

Analysis of the Current Development Status of Hydrogen-based New Energy Vehicle Energy Systems

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ABSTRACT

This study is focused on exploring the optimization of performance and sustainable development of hydrogen-based new energy vehicle systems. By taking into account critical factors such as hydrogen production, storage, fuel cell systems, and overall vehicle power systems, the objective is to enhance energy efficiency and mitigate environmental impact. The advancement of hydrogen vehicle technology is pivotal in achieving these goals. Hydrogen, recognized as a clean and plentiful energy source, holds potential for reducing greenhouse gas emissions and lessening reliance on fossil fuels within the transportation sector. The effective integration of efficient hydrogen production methods, dependable storage technologies, and cutting-edge fuel cell systems is essential for fully realizing the benefits of hydrogen-powered vehicles. These vehicles operate with zero emissions and can significantly contribute to addressing challenges related to climate change and urban air quality. Through this research, our aim is to contribute to ongoing efforts in developing sustainable transportation solutions. By optimizing the entire hydrogen energy chain—from production through to vehicle operation—we seek to maximize the advantages of hydrogen technology while minimizing its environmental footprint. This interdisciplinary approach merges engineering, environmental science, and policy analysis to pave the way toward a cleaner and more sustainable future for automotive transportation.

KEYWORDS

Hydrogen Energy; New Energy Vehicles; Performance Optimization; Sustainable Development; Hydrogen Fuel Cells.

1. INTRODUCTION

With increasing global emphasis on environmental protection and sustainable development, the development of new energy vehicles has become a focal area of investment for governments and businesses worldwide. Among them, hydrogen-based new energy vehicles are regarded as a crucial direction for future transportation development due to their advantages such as zero emissions, high efficiency, and environmental friendliness. However, hydrogen-based new energy vehicles still face numerous challenges in practical applications, including performance optimization, safety, and cost issues. Research on hydrogen-based new energy vehicle systems has advanced in recent years. In 2018, Abdalla M. Abdalla and colleagues discussed the challenges in the production, storage, transport, and application of hydrogen. In 2020, Olivier Bethoux highlighted the strengths and development pathways of hydrogen fuel cells in road transport applications. In 2021, Lixin Fan focused on proton exchange membrane fuel cells (PEMFC) for hydrogen electrification, particularly suitable for commercial vehicle applications requiring minimal hydrogen infrastructure support, such as taxis, buses, and logistics vehicles. In 2023, Qusay Hassan studied the utilization of hydrogen as

an energy carrier, noting its advantages in high energy content and clean combustion but also recognizing technical challenges in storage due to its low density and high reactivity. Against this backdrop, this paper investigates performance optimization and sustainable development of hydrogen-based new energy vehicle systems, contributing significantly to both theory and practical applications.

2. STRUCTURE OF THE ENERGY SYSTEM OF HYDROGEN-BASED NEW ENERGY VEHICLES

When discussing hydrogen-based new energy vehicles, we must not only consider the appearance and performance of the vehicles, but also pay attention to the structure and operational principles of their energy systems. These systems constitute the core of hydrogen energy vehicles, determining their performance in terms of environmental protection, efficiency, and sustainability.

The energy system of hydrogen-powered vehicles typically includes key components such as hydrogen storage, fuel cells, electric drive, hydrogen supply, energy management, and thermal management. Firstly, there is the hydrogen storage system, responsible for storing compressed or liquid hydrogen to supply the fuel cell system when needed. Fuel cells have diverse applications: they can serve as power sources for propulsion or electricity generation. They are the core power device of hydrogen-powered vehicles, utilizing stored hydrogen and oxygen to generate electricity and water through chemical reactions, thereby driving the electric motor. In the energy system, the electric drive system plays a crucial role by converting the electricity generated by the fuel cells into power to propel the vehicle. Simultaneously, the hydrogen supply system is responsible for transporting hydrogen to the fuel cell system, regulating and processing its pressure. The energy management system monitors and controls the operational status of various components to ensure efficient energy utilization and stable system operation. Additionally, thermal management is another indispensable part, controlling the temperature of fuel cells and other critical components to ensure they operate within the appropriate temperature range. Finally, the auxiliary power system provides additional electricity to meet the needs of the vehicle's electronic devices and other energy requirements[1].

