. Plug-in hybrid electric vehicles (PHEVs) extend their range by utilizing vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) charging infrastructure [59], but at the cost of higher capital investment and potential negative impacts on the grid.

Battery electric vehicles (BEVs) are in high demand for future transportation systems, but their widespread adoption faces several challenges. These include low specific energy density of batteries, thermal management issues, potential chemical leakages, mechanical failures, short-circuiting risks, and inefficient battery management

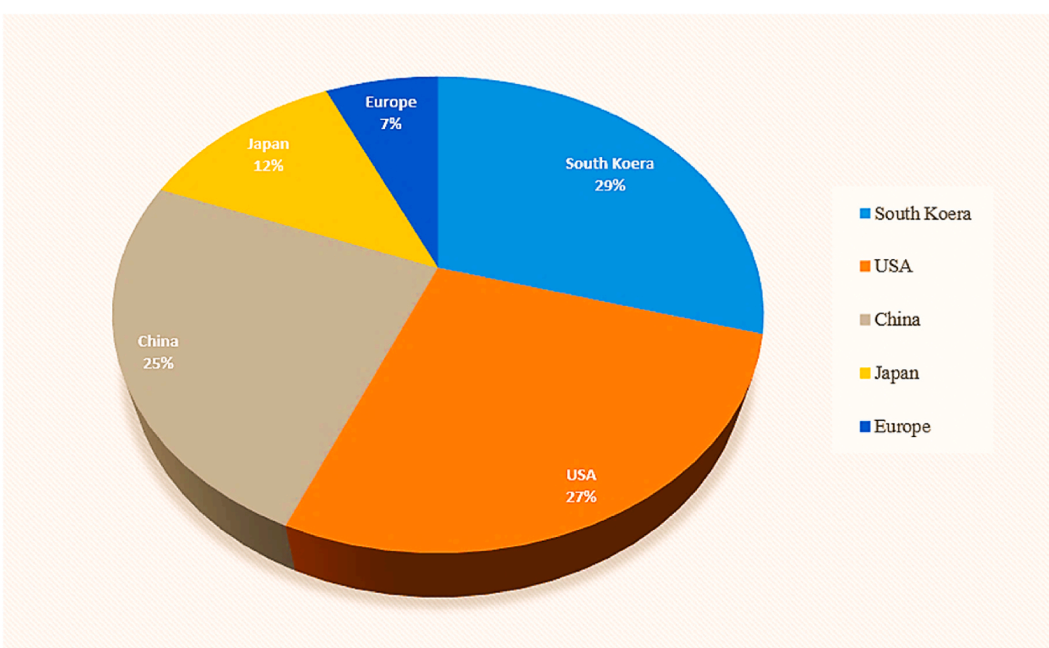

Fig. 2. Global spreading of Fuel Cell Electric Vehicles.

systems. Fuel cell-based hybrid electric vehicle technology is a promising future solution that can enable pure electric mobility with zero tailpipe emissions.

The current research gap in promoting fuel cell electric mobility is summarized in Table 1. Addressing these gaps through advancements in fuel cell technology, hydrogen infrastructure, and system integration is crucial for the successful transition to sustainable transportation.

NOMENCLATURE

Nomenclature	
FCEVs	Fuel Cell Electric Vehicles
PID	Proportional Integral Derivative
ECMS	Equivalent Consumption Minimization Controls
HEVs	Hybrid Electric Vehicles
EMSs	Energy Management Strategies
UCEVs	Ultracapacitor Based Electric Vehicles
BEV	Battery Electric Vehicle
ICE	Internal combustion engine
EM	Electric Motor
PHEVs	Plug-In Hybrid Electric Vehicles
IoT	Internet of Things
V2G	Vehicle-To-Grid
V2V	Vehicle-To-Vehicle
MEA	Membrane Electrode Assembly
GDLs	Gas Diffusion Layers
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
AFC	Alkaline Fuel Cell
FCHS	Fuel Cell Hybrid System
Symbols	
CO_2	Carbon Dioxide
H+	Protons
e−	Electrons
H_2O	Water
H_2	Hydrogen
O_2	Oxygen
CH_3OH	Methanol
CH_4	Methane
CO	Carbon Monoxide
NOx	Nitrogen Oxides
SOx	Sulfur Oxides

Table 1
Fuel-cell-based vehicle technology.

