The Technical and Industrial Challenges Faced by Fuel Cells—A Case Study of PEMFC And SOFC

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Abstract. Fuel cells are a proficient and environmental technology that directly transmutes chemical energy into electrical energy. Within this domain, Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs) are at the forefront of small-scale applications and industrial power generation, respectively. The efficacy and economic feasibility of PEMFCs are contingent upon key components, such as the proton exchange membrane and mass transport layers. Consequently, contemporary research is geared towards the optimization of these components to augment performance while concurrently mitigating costs. Conversely, the operational capacity of SOFCs at elevated temperatures has spurred research efforts aimed at material enhancement and the diversification of applications. These advancements encompass the integration of additives, the exploration of novel membrane fabrication methodologies, and the development of innovative structural designs for fuel cells. Although there have been progressive strides in the realm of hydrogen-powered vehicles and fuel cell power plants, their assimilation into the market has been somewhat languid, with commercialization still facing a myriad of challenges. Notwithstanding these hurdles, it is anticipated that with the ongoing evolution of technology and a concomitant reduction in costs, fuel cells will persist as a pivotal component in the quest for energy cleanliness and efficiency.

Keywords: Fuel cells, Proton Exchange Membrane Fuel Cells, Solid Oxide Fuel Cell Electrolyte, Hydrogen-powered vehicles.

1. Introduction

Fuel cells are a crucial energy conversion technology that directly converts chemical energy into electricity, overcoming the limitations of the Carnot cycle [1,2]. They are widely recognized as a clean and efficient energy solution, in stark contrast to fossil fuels (such as oil, natural gas, and coal) known for their low energy conversion efficiency, limited resources, greenhouse gas emissions, and atmospheric pollution, which pose multiple challenges to the environment and society [3].

In the context of the current societal environment and the carbon emission issue, fossil fuels have become a focal point of regulation. Fuel cell technology offers a higher energy conversion efficiency, produces fewer waste byproducts, and is, therefore, considered a more environmentally friendly and sustainable energy solution, making it a critical direction for future energy solutions [4]. Governments and relevant organizations have introduced numerous requirements to address clean energy and zero carbon emissions, and fuel cells are seen as an effective response to these challenges [5,6].

At present, there are several primary technological pathways for fuel cells, including proton exchange membrane fuel cells (PEMFC) [7], Alkaline fuel cells (AFC) [8], phosphoric acid fuel cells (PAFC) [9], Solid oxide fuel cells (SOFC) [10], and Molten carbonate fuel cells (MCFC) [11]. Among these, PEMFC and SOFC are the most widely used types. PEMFC is primarily used in applications such as cars and small-scale devices, while SOFC is employed in industrial applications, including power stations and factory power supply, representing civilian and industrial use cases, respectively. Therefore, selecting PEMFC and SOFC for research is quite representative. PEMFCs generally operate at lower temperatures and are suitable for mobile applications, such as cars, while SOFCs operate at higher temperatures, making them better suited for industrial and distributed power production. Both types use gaseous fuels as their energy source, with PEMFC primarily using hydrogen and SOFC being compatible with various fuels, such as natural gas and hydrogen.

Currently, these two technologies face certain technical challenges. PEMFCs have durability and lifespan requirements for proton exchange membranes, which are typically made from polymers [12]. In SOFCs, the performance of solid electrolytes, including chemical stability and material thickness, affects the efficiency of the fuel cell. Researchers use thin film fabrication techniques and doping methods to optimize the efficiency [13]. Both types demand high mass transfer performance in the gas diffusion layer, which can be achieved using carbon cloth materials [14].

Both of these technologies have made significant progress in terms of commercialization and industrialization. Hydrogen fuel cell vehicles based on PEMFC technology have been commercialized, with several automakers introducing hydrogen fuel cell models [15]. Simultaneously, companies have launched distributed energy systems based on SOFC technology, providing thermal energy and electricity to data centers, residences, and factories.

