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# Fuel Cell Hybrid Electric Vehicles: Energy Management Systems, Challenges, and Future Prospects

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## ABSTRACT

This work explores how Fuel Cell Hybrid Electric Vehicles (FCHEVs) can drive the shift toward the cleaner and more sustainable transportation. It focuses on Proton Exchange Membrane Fuel Cells (PEMFCs), which produce electricity through a reaction between hydrogen and oxygen, leaving only water and heat as the byproducts. The study reviews how fuel cells work alongside energy storage systems such as lithium-ion batteries and supercapacitors. Batteries provide steady energy and long-term storage, while supercapacitors handle quick bursts of power and help recover energy during braking. Together, they make the system more efficient and responsive. The paper also discusses key challenges, such as improving fuel cell lifespan, reducing costs, and building reliable hydrogen production and refueling networks. Research shows that combining PEM fuel cells with advanced storage technologies can reduce hydrogen use, improve performance, and extend system life. Overall, this study highlights that FCHEVs are not just an experimental idea but a practical solution for achieving zero-emission transport, provided continued innovation and infrastructure development keep pace.

**Keywords** - Fuel Cell Hybrid Electric Vehicle, PEMFC, Energy Storage System, Supercapacitor, Lithium-ion Battery, Sustainable Transport.

## 1. INTRODUCTION

The race to curb climate change and clean up the air in our cities has made finding truly sustainable transportation solutions a global imperative. The old internal combustion engine (ICE) [11] simply can't keep up with our new decarbonization goals. While battery-electric vehicles

(BEVs) are leading the charge, there's another clean technology that's proving indispensable, particularly for heavy-duty travel: Hydrogen Fuel Cell Electric Vehicles (FCEVs)

### 1.1 Hydrogen's Crucial Role in Green Mobility:

At the heart of the FCEV [12] movement is hydrogen (1\$H\_2\$), the universe's most abundant element, and a powerful, clean energy carrier. Unlike fossil fuels, when hydrogen is used in a fuel cell, the only things coming out of the tailpipe are water vapor and heat—a perfect zero-emission solution for air quality.

But hydrogen's importance extends beyond the vehicle itself. It acts as a versatile energy solution, allowing us to store surplus electricity generated by intermittent renewables like wind and solar. This process, often called Power-to-Gas, effectively links the transportation and energy sectors, making our entire power grid cleaner and more stable.

In recent years, carmakers and government agencies have been putting serious effort into developing fuel cell technology for vehicles. Companies like Honda, Ford, Toyota, and General Motors have built several prototype fuel cell hybrid electric vehicles (FCHEVs), though most were produced in small numbers and tested locally. A major step forward came in 2015 when Toyota launched the Mirai, the world's first FCHEV to be sold commercially. This marked the start of the technology's early commercialization phase. Following Toyota, Hyundai introduced the Tucson and Honda released the Clarity as their own commercial

FCHEVs. Other major manufacturers, including GM, Daimler, and BMW, are also working to bring similar vehicles to market soon.

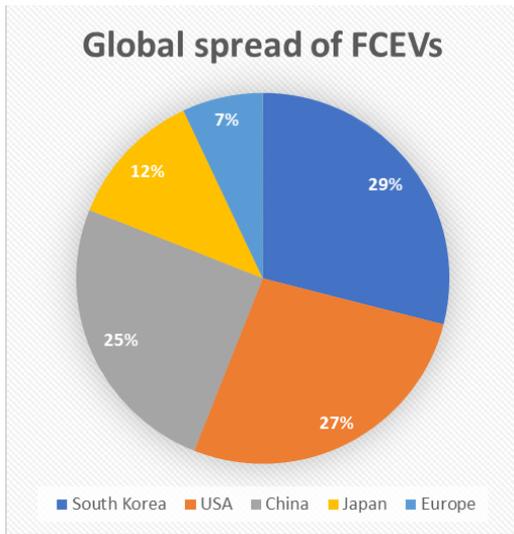


FIGURE 1 GLOBAL SPREAD OF FCEVS

1.2 The FCEV Advantage: Speed and Stamina:

While BEVs are great for daily commutes, FCEVs shine where stamina and quick turnaround are vital. When we compare FCEVs to the other vehicle types on the road, their unique benefits become clear:

TABLE 1: COMPARISON BETWEEN FCEVs & OTHER VEHICLES

Vehicle Type	Key Performance Feature	Why FCEVs are Essential
ICE Vehicles	Emissions	FCEVs offer a zero-local-emission solution, drastically reducing pollution compared to gasoline or diesel engines.
Battery Electric Vehicles (BEVs)	Refueling & Range	FCEVs can be refueled in minutes, much like a traditional car. This, combined with their long driving range, makes them the ideal, no-compromise option for heavy-duty trucking, public transit buses, and high-utilization fleets where downtime is simply not an option.

This makes the FCEV a crucial complementary technology to the BEV, especially as the world looks to fully decarbonize long-haul logistics and commercial transport.