Vehicular technology	Merits	Research gap
ICE vehicles	• Commercialized and mostly used vehicle technology • Convenient, efficient, and reliable	• Harmful emissions • Ecological unfriendly
Partial or mild hybrid vehicles	• Lower emission rate than ICE vehicles • Adaptable and impactful	• Need additional electric motor (EM) • Havier than ICE
Fully hybrid vehicles	• Excellent fuel effectiveness • Enhanced driving range than Mild HEVs	• Cost is not justified. • Dependent on gasoline
Plug-in hybrid vehicles	• Longer driving range • Smooth, noise-free performance • V2G and grid-to-vehicle (G2V) facility	• Higher initial cost • Depends on crude oil • Severe effect on grid
Pure electric vehicles	•Zero-emission • Efficient and independent on crude oil	• Thermal issues of battery • Safety issues of battery management
Fuel cell based electric vehicles	• Promote to zero-emissions • Independent from electric supply • Fuel production is feasible • Independent on crude oils • Long driving range	• Sufficient charging requirement • Lack of hydrogen refilling stations • High cost of fuel • Limited durability

2. Fuel cell

Fuel cells are electrochemical devices that convert the chemical energy from a fuel (typically hydrogen) and an oxidizing agent (often oxygen from air) into electrical energy through a reaction that generates water as the primary byproduct.

This process is highly efficient and environmentally friendly, as fuel cells produce little to no harmful emissions, unlike traditional combustion engines that burn fossil fuels. At the heart of a fuel cell lies the membrane electrode assembly (MEA), consisting of a polymer electrolyte membrane sandwiched between two electrodes (anode and cathode) coated with catalyst layers. Hydrogen fuel is supplied to the anode, where it dissociates into protons and electrons. The protons pass through the membrane to the cathode, while the electrons travel through an external circuit, generating an electrical current. At the cathode, the protons, electrons, and oxygen combine to form water vapor. Fuel cells offer a promising alternative energy technology for powering vehicles, stationary applications like homes and businesses, and portable electronics, enabling sustainable and clean energy production with reduced environmental impact [105–110]. There are several types of fuel cells that vary in their operating principles, materials used, and applications. This makes hydrogen fuel cells a clean and efficient source of power, with the potential to revolutionize various industries, including transportation and energy production [111–116].

Through an electrochemical reaction, chemical energy is converted into electrical energy. Fuel cells are used to produce electricity and are more advanced and energy-efficient technologies than combustion engines, which burn the fuel. The applications of fuel cells vary depending of the type of fuel cell to be used. Understanding the different types of fuel cells is crucial for harnessing their full potential in various industries and sectors. In this review paper, we will explore the characteristics and applications of different types of fuel cells to provide a comprehensive overview of this cutting-edge technology [117–128]. Fig. 3 provides a comprehensive breakdown of the element budgets for a fuel cell stack manufactured at an annual production rate of 500,000 units. The analysis reveals that the catalyst layer accounts for the largest portion, at 41%, highlighting the significant cost associated with this critical component.

The bipolar plates, responsible for conducting electricity and distributing gases, contribute 28% to the overall budget, underscoring their importance in the stack's performance and durability. The balance of stack, which encompasses auxiliary components such as gaskets and end plates, accounts for 10% of the budget. Finally, the GDLs (Gas Diffusion Layers), responsible for distributing reactants and facilitating water management, make up 6% of the element budgets. This analysis offers valuable insights into the cost distribution across various components, enabling informed decision-making and potential optimization strategies.

The membrane, a vital component that facilitates the transfer of protons, constitutes 8% of the total budget. The MEA(Membrane Electrode Assembly) frame, which provides structural support and sealing, accounts for 7% of the costs.

2.1. *Working principle*

A fuel cell is an electrochemical device that converts the chemical energy from a fuel (typically hydrogen) and an oxidant (usually oxygen from the air) into electrical energy through an electrochemical reaction [55–67]. Fig. 4 depicts the key components of a fuel cell include an anode, a cathode, and an electrolyte membrane assembly.

The working principle of a fuel cell can be explained as follows.

