Hydrogen Fuel Cells in Vehicles: Current Situation and Future Prospects

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Abstract. Hydrogen is emerging as a pivotal player in sustainable transportation, with hydrogen fuel cell electric vehicles (HFCEVs) gaining substantial traction. Despite the higher production costs compared to petroleum, hydrogen boasts a higher energy content by weight and produces zero toxic emissions. Advances in hydrogen storage, including cryogenic, pressurized tanks, and metal-organic frameworks, are overcoming density-related challenges. HFCEVs are making significant strides globally, particularly in South Korea, the United States, and China. By 2030, fuel cell prices are expected to be comparable with internal combustion engines due to advancements in technology. Enhanced control strategies, evolving safety measures, and supportive government policies are fostering the adoption of hydrogen as a viable clean power solution for future conveyance needs. Additionally, investments in infrastructure, such as hydrogen refueling stations, are expanding, further supporting the growth of HFCEVs. This paper explores the current advancements, challenges, and future outlook of hydrogen fuel cells in the automotive industry, highlighting their potential to revolutionize sustainable transport and contribute significantly to the reduction of greenhouse gas emissions.

Keywords: Hydrogen, storage, fuel cell, vehicles.

1. Introduction

Energy is crucial for the development of a country's economy. It is also significant for infrastructure, transportation, and overall living standards. The current global challenge lies in the imbalance between energy demand and resource availability. Currently, countries worldwide rely heavily on fossil fuels for energy production, which are unsustainable and pose environmental challenges, including the exacerbation of the greenhouse effect. The escalating global population and the looming depletion of non-renewable energy sources heighten the urgency to transition to alternative, sustainable energy sources. In the US, there has been a concerted effort to mitigate the environmental effects of the transportation industry and to reduce reliance on petroleum. Despite this, fossil fuels are expected to dominate energy production still, accounting for an estimated 75% by 2050 [1]. The current state of energy production is unsustainable and has numerous drawbacks, but the integration of sustainable energy sources offers a more hopeful outlook for future generations.

Environmentalists are optimistic that the most severe impacts of global warming can be averted through various initiatives. Over the past 20 years, there has been a noticeable increase in fuel efficiency, and the adoption of hybrid electric vehicles has become more prevalent. Electricity, serving as a substitute power option for vehicles, is rapidly gaining traction. However, electricity, similar to oil and coal resources, is not a source of power; it is a carrier of energy derived from other sources. Battery electric vehicles (BEVs) excel at transforming electrical energy from the grid into mechanical power and facilitate the recovery of energy through the implementation of regenerative braking systems. However, BEVs face limitations such as limited range due to battery cost and dimensions and lengthy charging times compared to the refueling process for conventional vehicles (CVs). To leverage the benefits of both electric and traditional vehicles, hydrogen emerges as a promising alternative.

Hydrogen, as a carrier of chemical energy, can generate electricity with an energy density peaking at 39.39 kWh/kg, surpassing the capacity of the majority of batteries. A fuel cell (FC) operates similarly to an internal combustion engine (ICE), transforming chemical energy into electrical energy directly while maintaining an eco-friendly approach [2, 3]. Unlike batteries, which deplete with use, both ICEs and FCs can continuously supply power as long as fuel is supplied, making hydrogen fuel cells a potential game-changer for transportation, addressing the limitations of BEVs and positioning hydrogen as a leading fuel for the upcoming days.

2. Hydrogen as an Alternative Fuel for Transportation

Hydrogen, in its purest form, stands out as a potent fuel due to its high energy content by weight despite having a lower energy content by volume compared to other fuels. It is omnipresent in nature, both as a gas in the air and dissolved in water. The appeal of hydrogen as a fuel source is amplified by its zero-emission characteristic and a heating value that surpasses petroleum threefold. However, the manmade nature of hydrogen production incurs a significant cost, roughly three times that of petroleum refining [4]. Advancements in hydrogen production technologies are being pursued vigorously to make it a sustainable and efficient energy option. Major automobile manufacturers, including Honda, Toyota, and Hyundai, have ventured into the market of fuel cell vehicles (FCVs), which use hydrogen as a power source for their operations. These vehicles are gaining traction in regions like North America, Asia, and Europe, with a notable market leader in California attributed to its extensive hydrogen refueling infrastructure. FCVs are often juxtaposed with BEVs, partaking in the advantages of having no exhaust emissions and the capability to harness clean energy sources. However, FCVs offer distinct advantages, such as a longer driving range and quicker refueling times, akin to conventional ICE vehicles.