3. KEY TECHNOLOGIES OF HYDROGEN FUEL CELLS

3.1. Electrode Plate Material

Technology In research on hydrogen-based vehicles, electrode plate material technology is crucial. Choosing appropriate materials, surface treatments, designing micro-nano structures, adding conductive agents, and other methods can effectively enhance the electrochemical activity and stability of electrodes, thereby improving the efficiency and cycle life of fuel cell systems. Additionally, environmental friendliness is also a consideration, striving for more environmentally friendly and sustainable fabrication methods. Continuous optimization of electrode plate material technology promotes the development and application of hydrogen energy vehicles.

One of the most promising methods for producing high-purity hydrogen (H₂) is electrolytic water splitting driven by renewable energy sources such as solar, wind, and hydroelectric power, which has garnered significant attention over the past decade [2]. However, the electrolytic water splitting process is severely affected by slow electrode reaction kinetics, especially the four-electron oxygen evolution reaction on the anode side, leading to high reaction overpotentials. Currently, emerging hybrid electrochemical water splitting strategies integrate thermodynamically favorable electro-oxidation reactions with hydrogen evolution reactions on the cathode, providing new opportunities for efficient H₂ production[2].

To achieve efficient and economical hybrid water splitting for large-scale practical H₂ production, ongoing efforts focus on developing alternative anode oxidation reactions and cutting-edge electrocatalysts.

3.2. Proton Exchange Membrane (PEM) Technology

Proton exchange membrane (PEM) technology is one of the key technologies in the field of hydrogen-powered vehicles. This specialized membrane plays a crucial role in fuel cell systems.

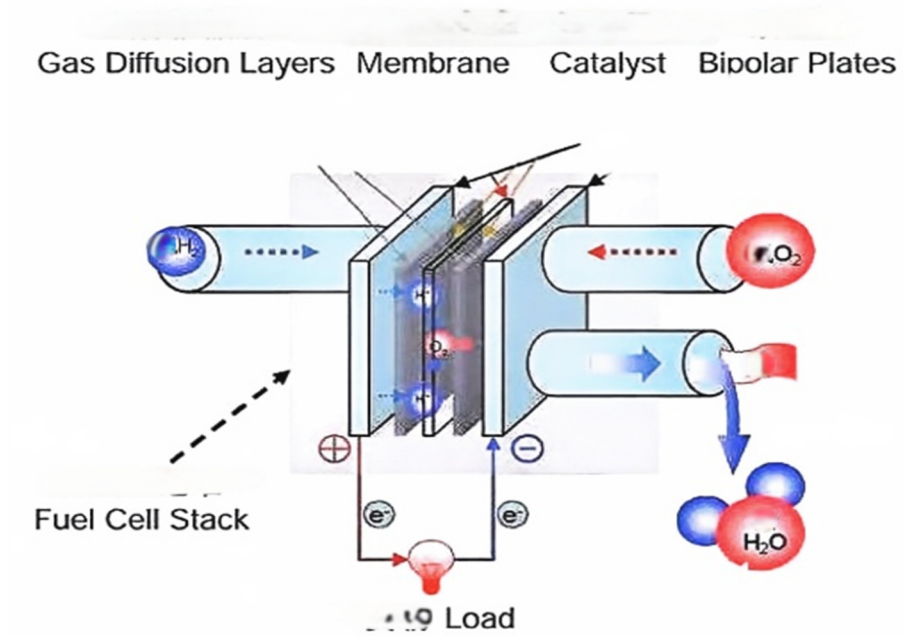


Figure 1. Proton Exchange Membrane (PEM) basic principle diagram

The functions of the proton exchange membrane include separating hydrogen and oxygen while conducting protons to complete electrochemical reactions. The diagram below illustrates the basic principle of a proton exchange membrane. In hydrogen-powered vehicles, PEM technology has multiple applications: Its primary role is to ensure the safe operation of fuel cell systems by effectively isolating hydrogen and oxygen to prevent safety issues arising from their mixing. Additionally, high-quality proton exchange membranes enhance the efficiency and stability of fuel cell systems, extending their operational lifespan.