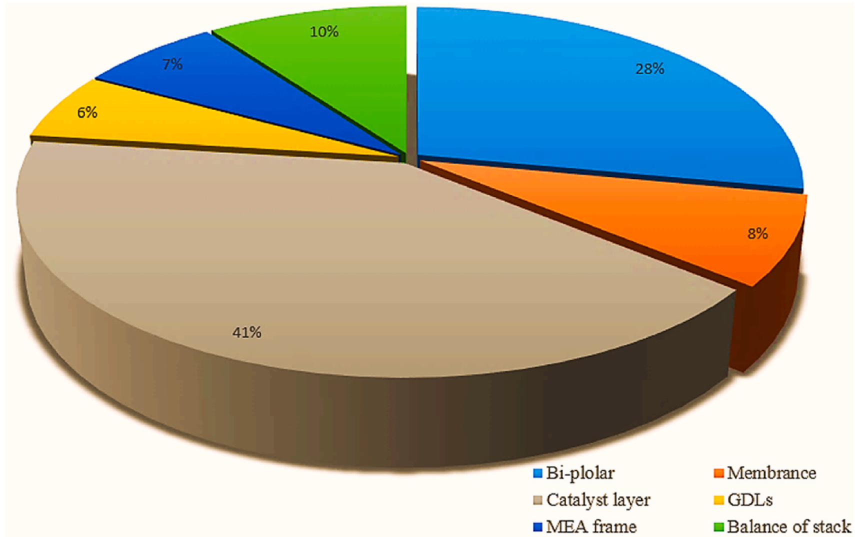

Fig. 3. Breakdown of component costs for an annual fuel cell stack production run of 500,000 units.

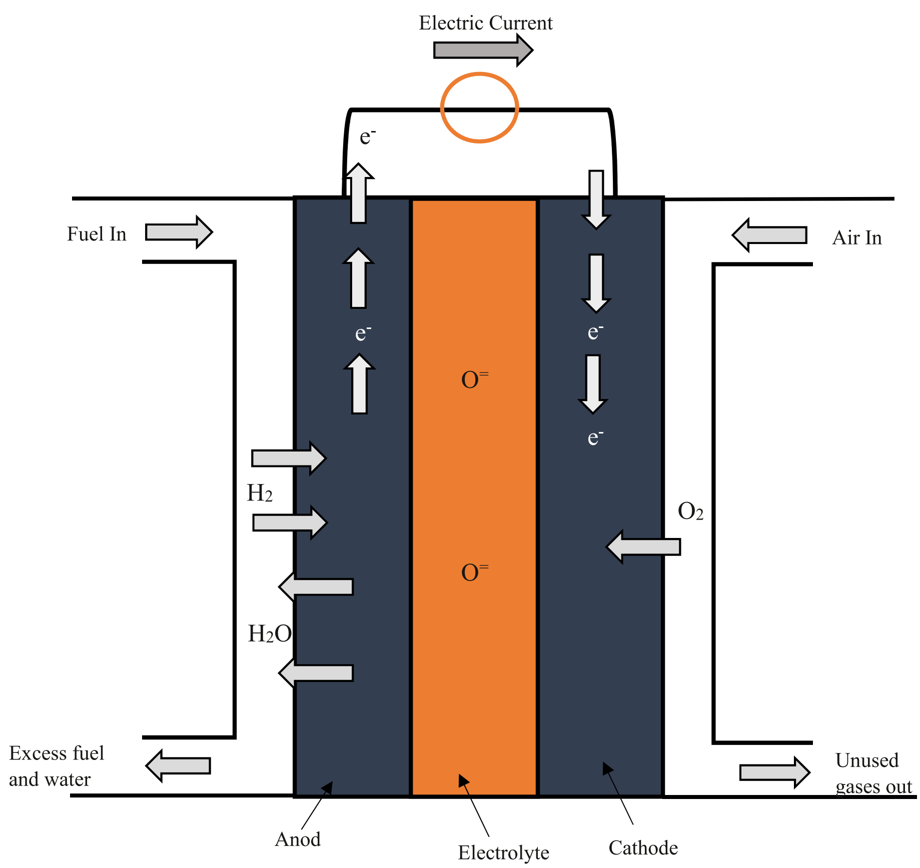

Fig. 4. Schematic representation of the fuel cell.

2.1.1. *Fuel supply (anode side)*

- Hydrogen fuel is supplied to the anode, where it is catalytically split into protons (H+) and electrons (e−).
- This reaction is facilitated by a catalyst, typically platinum or platinum-based alloys.