Herein, this paper examines the role of fuel cell technology in clean energy solutions, focusing on PEMFC and SOFC. It outlines the advantages and disadvantages of each type, highlighting technical challenges such as the proton exchange membrane, mass transfer layer, and high-temperature materials in SOFCs, and the paper also explores applications like hydrogen fuel cell vehicles and Bloom Energy's SOFC power systems. The future of fuel cells appears promising, with the potential to play an increasingly important role in the field of clean energy, reducing carbon emissions and promoting the widespread adoption of sustainable energy sources.

2. Fuel Cell Technology

2.1. Principles of Fuel Cell Technology

The working principle of fuel cells involves the oxidation-reduction reaction of fuel and oxidant (usually oxygen) in the presence of an electrolyte and a catalyst, converting chemical energy into electrical energy. Typically, fuel cells consist of an anode, a cathode, and an electrolyte, where the anode undergoes oxidation reactions, resulting in the generation of electrons, and the cathode undergoes reduction reactions, leading to electron consumption. Ionic species within the cell migrate through the electrolyte to maintain electrical neutrality. This process creates an electrical potential difference between the anode and cathode, allowing for the generation of electrical current.

In the two selected fuel cell types, the reaction mechanisms at the anode and cathode vary depending on the fuel used, with a notable distinction arising from the differences in the electrolyte structure.

In PEMFC, a proton exchange membrane serves as the electrolyte. This membrane selectively allows protons to pass through, restricting the use of hydrogen as the primary fuel due to its proton-conductive properties. In contrast, SOFCs typically employ solid oxide materials as electrolytes, usually composed of materials such as yttria-stabilized zirconia (YSZ) or other stable oxides [16], which exhibit good oxygen ion conductivity at high temperatures.

2.2. Advantages and Disadvantages of PEMFC and SOFC

SOFC and PEMFC each have their unique advantages and disadvantages, determined by their structure and principles. The need for good oxygen ion conductivity in SOFC necessitates higher operating temperatures, which bring certain limitations. However, it results in high electrochemical efficiency. In contrast, PEMFC has the advantage of not requiring high temperatures, primarily when using hydrogen as fuel, thanks to the characteristics of the proton exchange membrane. As a result, it can be used as a power source for small-scale devices. Below are detailed descriptions of their pros and cons.

Several studies have pointed out the advantages of PEMFC [17]. PEMFC offers a clean and efficient energy source with numerous advantages, including low operating temperatures ranging from 60°C to 100°C, which facilitate quick start-up and flexibility. This makes them ideal for applications with varying power demands, such as electric vehicles. Moreover, their emissions are primarily water vapor, significantly minimizing pollution and greenhouse gas emissions, and they

operate quietly, contributing to low noise pollution. However, PEMFCs are not without their disadvantages. They rely on precious metal catalysts like platinum, which can be expensive, and require a high-purity hydrogen supply to function effectively, which can be a challenge to procure.

As for SOFC, they are highly efficient for large-scale power generation and industrial heating due to their high electrochemical efficiency. Their adaptability to various fuels, including hydrogen, methane, and methanol, offers significant flexibility in fuel choice. Additionally, SOFCs typically have long lifespans, making them ideal for extended operation in industrial applications. However, their high-temperature operating requirement, usually between 800°C and 1,000°C, can result in longer start-up times and complex thermal management needs. The high-temperature operation also poses challenges to material stability, with issues such as thermal expansion matching, thermal stress, and lifespan stability of SOFC materials needing careful consideration.

In summary, PEMFC is suitable for low-temperature and small-scale applications, while SOFC is well-suited for large-scale power generation and industrial applications. Each technology has its unique advantages and limitations, depending on specific application requirements and environmental conditions.

3. Current Technical Challenges in PEMFC and SOFC

3.1. Proton Exchange Membrane (PEM)

The PEM is one of the core components of PEMFC. The commonly used PEM materials are primarily perfluorosulfonic acid membranes, with the main brand being Nafion (Figure 1) [17]. These membranes exhibit high chemical stability, good mechanical stability, and a high level of industrialization.