The future of hydrogen as an energy source is promising, with predictions estimating that by 2030, the costs associated with fuel cells will be on par with ICEs, thanks to continuous advancements in technology and greater accessibility [4]. Nonetheless, the efficient storage of hydrogen remains a challenge due to its low density, necessitating compression, cooling, or a combination of both methods. Current storage solutions include compressed hydrogen tanks, which, despite being costly and raising safety concerns due to the high-pressure requirement, are competitive when pre-cooled [5]. Research into alternative storage methods, such as tanks with internal skeletons, liquid hydrogen systems, and cryo-compressed tanks, is ongoing to improve energy efficiency and public acceptance. Hydrogen can be obtained from a multitude of sources for its production, which includes water, hydrocarbon fuels, and chemical elements, requiring external energy inputs like thermal, electrical energy, or photonic biochemical. The extraction of hydrogen from waste biology fuel through reactions of electrochemical is an environmentally friendly and cost-effective method, with potential feedstocks ranging from agricultural residues to newspapers.

In summary, hydrogen holds significant promise as a clean and effective energy carrier, with ongoing research and development aimed at overcoming the challenges of production and storage to realize its full potential in the future energy landscape.

3. The Storage of Hydrogen

A pivotal area of research in the development of FCVs is the storage of hydrogen. Cutting-edge solutions for the containment of hydrogen are under development to meet the evolving consumer demands effectively. Hydrogen's low energy density presents the challenge of achieving sufficient driving ranges in vehicles, as it requires either a very large or excessively heavy storage system. There are basically three measures for hydrogen storage, which are separately Cryogenic Liquid Hydrogen Storage, Pressurized Tank Storage, and Hydrogen Uptake in Metal-Based Compounds [6].

3.1. Cryogenic Liquid Hydrogen Storage

Hydrogen can be kept in its liquid state by employing the method of cryogenic liquefaction, which requires achieving an extremely low temperature of -259.2°C. The density of liquid hydrogen (LH_2) is low, and one liter of LH_2 is just 71.37×10^{-3}kg in weight. 8.52 megajoules of electricity may be produced from one-liter hydrogen. Preserving hydrogen at such a frigid temperature poses a huge challenge, and doing so requires insulation, which raises the cost. Nitrogen must be employed to evacuate the tank of all leftover gases prior to the addition of more hydrogen, given that LH_2 can be explosive upon contact with some gases [7, 8].

3.2. Pressurized Tank Storage

Pressurized tanks consisting of carbon-fiber wrapped cylinders with sufficient strength that includes impact resistance for safety in crashes. It has been demonstrated that compressed hydrogen in such tanks can operate for 500 kilometers at 34MPa pressure, 32.5kg mass, and 186L volume.

About 90% of a 55-gallon barrel is stored in the tank, making it large for single cars. Nevertheless, the low density of hydrogen prevents it from being stored in tanks in adequate amounts, unlike other gases. Low-temperature liquid hydrogen storage is not suitable for everyday car use, and several manufacturers are still conducting limited studies on this possibility. Furthermore, a storage system for liquid hydrogen can experience losses of up to 1% daily due to evaporation, and maintaining hydrogen at 20K necessitates substantial refrigeration [9].

3.3. Hydrogen Uptake in Metal-Based Compounds

Metal hydride storage is a method that allows for hydrogen storage at pressures lower than three or four MPa and at temperatures exceeding room temperature. Nevertheless, the use of metals in this process adds significant weight to vehicles and is also quite costly [10]. An alternative has been discovered in lithium nitride, which can store a substantial amount of hydrogen reversibly. This material can rapidly absorb hydrogen within the temperature range of 170 to 210 degrees Celsius, achieving a hydrogen uptake of 9.3 weight percent when the sample was exposed to 255 degrees Celsius for 30 minutes. In a vacuum environment of 10^{-9}MPa or 10^{-5}mbar, approximately two-thirds of the hydrogen was discharged at temperatures under 200 degrees Celsius. Residual hydrogen requires temperatures exceeding three hundred and twenty degrees Celsius for discharge. The hydrogen is absorbed in the form of lithium amide ($LiNH_2$) and lithium hydride (LiH). The research fellows propose that further investigation into metal-N-H systems could uncover more viable hydrogen-storage solutions in terms of both pressure and temperature [11].