2.1.2. *Electrolyte membrane*

- The electrolyte membrane, often made of a polymer material, allows only the positively charged protons to pass through while blocking the electrons and the fuel.

2.1.3. Cathode side

- At the cathode, oxygen from the air is supplied and combined with the electrons that traveled through an external circuit and the protons that passed through the electrolyte membrane.
- This reaction, also catalyzed, produces water as the main byproduct.

2.1.4. Electrical circuit

- The electrons generated at the anode travel through an external electrical circuit, providing electrical energy to power an electrical load (e.g., an electric motor in a fuel cell vehicle).

2.1.5. Water and heat management

- The water produced at the cathode must be managed to maintain proper hydration of the membrane and prevent flooding or drying.
- The electrochemical reactions also generate heat, which needs to be dissipated through a cooling system to maintain optimal operating temperatures.

The overall electrochemical reaction in a hydrogen fuel cell is:

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

Overall: $2H_2 + O_2 \rightarrow 2H_2O$ + Electrical Energy + Heat

The key advantages of fuel cells are their high efficiency in converting chemical energy into electrical energy, their low or zero emissions (depending on the fuel source), and their scalability for various applications, ranging from portable devices to transportation and stationary power generation [129–139]. However, challenges such as high costs, durability issues, and the need for a hydrogen infrastructure must be addressed for widespread adoption of fuel cell technology.

2.2. Types of fuel cells

Fuel cells are classified into several types based on the electrolyte used in the cell.

Proton Exchange Membrane Fuel Cell (PEMFC): PEMFCs are one of the most popular and widely used fuel cell types, particularly in automotive applications. They operate at relatively low temperatures (around 80 °C) and use a solid polymer electrolyte membrane to conduct protons from the anode to the cathode. The key advantages of PEMFCs include high power density, low operating temperature, and quick start-up time. However, they require expensive catalysts (typically platinum) and are susceptible to membrane degradation and fuel impurities.

Solid Oxide Fuel Cell (SOFC): SOFCs operate at high temperatures (600–1000 °C) and use a solid ceramic electrolyte to conduct oxygen ions from the cathode to the anode. They offer high efficiency, fuel flexibility (can use hydrogen, natural gas, biogas, etc.), and the possibility of combined heat and power generation. SOFCs are well-suited for stationary power generation and auxiliary power units. However, their high operating temperatures and material challenges pose durability concerns and longer start-up times.

Molten Carbonate Fuel Cell (MCFC): MCFCs operate at high temperatures (600–700 °C) and use a molten carbonate salt mixture as the electrolyte. They are suitable for large-scale stationary power generation and can efficiently use various hydrocarbon fuels (natural gas, biogas, etc.). MCFCs offer high efficiency and fuel flexibility, but their corrosive electrolyte and high operating temperatures present material challenges and durability issues.

Phosphoric Acid Fuel Cell (PAFC): PAFCs use phosphoric acid as the electrolyte and operate at around 200 °C. They were one of the first fuel cell technologies to be commercialized and have been used in stationary power generation applications. PAFCs offer high efficiency and good resistance to impurities, but their lower operating temperatures limit their fuel flexibility and require expensive platinum catalysts.

Alkaline Fuel Cell (AFC): AFCs were one of the earliest fuel cell technologies developed and used in space missions by NASA. They operate at low temperatures (around 80 °C) and use an alkaline electrolyte solution (typically potassium hydroxide). AFCs offer high electrical efficiency and a wide range of potential fuels, but they are highly sensitive to carbon dioxide poisoning, which can degrade the electrolyte and reduce performance.

Each fuel cell type has its own advantages and limitations, making them suitable for different applications based on factors such as operating temperature, fuel flexibility, and efficiency, cost, and durability requirements.

Fuel cells (FCs) use a fluid or gaseous fuel as the anode, while oxygen, air, or chlorine serve as the oxidants at the cathode side. Hydrogen fuel cells (HFCs), which combine hydrogen and oxygen to generate electricity, are particularly popular and commercially available. This combination of hydrogen and oxygen can make the process regenerative and reversible by utilizing water and energy [100–104,140–145]. Based on the fueling method, HFCs are categorized into direct system FCs and indirect system FCs. In direct system FCs, fuels like hydrogen and methanol react directly, while in indirect system FCs, fuels such as fossil fuels and natural gas first need to be reformed into hydrogen-rich gas before being supplied to the cell for reaction [146–149]. Fuel cells are classified into six types depending on the fuel and oxidant combination, the type of electrolyte, and the operating temperature, as shown in Table 2.