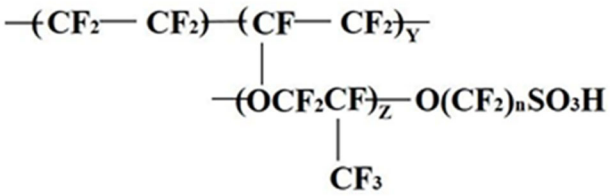


Fig. 1 Molecular Structure of Nafion Membrane [18]

In the membrane structure depicted in the above figure, the sulfonic acid groups (-HSO3) on the side chains can undergo decomposition into protons, which then combine with water to form hydrated protons. Because this polymer membrane is arranged in a network structure, the generated protons can directionally move within the membrane with the assistance of hydrogen bonds produced by hydrated protons, ultimately facilitating the transfer of protons to the cathode.

Different operating conditions have an impact on the performance of PEM. The key to ensuring the efficiency of PEMFC operation is to maintain the working performance of the PEM in an optimal range. Simulations conducted in research have shown that PEM primarily affects the cell's conductivity, which determines the cell's ohmic resistance and, consequently, the cell's output voltage (Figure 2) [18]. The conductivity of the PEM is also closely related to its water content and thickness (Figure 3). When the temperature increases in PEMFC to achieve optimal power, it enhances the water diffusion properties of the PEM, leading to an increase in hydrated protons, thereby increasing the proton migration rate and, in turn, improving the membrane's conductivity.

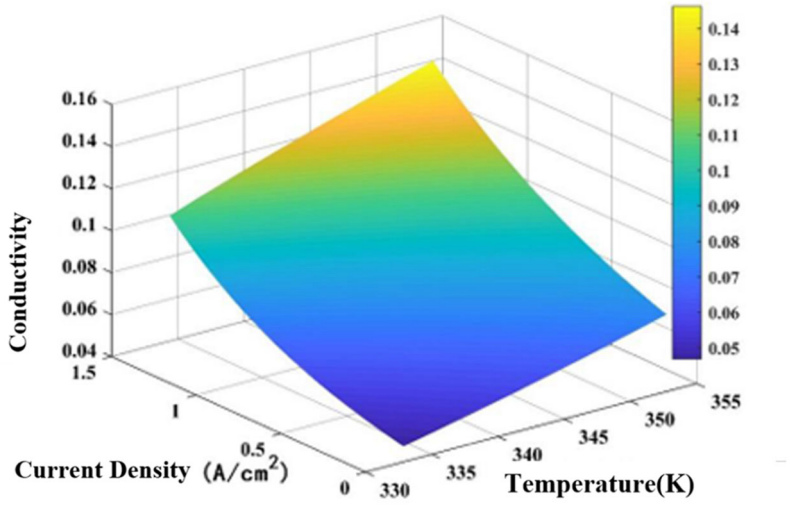


Fig. 2 Relationship Between Temperature, Current Density, and Conductivity [18]

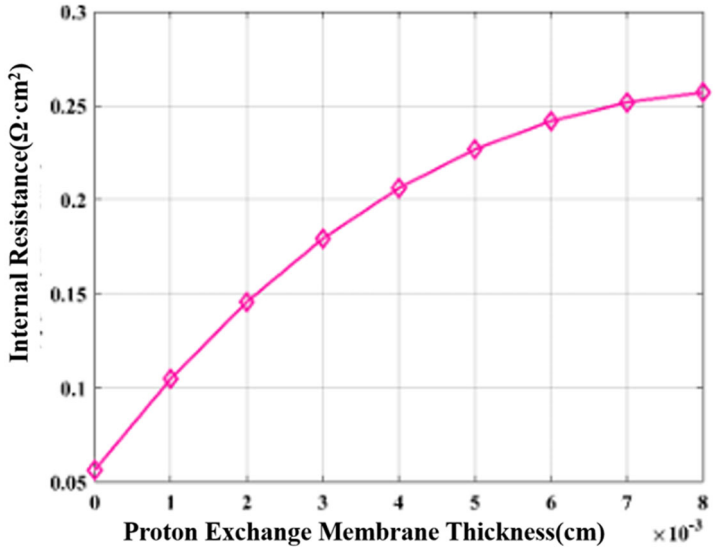


Fig. 3 Relationship Between Proton Exchange Membrane Thickness and Internal Resistance [18]

