Innovation and future development direction of hydrogen fuel cell vehicles

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Abstract. With the increasing problem of global climate change, reducing greenhouse gas emissions has become an urgent issue for all countries to solve. The pollution of the Earth is gradually becoming severe. The extensive use of fossil fuels is a major cause of this problem. In this critical situation, energy with the least carbon emissions should be used to minimize air pollution and the harm caused by it. Hydrogen energy is currently a clean energy alternative that can achieve low carbon emissions. As a new energy vehicle, hydrogen fuel cell vehicles have the advantages of being clean, efficient, and environmentally friendly. Compared with traditional fuel vehicles, hydrogen fuel cell vehicles only produce water and a small amount of oxygen during operation, and do not emit harmful substances such as carbon dioxide, which helps to significantly reduce carbon emissions in the transportation sector. So, hydrogen fuel cell vehicles are a viable and clean solution. In this paper, the performance evaluation, cost analysis, and future impact of hydrogen-powered vehicles are analyzed, and the future development trend of hydrogen energy battery vehicles is discussed. As a new energy vehicle, hydrogen fuel cell vehicles have important strategic significance and market prospects. The purpose of this paper is to provide a useful reference for the development of China's new energy vehicle industry through the study of hydrogen fuel cell vehicles.

Keywords: hydrogen fuel cell vehicles; global warming, GHG emission.

1. Introduction

With technological innovation and advancement, hydrogen fuel cell technology has garnered increased attention in the automotive industry, gradually becoming an eco-friendly alternative to traditional fossil fuel vehicles. Hydrogen Fuel Cell Vehicles (HFCVs) use hydrogen to power onboard electric motors, emitting only water vapor and heat. Despite the excellent energy efficiency and power-to-weight ratio of hydrogen fuel cells, as well as their significant emission reduction potential, there remain key technical and infrastructure challenges to their widespread application [1, 2]. The primary technical obstacles currently include high manufacturing costs, low hydrogen energy density, safety assurance issues, insufficient battery durability, inadequate hydrogen refueling infrastructure, and the complexity of hydrogen transportation and storage [2, 3].

Additionally, the production of hydrogen fuel itself is a critical issue that needs addressing. Currently, most hydrogen is produced through fossil fuel reforming, which, while efficient, still relies on non-renewable resources. To truly achieve environmental goals, the development of water electrolysis technology using renewable energy is crucial. In the future, widespread application of solar and wind energy could drive green hydrogen production, thereby reducing carbon emissions. Government policies and support are also significant in promoting hydrogen fuel cell technology. Various governments have begun to introduce a series of incentives and subsidies to foster the research, development, and market adoption of hydrogen energy technologies. These policies not only help reduce the costs of hydrogen fuel cells but also accelerate the construction of hydrogen refueling stations and other necessary infrastructure. Furthermore, international cooperation and standardization will aid in addressing the complexities of hydrogen transport and storage, enhancing the efficiency of the global hydrogen supply chain. Despite the numerous challenges, continuous technological advancements and policy support suggest that hydrogen fuel cell vehicles could become a vital component of clean energy transportation in the future.

Despite some progress in the application of hydrogen fuel cell technology in automobiles in recent years, the high production and maintenance costs have limited the market competitiveness of hydrogen fuel cell vehicles [1, 2]. Additionally, the lack of hydrogen infrastructure and safety issues remain critical bottlenecks [3].

The objective of this study is to explore the status, challenges, and future development directions of hydrogen fuel cell vehicles. By analyzing existing technologies, the study aims to propose improvement suggestions and future research directions to provide theoretical support for the widespread application of hydrogen fuel cell vehicles.