4. Principles of Fuel Cell

FC come in a variety of types, but they all operate on a similar fundamental principle. The operation of a fuel cell system hinges on three essential components: an anode, a cathode, and an electrolyte. The categorization of FCs is determined by the category of electrolytic substance they utilize. A single fuel cell can consist of numerous individual cells, yet each cell contains the same three core elements. The electrolyte is situated between the positive electrode and the negative electrode. Fig. 1 illustrates the operational diagram of a polymer electrolyte membrane fuel cell (PEMFC) [12]. The function of an FC is consistent across different types despite the variation in electrolyte materials. The general operation of a fuel cell involves the introduction of fuel—typically unadulterated hydrogen—into the anode compartment while air or pure oxygen is supplied to the negative electrode compartment. Within the anode chamber, the hydrogen gas releases electrons as it attempts to traverse the proton-exchange membrane. This membrane serves as a selective barrier, allowing only hydrogen ions to go through while filtering out the electrons. On the cathode side, these hydrogen ions unite with oxygen in the air to form water (H_2O) as a secondary output, along with the generation of heat [13].

Unlike conventional internal combustion engines, which mix fuel with air and involve combustion, fuel cells maintain a separation between the fuel and the oxidant, eliminating the need for fuel combustion. As a result, fuel cells are devoid of the detrimental emissions associated with internal combustion engines.

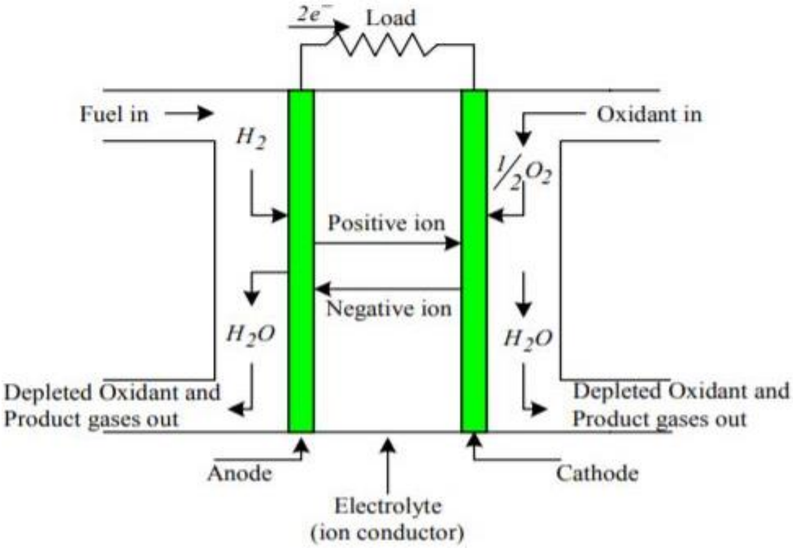

Figure 1. Fuel cell operation diagram [12]

5. Fuel Cell Hybrid Vehicles

Fuel cells are used in hybrid vehicles, including parallel, series and series-parallel hybrid systems.

5.1. Parallel Hybrid

In the early stages of hybrid vehicle development, the parallel hybrid system was a pioneering design. This system enables the use of either the ICE, the electric drive, or a combination of both to force the vehicle without dependence on each other. The ICE tends to exhibit reduced efficiency during low-speed operation and in conditions characterized by frequent stops and starts due to its low torque at those speeds. On the other hand, electric motors are capable of delivering torque quickly, which makes them particularly suitable for the variable demands of urban driving, where quick acceleration and deceleration are common. Utilizing a parallel hybrid system enables the power sources to function individually or in tandem at different levels of efficiency throughout the drive cycle. [8]. In the parallel hybrid configuration, it is possible to engage not only the ICE but also the electric motor simultaneously to meet high torque demands. This capability allows for a downsizing of both power units, as the drive cycle typically does not require peak torque continuously. The reduced size of the engine and motor contributes to enhancing the comprehensive performance efficiency of the hybrid configuration in parallel mode.

Additionally, the parallel hybrid system benefits from the incorporation of regenerative braking, which enables energy recovery during the deceleration phases of driving. This recovered energy is stored and can be reused, further improving the system's efficiency and performance. The train driven by parallel hybrid is visually pictured in the figure below, labeled as Fig. 2 [14].