Table 3 summarizes various hybrid systems proposed by different researchers, where fuel cells serve as one of the primary energy sources. The table outlines the following details for each fuel cell hybrid system (FCHS).

1. Sources: The energy sources utilized in the hybrid system, including fuel cells and other sources.
2. Power Conversion Strategies: The methods or techniques employed to convert the energy from the sources into useable electrical power.
3. Control Strategies: The approaches or algorithms used to manage and control the operation of the hybrid system effectively.
4. Application Areas: The specific domains or applications for which the respective fuel cell hybrid systems are designed or targeted.

In essence, the table provides a comprehensive overview of the energy sources, power conversion methods, control strategies, and intended applications for different fuel cell-based hybrid systems proposed by various researchers.

2.3. Applications of different types of fuel cells

Fuel cells have a wide range of applications due to their efficiency and environmental benefits.

- Proton Exchange Membrane Fuel Cells (PEMFCs) are commonly used in transportation, such as in cars and buses, where their quick start-up time and high power density are advantageous.
- Solid Oxide Fuel Cells (SOFCs) are often employed in stationary power generation for buildings or remote locations, as they can operate at high temperatures and produce both electricity and heat. Fuel cell technology is very useful and has a wide and varied range of applications. Proton Exchange Membrane Fuel Cells (PEMFCs) are used in vehicles due to their high power density – they weigh less and take up less space for the same power compared to other fuel cells. Another type is the solid oxide fuel cell (SOFC), which operates at higher temperatures and is often used in stationary power generation.

Table 2
Fuel cells technologies and working features.

Fuel Cell Class	Fuel Used	Working temp (°C)	Cell potential (V)	Electric efficiency	Power limit (kW)
Alkaline	H_2	90–100	1.0	65	10–100
Phosphoric acid	H_2	150–200	1.1	42	50–1000
Solid oxide	H_2, CO, CH_4	650–1000	0.8–1.0	35–43	5–3000
Molten carbonate	H_2, CO, CH_4	600–700	0.7–1.0	45–60	1–1000
Proton exchange membrane	H_2	50–100	1.1	50–60	1–250
Direct methanol	CH_3OH	60–200	0.2–0.4	40	0.001–100

Table 3
Examples of various FCHS and their application.

Reference	Sources	Converter Structure	Control algorithm	Power specification	Application
Fuel cell battery hybrid system model with battery charging from grid (Chowdhury et al., 2016).	Fuel cell, PV and Battery	DC–DC	PWM	85.5 kW	Hybrid Electrical Vehicle
FC battery/supercapacitor hybrid system with regenerative braking (Feroldi et al., 2009).	Fuel cell, Battery, and Supercapacitor	DC–DC and DC–AC	NA	35 kW	Automotive applications
PV-FC hybrid structure is controlled by supervisory control (Taoufik and Lassad, 2017).	Fuel cell, and PV panel	DC–DC	Fuzzy Controller	720 W	Lighting, cooling, and audiovisual equipment.
Stand-alone hybrid PV fuel cell cost optimization (Wang et al., 2017).	Fuel cell, and PV	DC–DC	Model predictive control (MPC)	800 W	DC loads
FC battery hybrid system for portable DC load (Wang and Xiao, 2018).	Fuel cell, and battery	DC–DC	PWM	630 W	Outdoor and some other multiple applications.
Techno-economic analysis of the off-grid hybrid system using Homer software (Duman and Güler, 2018).	PV, wind, diesel generator, battery, fuel cell, H2	DC–DC and DC–AC	NA	13.7 kW–28.4 kW	Household AC and DC loads
Modeling and control of a hybrid power system based on fuel cell and wind turbine (WT) system (Kadri et al., 2020)	Wind, fuel cell, supercapacitor	DC–AC, and DC–DC boost and buck-boost	Fuzzy Logic control	20 kW	DC Loads
Optimized energy management strategy (EMS) based on maximum efficiency range (Wang et al., 2020)	Fuel cell and battery	DC/DC	PID	1.68 kW	Hybrid electric vehicle
Finite-state machine-based energy management for vehicular power system (Wang et al., 2019)	Battery, supercapacitor, fuel cell	DC–DC and DC–AC	PID	NA	Hybrid electric vehicle
MPPT-based optimized hybrid system (Khan and Mathew, 2019)	PV, wind, fuel cell	DC–DC buck and boost	Fuzzy Logic control	0.5 kW–1.6 kW	DC Loads
Off-grid community energy systems in the desert region (Ghenai et al., 2020)	PV and fuel cell	DC–AC	PI controller	800 kW	Residential Loads
Non-isolated multi-port high voltage converters control (Ma et al., 2021)	Fuel cell and battery	DC–DC	MPC controller	0.4 kW	DC Loads