2. Performance assessment

2.1. Working mechanism and performance evaluation method

Hydrogen fuel cells do not generate kinetic energy through the violent reaction of hydrogen and oxygen combustion like rockets; instead, they release the Gibbs free energy in hydrogen through catalytic devices. The working principle of the battery is that hydrogen is decomposed through a catalyst at the cathode of the fuel cell. Protons then reach the negative electrode through proton exchange membrane technology and react with oxygen to form water and heat. There are many advantages to using hydrogen as an energy fuel. It can achieve zero pollution, low noise, and high efficiency. Additionally, hydrogen energy is relatively sufficient, so there is no need to worry about energy shortages.

The indicators used to evaluate the effectiveness of hydrogen fuel cell models typically involve a series of performance, safety, and environmental standards. Follows are some key evaluation metrics. Performance indicators require considering battery power density, efficiency, and battery life. Safety indicators need to consider leak detection, explosion and fire risk, and thermal management. Environmental indicators must account for pollution emissions and sustainability. Regulatory and standard compliance requires adherence to relevant national and international standards. Analyzing and obtaining the data for evaluation usually requires laboratory testing, field testing, simulation analysis, and long-term operational data. In addition, the evaluation process should also consider the needs of the specific use case and user feedback. Through these comprehensive evaluations, a comprehensive judgment can be made about the effectiveness of the hydrogen fuel cell model.

2.2. Performance evaluation

The advent of hydrogen battery cars and battery electric vehicles (BEVs) presents a promising alternative to traditional fuel-powered automobiles. These eco-friendly vehicles stand out for their potential to achieve zero emissions, which has led to a surge in their adoption in recent years. Nevertheless, battery cars are not without their drawbacks. The high cost of batteries, inclusive of the vehicle itself, battery charging, and frequent replacements, poses a significant challenge. The environmental impact is exacerbated with each battery swap, as batteries contain substances that are harmful to the ecosystem and take a considerable amount of time to decompose.

The limited range of a battery-powered vehicle is a significant drawback, exacerbated by the relatively low efficiency of battery packs. To extend the driving distance, one must repeatedly stack these packs, which not only increases cost but also undermines economic viability. Conversely, hydrogen fuel cell vehicles offer a more promising outlook, with charging times significantly reduced to approximately five minutes at 700 bar pressure [4]. Hydrogen holds immense potential as an energy carrier for transportation. While the scarcity of pure hydrogen necessitates extraction from external sources, these can be derived from renewable means such as wind power [5], Ocean Thermal Energy Conversion (OTEC) [6], and the supercritical water gasification of almond shells [7]. These methods of energy generation are comparatively clean and sustainable. According to a report by the International Energy Agency (IEA) on the future of Fuel Cell Vehicles (FCVs), the market share of FCVs is projected to reach 17% by the year 2050 [8]. This indicates a promising trajectory for hydrogen-powered vehicles, offering a cleaner and more efficient alternative to conventional battery-operated cars.

3. Cost analysis

3.1. Fuel Cell System

The fuel cell system is the core component of hydrogen fuel cell vehicles, comprising the proton exchange membrane, the electrocatalyst layer, and the gas diffusion layer. The membrane electrode assembly (MEA) typically uses expensive platinum as a catalyst. According to market analysis, the cost of the fuel cell system is approximately $230 per kilowatt [9].

3.2. Hydrogen Storage System

Hydrogen storage typically uses high-pressure hydrogen tanks as storage devices. These tanks are usually made of carbon fiber composites, which are costly. The cost of high-pressure hydrogen storage tanks ranges between $2,000 and $4,000 per vehicle [9].

3.3. Power System and Electronic Equipment

The power system of hydrogen fuel cell vehicles mainly includes electric motors and power electronic devices (such as inverters and DC-DC converters). Although the costs of these systems are high, production costs are expected to decrease with economies of scale. Currently, the cost of the electric drive system is approximately between $3,000 and $5,000 [9].