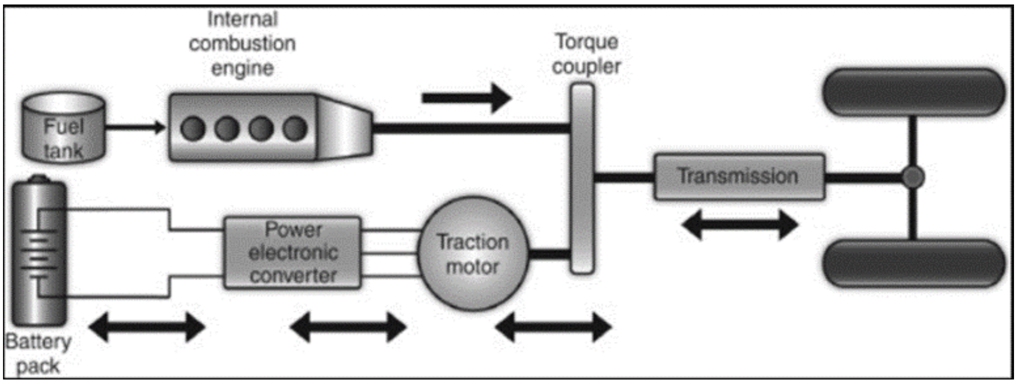

Figure 2. Parallel hybrid structure [14]

5.2. Series Hybrid

The arrangement of a range-extender hybrid propulsion system is uniquely different from a parallel hybrid system in that it does not permit the two power sources to drive the vehicle independently. In a series hybrid arrangement, the ICE primarily functions as a generator, charging the batteries. The electricity stored in these batteries then powers the electric motor, which is the sole mechanism for propelling the vehicle. This configuration eliminates the need for the ICE to force the vehicle directly, allowing it to operate at optimal efficiency while generating electricity for the motor and battery system. One benefit of this design is the elimination of the need for a gearbox, given that the ICE does not directly drive the car. The series hybrid configuration possesses the capability to harness regenerative braking, enabling energy recuperation during deceleration and braking phases. This process involves the electric motor operating in a generator mode, similar to parallel hybrids. However, a limitation of the series hybrid design is the necessity for a more substantial electric motor. This requirement arises because the configuration does not facilitate the simultaneous engagement of both power sources to provide additional power during intense acceleration events.

5.3. Series-Parallel Hybrid

A series-parallel hybrid integrates elements from both series and parallel hybrid drive train setups. In a series-parallel hybrid vehicle, the electric motor and the ICE are both capable of propelling the vehicle, either separately or in tandem. The ICE has the unique ability to power the vehicle while also replenishing the battery charge concurrently. This setup offers exceptional control flexibility, allowing for operational modes to be fine-tuned based on the specific driving conditions at hand. Nonetheless, this design comes with a trade-off, namely the increased complexity and additional components needed to support the dual powertrain functionality. The series-parallel hybrid design contains the assets of both series and parallel structures, offering greater adaptability to multiple driving patterns, but at the same time, it inherits the disadvantages of the two [15, 16]. An example of this design is depicted in Fig. 3 below [8].

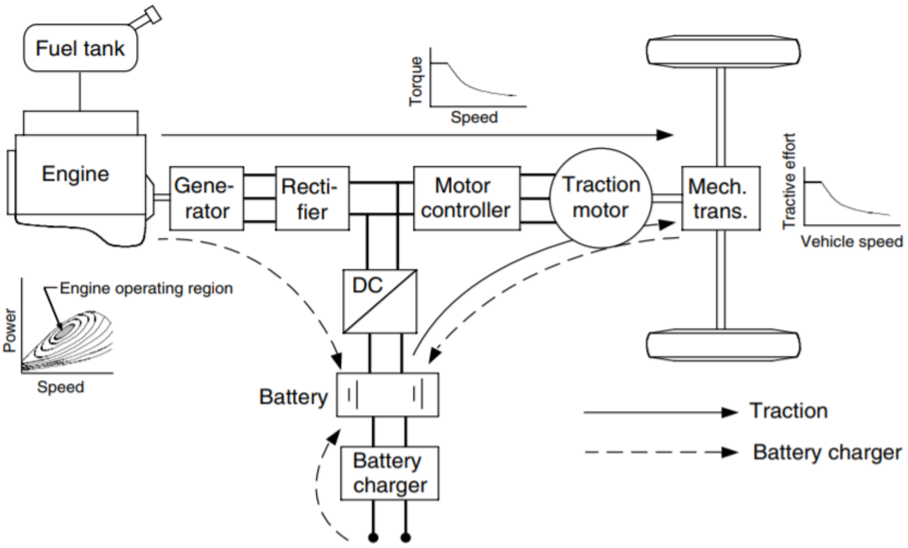

Figure 3. Series hybrid structure [8]