Furthermore, PEM technology plays a significant role in hydrogen storage for hydrogen-powered vehicles. It safely transports hydrogen to the fuel cells, ensuring stable vehicle operation.

Continuous optimization of PEM technology also contributes to improving the electrochemical performance of fuel cell systems. By selecting high-quality materials, employing rational structural design, and optimizing catalysts, proton conductivity can be enhanced, resistance reduced, and membrane chemical resistance strengthened, thereby improving energy conversion efficiency[2].

In summary, PEM technology is crucial for the development of hydrogen-powered vehicles. It drives the adoption of hydrogen energy vehicles and promotes the development and enhancement of hydrogen energy infrastructure.

3.3. Hydrogen Fuel Cell Technology's Overall Optimization Involves Several Key Aspects

First, optimizing electrochemical reactions is crucial. Improving catalyst design and material selection can enhance the efficiency of electrochemical reactions between hydrogen and oxygen, thereby increasing the overall energy conversion efficiency of the system. Additionally, optimizing the electrode and electrolyte interfaces can reduce resistance and enhance proton conductivity, further improving system performance.

Secondly, effective thermal management is critical. Efficient thermal management can enhance system stability and safety, avoiding performance degradation or safety hazards caused by excessively high or low temperatures. By optimizing heat dissipation design, introducing heat recovery systems, and selecting materials with good thermal stability, the efficiency of system thermal management can be effectively improved[4].

Material selection and design are also crucial aspects of overall optimization. Choosing materials that are resistant to high temperatures and chemical corrosion can improve system stability and durability. Additionally, consideration should be given to the renewability and environmental friendliness of materials to ensure sustainability throughout the system's lifecycle.

Smart and integrated systems are key to optimization. By introducing advanced control systems and intelligent sensing technologies, real-time monitoring and adjustment of system operating conditions can be achieved, thereby enhancing system stability and performance. Furthermore, integrated design can simplify system structure, reduce energy losses, and minimize the risk of component failures, thereby improving overall efficiency and reliability of the system.

In summary, through optimization of electrochemical reactions, effective thermal management, appropriate material selection and design, and integration of smart systems, the performance, stability, and sustainability of hydrogen fuel cell systems can be significantly enhanced, promoting their widespread application and development in the future energy sector.

4. CHALLENGES FACING HYDROGEN FUEL CELLS

4.1. Hydrogen Production, Transport, and Storage

Hydrogen Production:

Hydrogen gas can be produced through various methods, including natural gas steam reforming, water electrolysis, biomass gasification, and solar-powered photoelectrolysis. Among these, water electrolysis is an environmentally friendly and renewable method that uses electricity to split water into hydrogen and oxygen. Additionally, solar-powered photoelectrolysis is a promising hydrogen production technology that utilizes solar energy to drive photoelectrochemical catalysts to split water into hydrogen and oxygen.

Looking at the issues in the development of hydrogen energy and fuel cells, in terms of hydrogen production costs, China's focus is on "green hydrogen" primarily based on renewable energy sources. The reason for emphasizing green hydrogen is that China has overly relied on proton exchange membrane fuel cells. Proton exchange membrane fuel cells operate at low temperatures and require high purity hydrogen, typically sourced from electrolyzed water.

Hydrogen production technologies and their maturity and environmental performance comparison

The table below compares the maturity and environmental performance of different hydrogen production technologies. It is evident that water electrolysis technology is relatively mature, whereas more optimized methods such as photoelectrolysis of water and biomass hydrogen production are still in the basic research stage.