3.4. Comparison of Production Costs and Focus Analysis

The Toyota Mirai benefits from efficient mass production and long-term investment, resulting in relatively low production costs [9]. Conversely, the Hyundai NEXO's higher costs are attributed to its advanced fuel cell technology and performance-oriented design [9]. The Honda Clarity Fuel Cell experiences elevated costs due to the complexities within its supply chain and the intricacies of system integration [9]. Furthermore, the BMW iX5 Hydrogen incurs significant costs driven by its high-end design and the implementation of high-performance fuel cell systems [9].

3.5. Market Trend Analysis

In the future, with technological advancements, economies of scale, and policy support, the production costs of hydrogen fuel cell vehicles are expected to decrease. For example, new catalyst materials and more efficient production processes will further reduce the costs of fuel cell systems. Additionally, government subsidies and tax incentives will encourage more companies to enter the market, driving costs down further [1, 2].

4. Environmental effect analysis

As time progresses, the reliance on fossil fuels globally is escalating at an alarming rate. These fossil fuel contribute to global warming. In the United States, a recent decline in fossil fuel consumption has led to a reduction in greenhouse gas emissions by a staggering 450 million tons [4]. Considering this issue, it is imperative that we explore and harness alternative energy sources such as methanol, ethanol, and natural gas. Nonetheless, it is crucial to acknowledge that these substitutes are not without their drawbacks, as they are susceptible to energy shortages and may have adverse environmental consequences.

Governments around the world are actively promoting the development of hydrogen fuel cell vehicles, trying to replace the original fuel vehicles with new models. Experts such as Thomas, a fuel expert in United States, believe that fuel cells and hydrogen fuel will be the best automotive technology solutions to effectively combat global warming in this century [10]. A natural gas-to-hydrogen hydrogen battery vehicle can reduce CO_2 equivalent emissions by 15.40 t, pollutant emissions equivalent by 29.96 kg, and the emission cost is correspondingly 1176.73 yuan [11]. Therefore, when the proportion of such hydrogen battery vehicles exceeds a certain number, it can effectively reduce the carbon emission rate. However, the production of hydrogen from natural gas still leads to the emission of some fossil fuel waste, so the use of water electrolysis to produce hydrogen can increase the environmental impact of hydrogen energy electric vehicles. Therefore, in the future, it is necessary to continuously improve the emission reduction effect of hydrogen production technology and expand the benefits of environmental protection.

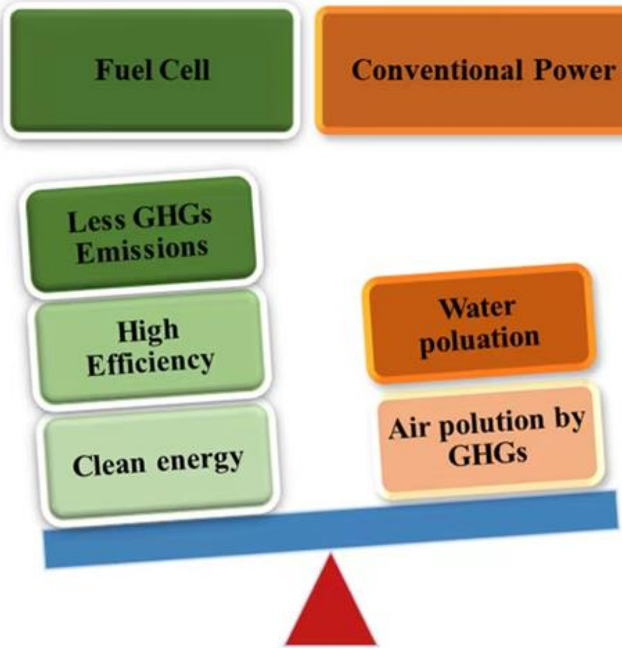

Fig 1. Environmental effects of hydrogen fuel car [12]

5. Future Trends and Recommendations

5.1. Future Prospects

Hydrogen fuel cell technology holds tremendous potential for the future development of the automotive industry. With technological advancements and policy support, HFCVs are expected to become mainstream green transportation tools in the future.