6. Global Overview of Hydrogen-Powered Fuel Cell Vehicles

As of 2021, globally, there were around 51,437 HFCEVs in operation, with the majority being cars, which account for 82% of the total. Buses made up 9.2% of these vehicles, while medium and heavy-duty trucks constituted 8.7%. Additionally, there were 729 stations dedicated to providing hydrogen fuel for these vehicles across the world [12]. South Korea takes the lead in utilizing HFCEVs, holding approximately 38% of the worldwide total and a significant 56% of the cumulative count of these types of vehicles across Asia. The United States comes in as the second-largest adopter of HFCEVs, with roughly 12,358 vehicles, trailed by Japan with 6741 vehicles and 8474 by China. In 2021, the count of fuel cell-powered vehicles experienced a substantial increase, growing about 7.2 times compared to 2017, which saw 7,186 vehicles. This growth pattern is well-captured by a second-degree polynomial, indicating a rapid acceleration in the adoption of these vehicles [12].

7. Prospect of Hydrogen Fuel Cell

7.1. Control Strategies for Improving Efficiency of Fuel Cell Vehicles

The limitations of FCVs, including issues with low energy output per unit volume and delayed power delivery, can be effectively mitigated by integrating supercapacitors (SCAPS) and batteries (BATs) alongside the FC [17, 18]. An example of such a vehicle is the Fuel Cell Electric Vehicle (FCEV), which is equipped with a multiphase propulsion motor, a system to store energy, a direct current (DC) bus, and various auxiliary devices. The energy flow in this system is sequential, starting from the fuel cell to the battery, then to the supercapacitor, with an inverter managing the energy supply to the traction motor and the discharge from the supercapacitor. The controllers for these systems commonly employ specific control strategies, which are outlined as follows.

7.1.1 Peaking power source strategy (PPSS)

In a Power-Propulsion System (PPSS), electronic interfaces connect the controllers, wheels, traction motor, and pedals to gather signals. The vehicle's power and torque are managed by the vehicle controller, which responds to inputs from the gas and brake pedals. Depending on the power demand, energy is dynamically allocated between the FC and the Power-Propulsion System (PPS) to fulfill the vehicle's power needs. The energy required is supplied by the FC, the PPS, or a combination of both, depending on the driver's demand for quick response. The traction system is designed to regulate the output power effectively, ensuring that the vehicle can promptly adjust to the driver's commands and maintain optimal performance [19].

7.1.2 Operating mode control strategy (OMCS)

The Onboard Management and Control System (OMCS) is responsible for regulating power fluctuations and coordinating power distribution between the FC and the BAT. During the discharge phase, the vehicle's energy requirement, denoted as E_r can be either less or greater than the standard energy output of the FC (E_{FC}), depending on the driving conditions, such as acceleration. When E_r is less than E_{FC}, the FC alone supplies the necessary energy. Conversely, if E_r exceeds E_{FC}, the energy is sourced from both the FC and the BAT to meet the demand. In the charging mode, E_r is equivalent to E_{FC}, with the FC fulfilling the power requirement and simultaneously recharging the BAT.

In the scenario of fast charging, E_r is significantly lower than E_{FC}. Under this condition, the FC not only meets the power demand but also supplies power to various systems that require additional energy [20].

7.1.3 Fuzzy logic control strategy (FLCS)

To optimize the energy storage system and improve the FCV’s efficiency, a Fuel and Load Control System (FLCS) is implemented. When the power levels of the SCAP and the battery reach a low State of Charge (LSOC), the Power Demand Control (PDC) should be set to its maximum value (DC_{max}). This ensures that the energy storage devices are charged to a level that can support the vehicle's power needs effectively.