Table 1. Hydrogen production technologies and their maturity and environmental performance comparison

hydrogen production technologies	technological maturity	cost-effectiveness	low-carbon environmental performance
Coal-to-hydrogen	TRL9	6—10	11—25
Natural gas reforming	TRL9	9—18	8—16
Coal-to-hydrogen with CCS	TRL5-7	12—16	2—7
Natural gas reforming with CCS	TRL5-7		1—6
Industrial by-product hydrogen production	TRL9	10—16	
Abandoned wind/solar power electrolysis	TRL9	18—23	1—3
Biomass-to-hydrogen	TRL9		—45

Hydrogen Energy Transport: Hydrogen can be transported using various methods, including compressed hydrogen, liquefied hydrogen, and hydrogen carriers in the form of compounds. Compressed hydrogen is one of the most common methods currently used, where hydrogen is compressed into high-pressure tanks and then transported via pipelines or cylinders. Liquefied hydrogen involves cooling hydrogen to extremely low temperatures to liquefy it, thereby increasing its storage density, which is suitable for long-distance transportation. Additionally, hydrogen carriers such as ammonia or methane are also used for storing and transporting hydrogen energy[5].

Hydrogen Energy Storage: Storage technology for hydrogen is a critical challenge in the development of hydrogen energy. Current major hydrogen storage technologies include compressed hydrogen storage, liquefied hydrogen storage, adsorption storage, and chemical storage. Compressed hydrogen storage involves compressing hydrogen into high-pressure containers, while liquefied hydrogen storage requires cooling hydrogen to extremely low temperatures to maintain it in liquid form. Adsorption storage utilizes specific adsorbents to adsorb hydrogen, whereas chemical storage involves reacting hydrogen with certain compounds to produce storable hydrides.

4.2. Safety Issues in the Use of Hydrogen

Firstly, the flammability of hydrogen is one of the main safety hazards. Hydrogen has a wide range of explosive limits in air, and its flame is not easily visible. Once leaked, it can easily form combustible mixtures, leading to fires or explosions. The leakage of hydrogen is a critical issue that requires high attention during the use of hydrogen energy. Hydrogen leaks can occur in storage tanks, pipelines, or equipment, especially in high-pressure storage and transportation processes. Released hydrogen not only increases the risk of explosions but can also pose hazards to the surrounding environment and personnel.

In addition, pressure management of hydrogen is also a key focus of safety management. Hydrogen is typically stored and transported under high pressure, necessitating strict control and management of hydrogen pressure to prevent tank or pipeline rupture or leakage due to excessive pressure. Under certain circumstances, hydrogen may also undergo chemical reactions, producing harmful or dangerous compounds. For example, explosive mixtures formed by the reaction of hydrogen with oxygen, or metal hydrides formed by the reaction of hydrogen with metals, can pose safety hazards. Electrostatic discharge can also trigger fires or explosions involving hydrogen. Anti-static measures are required in hydrogen storage and use areas to prevent electrostatic discharge from causing fires or explosions.

Although hydrogen itself is non-toxic to humans, a hydrogen leak may displace oxygen in the air, leading to asphyxiation, or it may form harmful mixtures with other toxic gases. Therefore, it is essential to ensure good ventilation in hydrogen use areas and promptly eliminate hydrogen leaks.

Safety issues in the use of hydrogen energy encompass various aspects, including flammability, leaks, pressure management, chemical reactions, electrostatic discharge, and toxicity. Comprehensive safety management measures are necessary to ensure the safe use of hydrogen energy.

5. SUMMARY

Based on hydrogen, new energy vehicles are an advanced technology, with the hydrogen fuel cell system at its core. Key components of this system include the energy system structure, electrode material technology, proton exchange membrane technology, overall optimization of hydrogen fuel cells, as well as hydrogen production, transportation, and storage. However, as hydrogen energy technology continues to develop and be applied, a series of safety issues must also be given significant attention and resolution.

The energy system structure of new energy vehicles is pivotal to their operation. This involves effectively transporting hydrogen gas to the fuel cell for reaction to generate electricity. Designing a safe and reliable energy system structure is crucial, taking into account hydrogen pressure management, selection of pipeline materials, and system sealing.

In summary, although hydrogen-based new energy vehicle technology holds tremendous development potential, safety issues must be thoroughly addressed during its promotion and application. Only through continuous technological innovation and strict safety management measures can the safety and reliability of hydrogen energy technology be ensured, thereby promoting the sustained and healthy development of the new energy vehicle industry.

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