- Molten Carbonate Fuel Cells (MCFCs) are suitable for large-scale power plants, offering high efficiency and the ability to utilize various fuels.
- Direct Methanol Fuel Cells (DMFCs) have potential applications in portable electronics or backup power systems due to their simplicity and low operating temperature requirements. Each type of fuel cell has unique characteristics that make them suitable for specific applications across various industries. Molten Carbonate Fuel Cells (MCFCs) are mainly used for large megawatt-scale stationary power generation. DM fuel cells are used as portable power sources as they do not require any fuel processing and operate at low temperatures. Also, each fuel cell type has its own unique characteristics and merits for a given application.

2.4. *Current applications of fuel cells in automobiles*

Fuel cells have emerged as a promising alternative to traditional internal combustion engines in automobiles. Current applications of fuel cells in automobiles include powering electric vehicles (EVs) with hydrogen fuel cells, offering longer driving ranges and faster refueling times compared to battery-powered EVs [150–155]. Fuel cell electric vehicles (FCEVs) are becoming increasingly popular due to their zero-emission capabilities and potential for reducing greenhouse gas emissions in the transportation sector. Additionally, fuel cells are being used in hybrid vehicles as a range extender, providing electricity to recharge the battery and increase overall efficiency [156–162]. As technology continues to advance, the integration of fuel cells in automobiles is expected to play a significant role in reducing dependence on fossil fuels and promoting sustainable transportation solutions. Fuel cell electric vehicles (FCEVs) are one of the most promising applications of fuel cell technology in the automotive sector. These vehicles use a proton exchange membrane fuel cell (PEMFC) to generate electricity from hydrogen, which powers an electric motor to propel the vehicle.

Passenger Cars: Several major automakers have developed and commercialized fuel cell electric passenger cars, including.

- Toyota Mirai: Toyota's flagship FCEV, first introduced in 2014. The second-generation Mirai was launched in 2020 with improved range and efficiency.
- Honda Clarity Fuel Cell: Honda's fuel cell sedan, launched in 2016, with a range of over 360 miles.
- Hyundai NEXO: Hyundai's second-generation FCEV, introduced in 2018, with a range of around 380 miles.
  These passenger FCEVs offer zero tailpipe emissions, long driving ranges, and refueling times comparable to gasoline vehicles. However, their adoption is currently limited by the lack of widespread hydrogen refueling infrastructure. Commercial Vehicles: Fuel cells are also being applied in commercial vehicles, such as buses and trucks, where their extended range and rapid refueling capabilities offer advantages over battery-electric vehicles.
- Fuel Cell Buses: Several cities around the world have deployed fuel cell buses in their public transportation fleets, including Vancouver, London, and Shanghai.

- Fuel Cell Trucks: Companies like Hyundai, Toyota, and Nikola are developing fuel cell semi-trucks for long-haul transportation, leveraging the advantages of fuel cells for heavy-duty applications.

  Material Handling: Fuel cells have found early adoption in material handling equipment, such as forklifts, where their ability to operate for long periods without recharging is beneficial.
- Fuel Cell Forklifts: Companies like Plug Power and Nuvera have deployed fuel cell-powered forklifts in warehouses and distribution centers, offering longer runtimes and faster refueling compared to battery-powered forklifts.

While fuel cell technology is still in the early stages of automotive adoption, it holds significant promise as a sustainable alternative to traditional internal combustion engines [163–180]. However, the widespread adoption of fuel cell vehicles will depend on the development of a comprehensive hydrogen refueling infrastructure and continued improvements in fuel cell system costs and durability.