Conversely, when the SCAP and BAT are at high power levels, the PDC should be adjusted to a minimum level (DC_{min}) or a middle level (DC_{middle}) based on the actual P_r. This objective is to maintain the SCAP and BAT at their optimal power levels to satisfy P_r, enabling the vehicle to operate at its nominal E_{FC}. This strategy helps in balancing energy usage and prolonging the life of the energy-storing components.

7.1.4 Equivalent Consumption Minimization Strategy (ECMS)

The Energy Management Control System (ECMS) is utilized to oversee the energy resources within the energy-storing devices. It performs a crucial function by translating the electrical energy expenditure of the SCAP and the BAT into a corresponding measure of hydrogen utilization. This conversion allows for a more unified approach to energy management within the vehicle.

Furthermore, the ECMS can treat electrical energy provided by the energy storage systems, for example, the SCAP and the BAT, as if they were the FC supplying hydrogen. This is achieved through the notion of comparative fuel consumption, which enables the system to optimize energy use by considering all forms of energy in terms of their hydrogen equivalent. This approach ensures that the vehicle operates efficiently, making the best use of all available energy resources [21].

7.2. Safety Problems of Hydrogen

Hydrogen, like many other fuels, does not inherently pose a higher level of risk. The unique properties of hydrogen necessitate specific safety measures and protocols, but it is a common characteristic of fuels to have some risk of accidents—after all, their combustibility is what makes them useful as fuels. Hydrogen is already extensively utilized in various sectors, such as the petroleum, chemical industries, and beyond. Historically, in the United States, hydrogen was a regular component of "town gas," which was used as a fuel before natural gas became prevalent. Even today, town gas continues to be utilized in certain countries. In terms of safety, hydrogen is comparable, falling between the safety profiles of propane and methane, which are the main constituents of natural gas.

Hydrogen's distinctive physical attributes result in safety profiles that set it apart from other fuels. Its low density is a key factor; in the case of an escape, hydrogen is inclined to ascend and diffuse rapidly into the atmosphere rather than pooling on the ground. This behavior enhances safety in areas with good air circulation. Additionally, due to its low density, a hydrogen explosion, for a given volume, yields less energy than those of other fuels. When compared to gasoline or natural gas, achieving an explosive mixture in the air requires a much higher concentration of hydrogen.

Moreover, hydrogen's low ignition temperature and its broad flammability range pose significant fire risks, particularly in enclosed environments like garages, should leaks occur. The challenge of detecting hydrogen leaks is compounded by its clear, colorless, and odorless nature, making it less perceptible than fuels like gasoline. Even the flame produced by burning hydrogen is hard to see.

Developing effective leak detection methods is and remains a critical area of research. One straightforward solution is to incorporate odorants similar to those used in natural gas, or even colorants, to enhance detectability. However, any additives must be carefully selected to ensure they do not compromise the environmental benefits of using pure hydrogen. It is important to avoid additives that could diminish the efficiency or lifespan of fuel cells, as they might introduce contaminants that could be detrimental to the fuel cell's performance.

Like many fuels, the primary safety concerns with hydrogen revolve around fire and explosion risks. There may also be specific scenarios, such as when hydrogen is stored under high pressure or at very low temperatures, that present additional safety challenges. However, these issues can generally be mitigated through careful equipment design and adherence to proper operational protocols. The broader consensus is that these concerns are secondary to the flammability of hydrogen when it comes to prioritizing safety measures.

8. Conclusion

HFCEVs represent a promising avenue for sustainable transportation, offering high energy content and producing no toxic emissions. Despite the challenges of hydrogen production costs and storage, advancements in technologies such as cryogenic liquid storage, pressurized tanks, and metal-based compounds are paving the way for practical solutions. Fuel cell systems, with their distinct advantages over internal combustion engines, are at the core of HFCEVs, providing efficient and clean energy conversion. Hybrid systems, including parallel, series, and series-parallel configurations, enhance the flexibility and efficiency of these vehicles. The global adoption of HFCEVs is on the rise, with significant growth observed in recent years, particularly in countries like South Korea, the United States, and China. Looking ahead, control strategies like PPSS, OMCS, FLCS, and ECMS are set to optimize the efficiency of HFCEVs further. While safety concerns regarding hydrogen's flammability and detection are valid, they are manageable with proper protocols and equipment design. The outlook of hydrogen fuel cell technology holds great potential, with ongoing research and development expected to address current limitations and unlock the full potential of this clean energy source for transportation.

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