3.2. Efficiency of PEMFC Mass Transfer Layer

The mass transfer layer is also a critical component of PEMFC. The gas diffusion layer (GDL) is a material layer typically composed of carbon fibers or carbon cloth, possessing a porous structure [19]. Its primary function is to facilitate the distribution and transport of hydrogen gas or fuel gases to the membrane electrode while also aiding in the removal of generated water from the membrane electrode. In PEMFC, hydrogen gas or fuel gases must be transmitted through the GDL to the anode catalytic layer, while the generated water must be transferred from the cathode catalytic layer to the GDL and then discharged from the cell. The performance of PEMFC depends on its reaction rate. To ensure its maximum operational performance, the mass transfer in the mass transfer layer must be guaranteed [19].

Common methods of GDL preparation include spray coating, electrospinning, and coating, all of which require conductive carbon fibers. New carbon materials such as carbon nanotubes and graphene have been used as materials for GDL, bringing excellent performance [20], but this has led to the issue of higher costs. GDLs prepared in this manner can account for 40~50% of the cost of the membrane electrode (a five-layer membrane electrode structure, including anode and cathode GDLs, catalytic layers, and the PEM) [21]. Therefore, developing high-performance, low-cost GDLs can enhance the commercial application prospects of PEMFC. Tian et al. utilized biomass to prepare

carbon cloth, using readily available and cost-effective cellulose cloth as the raw material. The resulting biomass carbon cloth exhibited satisfactory porosity and conductivity, meeting the mass transfer and conductivity requirements of GDL without the need for additional conductive carbon fiber materials, thereby reducing costs [22].

The general preparation process is as follows: cellulose cloth (CLC) with a size of 4 cm × 4 cm was used as the raw material. After washing with distilled water, it was dried. The dried biomass cotton cloth was soaked in a FeCl3 soaking solution, subjected to 20 minutes of ultrasonic treatment, and then dried at 80°C to obtain FeCl3-modified cellulose cloth (FeCl3-CLC). Subsequently, FeCl3-CLC was placed in a tube furnace, heated to 1000°C under an ammonia atmosphere, maintained for 30 minutes, and finally, the atmosphere was switched to argon for a 3-hour treatment at 1500°C, resulting in nitrogen-doped iron carbon cloth, the final product [22].

The produced carbon cloth possessed excellent porosity, with a high rate of 76.93%. It demonstrated good drainage efficiency and superior conductivity compared to existing commercial carbon cloth materials.

3.3. Performance of High-Temperature SOFC Materials

In general, oxygen-ion-conducting SOFCs follow the traditional three-layer structure comprising the cathode, electrolyte, and anode. The reactions at the cathode and anode are largely unaffected by temperature, while the electrolyte exhibits the necessary high oxygen ion conductivity only at elevated temperatures [23]. Currently, the most widely used electrolyte material is yttria-stabilized zirconia (YSZ) [24]. Its oxygen-ion conductivity is notably excellent at high temperatures, with the highest ionic conductivity observed at around 1000°C.

However, at high temperatures, the materials commonly employed for the electrodes tend to react with YSZ, leading to the formation of new phases with lower ionic conductivity, resulting in ohmic losses. Therefore, ensuring the required conductivity while reducing the operating temperature of the electrolyte layer can enhance the practicality of SOFCs.

Chauoon et al. utilized thin-film technology to directly deposit YSZ films on porous anode substrates, achieving film thicknesses of approximately 2.12 and 2.93 μm [24]. Their research demonstrated that these thin films maintained a dense structure and still exhibited excellent ionic conductivity. The thin-film fabrication method can lower the operating temperature of the electrolyte material by approximately 100°C while maintaining the highest ionic conductivity.

Another innovative approach transcends the limitations of the traditional three-layer SOFC structure by adopting a single homogeneous layer. This structure is referred to as the "no electrolyte material" design and is further termed as a single-layer fuel cell. In this design, ion-semiconductor materials play multiple roles as the cathode, anode, and electrolyte. This structure eliminates the two-layer interfaces in the conventional three-layer structure, avoiding the potential formation of low ionic conductivity phases due to interface diffusion. It can maintain satisfactory ionic conductivity even at lower temperatures, a realization potentially attributed to specialized ion conduction pathways [24].