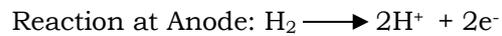
1.3 The Engine of Change: How Fuel Cells Work:

To appreciate the FCEV's potential, we must understand the ingenious device at its core: the fuel cell. For vehicles, the go-to technology is the Proton Exchange Membrane Fuel Cell (PEMFC), favored for its high-power density and efficient performance at lower operating temperatures.

A PEMFC is an elegant electrochemical engine that generates electricity without combustion. It works by having three main sections:

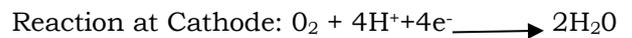
1.3.1 The PEMFC Process

a. *Hydrogen Splits at the Anode:* Hydrogen gas is fed to the anode, where a platinum catalyst strips the hydrogen atoms of their electrons.<sup>8</sup> This creates positively charged protons (H<sup>+</sup>) and negatively charged electrons (e<sup>-</sup>).



b. *Electricity is Generated:* The protons pass directly through the central membrane (the electrolyte). However, the electrons are forced to travel the long way around—through an external circuit—to reach the cathode. This movement of electrons is the electric current that powers the vehicle.

c. *Water is Formed at the Cathode:* At the cathode, oxygen (from the air) combines with the incoming protons and electrons. This reunion forms the clean exhaust: water (H<sub>2</sub>O) and heat.



This simple, continuous reaction ensures a steady supply of clean power for the electric motor.

1.4 The Road Ahead: Challenges to Widespread Adoption:

While the technology is sound and its benefits are clear, the path to mass FCEV adoption faces significant hurdles that researchers and industry leaders are working hard to overcome:

1.4.1 The "Green Hydrogen" Challenge:

The environmental promise of FCEVs hinges entirely on using green hydrogen, produced via electrolysis powered by renewables. Today, most hydrogen is still sourced from fossil fuels (Grey Hydrogen), which compromises the overall well-to-wheel environmental benefits. Scaling up clean production is an absolute necessity.

1.4.2 Infrastructure and Cost Barriers:

Consumers and fleets need a reliable place to refuel. The lack of a widespread, convenient, and cost-effective refueling network remains the biggest obstacle. Furthermore, the high initial cost of FCEVs, primarily due to the platinum required in the fuel cell catalyst, must fall dramatically to achieve price parity with other vehicles.

### 1.4.3 Technical Improvement:

Ongoing research focuses on improving the durability and lifespan of the fuel cell stack, reducing the amount of costly platinum required, and optimizing the onboard hydrogen storage systems for greater energy density and lower weight.

In conclusion, recent research confirms that FCEVs are not a niche experiment, but a mature technology with the potential to fundamentally transform mobility, especially for the heavy transport sector. The task ahead is clear: focus on infrastructure, drive down costs, and ensure the hydrogen fueling these vehicles is sourced from the cleanest possible methods. The future of sustainable transport will undoubtedly feature both batteries and fuel cells working together.

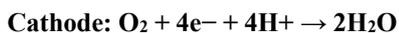
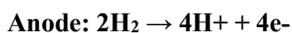
## 2. CHARACTERISTICS OF POWER SOURCES

In modern hybrid electric vehicles, the selection and integration of sources of power are essential in impacting performance, efficiency, and overall reliability. This section delves into the specific characteristics of the primary power sources used in these vehicles, namely fuel cells and various energy storage systems.

### 2.1 Fuel Cell:

A proton exchange membrane fuel cell (PEMFC) generates electrical energy by enabling reaction between hydrogen and oxygen. This process involves converting chemical energy into electricity through electrochemical means. Hydrogen, stored in the FCHEV tank after compression, enters the fuel cell's anode, where protons and electrons are separated from hydrogen with the help of a catalyst. When an external load connects the anode and cathode, free

electrons generate an electric current as they move. The hydrogen protons travel through the electrolyte to reach the cathode, where they, along with electrons and oxygen, combine to produce water. The following equation represents the chemical reaction of the PEM fuel cell.



The only byproducts of this entire reaction are water and heat. The fuel cell generates a low voltage, typically ranging from 0.4 to 1V, which falls short of powering an FCHEV. As a result, a PEMFC is constructed in a stack configuration to boost the voltage output, allowing it to function at a more viable current level. Apart from the array of FC cell, supplementary systems are essential to maintain the consistent functioning of mechanism. This system represents fuel cell, which comprises four core auxiliary systems: hydrogen, air, water, and coolant circuits. The necessary power for these auxiliary systems is sourced from the PEMFC stack while it is operational. Fuel cell durability is a complex challenge, unlike other fuel cell goals. This is because the mechanisms behind fuel cell degradation are still partly unknown. As fuel cells operate, the membrane electrode assembly (MEA) gradually deteriorates, causing performance to decline.

Here's a closer look at operating conditions that can potentially speed up this decline –

- Local starvation may occur during the startup and shutdown of fuel cells.
- The catalyst layer may deteriorate due to the fuel cell's low power requirements.
- A significant rapid change in power will also result in local deprivation

Controlling temperature and moisture levels is crucial in preventing fuel cell degradation. However, addressing these aspects falls outside the EMSs' scope for FCHEVs in this paper, hence their impact on fuel cell degradation isn't examined.