2.5. Benefits of using fuel cells in EVs

One of the main benefits of using fuel cells in automobiles is their environmental friendliness. Fuel cells produce electricity through a chemical reaction between hydrogen and oxygen, with water vapor as the only byproduct. This means that fuel cell vehicles do not emit harmful pollutants such as carbon dioxide, nitrogen oxides, or particulate matter like traditional gasoline-powered vehicles do. By using fuel cells in automobiles, we can significantly reduce greenhouse gas emissions and improve air quality in our cities. One of the primary benefits of hydrogen fuel cell vehicles is their positive impact on the environment. Fuel cells combine hydrogen and oxygen to produce electricity with water and heat generated as byproducts. Unlike traditional internal combustion engine vehicles that emit harmful pollutants like carbon monoxide, nitrogen oxides, and particulate matter, hydrogen fuel cell vehicles generate electricity through a clean chemical process. Hydrogen fuel cells do not generate greenhouse gas emissions as for fossil fuel sources, thus reducing pollution and improving air quality as a result [163–166]. Additionally, fuel cell vehicles are also more energy-efficient compared to internal combustion engine vehicles, resulting in lower operating costs for consumers. Overall, the adoption of fuel cells in automobiles has the potential to revolutionize transportation and pave the way for a cleaner and more sustainable future.

3. Future prospects and research directions

3.1. Future prospects

- Increased Adoption and Commercialization: As fuel cell technology continues to mature and costs decrease, it is expected that more automakers will introduce fuel cell electric vehicles (FCEVs) into the market. The development of a comprehensive hydrogen refueling infrastructure will be crucial for widespread adoption.
- Extended Range and Improved Efficiency: Ongoing research aims to increase the energy density of hydrogen storage systems and improve the efficiency of fuel cell systems, enabling longer driving ranges and better fuel economy for FCEVs.
- Hybridization: Combining fuel cells with battery systems in hybrid configurations can leverage the strengths of both technologies, providing extended range and improved performance.
- Fuel Flexibility: While hydrogen remains the primary fuel for automotive fuel cells, research is exploring the possibility of using alternative fuels, such as methanol or ethanol, which could simplify fuel distribution and storage.
- Stationary and Auxiliary Power Applications: In addition to transportation, fuel cells are expected to find applications in stationary power generation, backup power systems, and auxiliary power units for vehicles, leveraging their efficiency and low emissions.

3.2. Research directions

- Membrane and Catalyst Development: Improving the performance and durability of proton exchange membranes and reducing the reliance on expensive platinum catalysts are major research areas, aiming to enhance fuel cell efficiency and reduce costs.
- Hydrogen Storage and Infrastructure: Developing safe, compact, and cost-effective hydrogen storage solutions, as well as establishing a widespread hydrogen refueling infrastructure, are critical research and development areas.
- System Integration and Control: Optimizing the integration of fuel cell systems with other vehicle components, such as electric motors and power electronics, and developing advanced control strategies for improved efficiency and performance.
- Manufacturing and Scaling: Research focuses on improving manufacturing processes and scalability to enable mass production of fuel cell systems at lower costs.
- Recycling and End-of-Life Management: Investigating efficient recycling methods and end-of-life management strategies for fuel cell components to improve sustainability and reduce environmental impact.
- Modeling and Simulation: Advanced computational modeling and simulation techniques are being employed to optimize fuel cell design, predict performance, and accelerate the development process.

Interdisciplinary collaborations among researchers, automakers, and policymakers are crucial for overcoming the remaining technical and economic challenges and realizing the full potential of fuel cell technology in the automotive sector.

4. Conclusion

Despite these challenges, the future prospects for fuel cell technology in the automotive sector are promising. As fuel cell technology continues to mature and costs decrease, it is expected that more automakers will introduce FCEVs into the market. The development of a comprehensive hydrogen refueling infrastructure will be crucial for enabling widespread adoption. Additionally, the exploration of alternative fuels and hybridization with battery systems could further enhance the performance and versatility of fuel cell vehicles. In conclusion, fuel cell technology presents a promising path toward a sustainable and energy-efficient future for the automotive industry and beyond. With continued research and development efforts, as well as supportive policies and infrastructure development, fuel cells could play a pivotal role in mitigating global warming, reducing air pollution, and addressing energy security concerns.

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