Advances in material science and engineering will further improve fuel cell efficiency and durability. New catalyst materials and more efficient proton exchange membranes will significantly reduce costs and enhance performance [13,14].

Developments in renewable energy-based electrolysis for hydrogen production will greatly reduce hydrogen production costs. Additionally, advancements in high-pressure and liquid hydrogen storage technology will address hydrogen storage and transportation challenges [15,16].

As market demand grows, mass production of HFCVs will be achieved, significantly reducing production costs. For example, Toyota has made substantial progress in reducing production costs through mass production and long-term investment [17]. As the HFCV industry matures, supply chain optimization will further reduce costs. Standardized fuel cell components and more efficient supply chain management will help minimize production waste and costs [18].

Many governments have implemented policies to support the development of HFCVs, including purchase subsidies, tax incentives, and infrastructure construction funds. For instance, the governments of China and Japan are heavily investing in HFCV infrastructure to promote market adoption [15,19].

With global emphasis on environmental protection, stringent emission standards will drive demand for HFCVs. For example, zero-emission vehicle (ZEV) regulations in the EU and California have prompted automakers to invest more in hydrogen fuel cell technology [20,21].

5.2. Recommendations

Enterprises and governments should increase R&D investment in hydrogen fuel cell technology, focusing on basic research and applied technology development. New catalyst materials and efficient electrolysis technologies for hydrogen production are key future research directions [13, 15].

Governments and enterprises should collaborate to accelerate the construction of hydrogen refueling stations to address the current challenges of refueling HFCVs. For example, the Japanese government plans to build about 900 hydrogen refueling stations nationwide by 2030 to support HFCV development [16,17].

Countries should strengthen international cooperation on hydrogen fuel cell technology and standards, sharing achievements and best practices. Organizations like the International Energy Agency (IEA) and the Hydrogen Council are already promoting global hydrogen cooperation [17, 20].

Enterprises should increase market promotion efforts for HFCVs and enhance consumer awareness of hydrogen fuel cell technology through public education. For example, companies like Toyota and Hyundai actively promote the advantages of HFCVs through exhibitions and test drive events [21].

6. Conclusion

Hydrogen fuel cell vehicles represent a crucial direction for future green transportation, demonstrating significant environmental and performance advantages. By utilizing hydrogen as an energy source, HFCVs achieve zero emissions, substantially reducing carbon emissions and air pollution. This is especially pertinent in the transportation sector, where HFCVs offer a viable solution to mitigate global warming and environmental degradation. Their high efficiency and rapid refueling capabilities uniquely position them to meet the growing demands for sustainable mobility. However, the development of HFCVs still faces several notable challenges. Primarily, the high production costs of fuel cells, including the expense of the cell systems and hydrogen storage solutions, pose a significant barrier to market acceptance. Additionally, the current infrastructure for hydrogen production, storage, and refueling, as well as safety concerns, remains underdeveloped. While water electrolysis presents a promising technology for green hydrogen production, its economic feasibility and environmental benefits need further enhancement. Addressing these challenges will require concerted efforts in technological advancement, policy support, and market stimulation. Innovations in catalyst materials and more efficient hydrogen production methods are expected to reduce the costs associated with fuel cells, improving their economic viability. Government subsidies, incentives, and the expansion of refueling infrastructure, along with international cooperation on technology and standardization, will play a critical role in facilitating the widespread adoption of HFCVs. Increased investment in research and development, accelerated infrastructure development, and enhanced public awareness and promotion of hydrogen fuel cell technology are essential to overcoming existing obstacles and advancing the market readiness of HFCVs. In summary, hydrogen fuel cell vehicles hold significant strategic importance and potential for future development. Despite the current challenges, ongoing technological progress and supportive policies suggest that HFCVs are well-positioned to become a key component of sustainable transportation systems. Their advancement will be instrumental in achieving global sustainability goals and addressing the pressing issue of climate change.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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