### 2.2 Power Storage Sources

Reliable ESS plays a vital role in FCHEV to supply power and regenerate braking energy. Minimizing hydrogen consumption, protecting the fuel cell from the fast dynamical load, storing braking energy, and maintaining power over the load within the prescribed limits can be achieved using ESS. Battery and supercapacitor are two widely used ESSs in the FCHEV. A battery functions as a device that converts chemical energy into electrical energy through electrochemical processes, serves multiple roles. It not only provides power to the vehicle, and assists in regenerating braking energy, but can also operate as the primary energy provider to satisfy the power needs of the vehicle. The primary focuses of battery research include enhancing performance, extending lifespan, reducing charge time, and minimizing costs. Lead acid batteries, Ni-MH batteries, and Li-ion batteries are widely utilized, with Ni-MH and Li-ion batteries being favoured in battery powered vehicle due to their high energy density and specific energy. A supercapacitor has also been chosen as the ESS of the vehicle in some research. Because of the high specific active surface area of porous carbon electrodes, having much higher energy storage density than the traditional capacitor, which can even be up to 12Wh/kg. Supercapacitor also has a wide operating temperature range, low maintenance cost, high tolerance to overcharge and over temperature, long durability, and reasonable cost. The charging time of a supercapacitor can reach 1 to 10 s, compared with the new fast lithium-ion battery, which is charged at 70% in a few minutes. Therefore, the supercapacitor is an ideal candidate for the peak-load supplier of FCHEV. The supercapacitor serves as the supplier of peak power, while the battery acts as the primary ESS. Besides, in research such as the supercapacitor stands as the sole ESS, supplying kinetic energy to the propulsion system. This includes delivering high-torque output during acceleration or high-speed operation and retrieving energy during deceleration or braking.

### 2.3 FCHEV Power Source-Based Architectures

The various configurations of FCHEV are categorized by the type and quantity of power sources they utilize, such as a FC-battery combination, a fuel cell-SC fusion, and a system integrating fuel cell, battery, and supercapacitor. A converter is capable of transferring power bidirectionally between the storage cell and the direct current network. The DC power produced by both the FC and the storage unit is converted into alternating current power by a DC/AC inverter, which

propels the AC motor. Upon the initial startup of the fuel cell, the reservoir operates as the sole

energy source until the fuel cell reaches optimal operating temperature. In some research scenarios, depending on the battery and direct network voltage, the two-way DC-to-DC converter linked to the battery may be unnecessary. Connecting the supercapacitor directly to the

direct bus without a corresponding regulator is uncommon due to the potential for significant SOC variations under full exploitation conditions, leading to notable voltage fluctuations in the dc bus. The main contributor of power is the fuel cell (FC), while the battery or supercapacitor serves as a supplementary energy provider and recovers braking energy. This topology is ideal for single-stage power transformation. Hence, it is difficult to get references for it. To address the low voltage power supplied by the energy source, a single-way DC-to-DC adaptor is added in to boost the direct current bus's higher voltage levels. Due to its ability to enable power split control between FC and battery/ultracapacitor, this design is generally utilized. The FCHEV architecture is widely favoured by researchers for its flexible control of FC and storage power flow. To ensure the sources meet power demands and maintain a stable DC bus voltage, strict control of both converters is required.

#### 2.4 Comparing the three varieties of batteries alongside a supercapacitor [8][9][10]

TABLE 2: COMPARISON OF BATTERIES AND SUPERCAPACITOR

Categories	Lead acid Battery	Ni-MH battery	Li-ion battery	Supercapacitor
Energy density (Wh/kg)	30-40	60-80	100-200	4-15
Power density(W/kg)	200-300	800-1500	600-2000	1000-10000
Life cycle (Times)	300-400	>1000	>1000	>100000
Efficiency	75	75	90	85-98
Strengths	Inexpensive, rapid discharging, and efficiency recycling	High energy storage capacity, rapid charging and discharging and extended lifespan	Elevated voltage, superior energy density, lightweight construction, extended cycle lifespan, minimal self-discharge and absence of memory effect.	Rapid charge and discharge rates, along with an exceptionally length lifespan.
Weaknesses	Reduced effectiveness in cold temperatures, limited lifespan	Significant self-discharge, requirement for cooling system and elevated manufacturing expenses	Decreased lifespan in elevated temperatures, strict requirement for preventing overcharging, and stringent security standards	Limited energy density

### 3. CONCLUSION

This study makes it clear that the fuel cell hybrid electric vehicles can support a cleaner and sustainable transport system when their power sources work together efficiently. The Fuel cells, batteries, and the supercapacitors each play a part in reducing hydrogen use and keeping the system stable under different driving conditions. The bigger hurdles are cost, durability, and the need for a reliable hydrogen network. With steady improvements in these areas, FCHEVs can move from promising technology to a practical choice for cleaner transportation, especially in heavy transport where performance and range matter the most.

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