4. Application of Fuel Cells

This paper presents a comparative analysis of fuel engines and hybrid engines in terms of fuel efficiency, environmental impact, cost-effectiveness and performance. In terms of fuel efficiency, oil-powered engines running solely on conventional fuels such as petrol or diesel have been the standard for automotive propulsion for decades. However, hybrid engines, which combine ICE and electric propulsion, have shown significant improvements in fuel efficiency. By utilizing electricity in low demand driving conditions, hybrid vehicles can significantly reduce fuel consumption, typically achieving fuel economy figures that are 25% to 50% higher than their conventional counterparts [5]. The environmental impact of these engines also varies greatly. Conventional engines emit large amounts of greenhouse gases and pollutants due to their reliance on fossil fuels [5]. In contrast, hybrid engines reduce emissions by supplementing or replacing fuel combustion with electricity [5]. This

reduction in emissions is consistent with global efforts to mitigate climate change and reduce air pollution, making hybrid technology a more environmentally friendly option [5].

4.1. Hydrogen Fuel Cell Vehicles

Hydrogen fuel cell vehicles are a type of electric vehicle that utilizes hydrogen as a fuel source, characterized by zero emissions, emitting only water vapor. While hydrogen fuel cell vehicles hold tremendous potential in sustainable transportation, they face several challenges during their development [25].

However, establishing the infrastructure for hydrogen fuel cell vehicles remains a challenge, encompassing hydrogen production, storage, and distribution systems. Moreover, these vehicles still have relatively high costs and lower energy efficiency compared to battery electric vehicles, which presents certain disadvantages. To achieve genuine environmental benefits, the sustainable production and storage of hydrogen must be addressed, posing technological and infrastructural challenges. Critics remain skeptical about the sustainability of hydrogen production [25]. Despite the challenges, hydrogen fuel cell vehicles have achieved some success in specific applications such as commercial vehicles and long-distance transportation. However, their market adoption rate has been relatively slow, requiring further development and promotion. Although signs of industrialization and commercialization have emerged, it will take time for full realization [26, 27].

4.2. Commercial Applications of Fuel Cells

Bloom Energy is a company that provides distributed power generation and hydrogen production using solid oxide fuel cell (SOFC) technology, featuring high efficiency, environmental friendliness, low noise, and reliability.

Bloom Energy's fuel cell technology offers reliable, sustainable, and efficient power solutions for various sectors, including data centers, industrial applications, commercial facilities, and residential settings. Bloom Energy's primary product is the Energy Server, a distributed energy system based on solid oxide fuel cell technology. This system can be customized according to the energy needs of different customers.

However, it is worth noting that reports have raised concerns about Bloom Energy's profitability. Their electricity production is relatively costly, their operation temperature is high, and installation expenses are relatively expensive. As a result, market acceptance may be limited [28].

5. Conclusion

Fuel cells represent a crucial energy conversion technology that directly converts chemical energy into electrical energy, offering a more efficient and cleaner alternative to traditional energy utilization methods. PEMFCs and SOFCs are, respectively, at the forefront of small-scale applications and industrial power generation. Despite their advantages, several challenges persist in their technological and industrial application.

In PEMFCs, both the PEM and the GDL serve as core components, with their efficiency and cost significantly impacting the development of PEMFCs. Typically, PEMs are constructed using perfluorosulfonic acid membranes, which exhibit different properties under varying conditions. Maintaining their operation in optimal conditions is advantageous for sustaining their performance, enhancing durability, and extending the lifespan of the fuel cells. GDL materials, often composed of carbon fabric, can be relatively expensive when using carbon fiber materials. Some innovative research has explored the use of biomass materials to create low-cost biomass carbon fabric.

For SOFCs, the high operating temperatures constrain both materials and applications. Consequently, research efforts have focused on three primary directions: 1) Utilizing dopants to synthesize electrolyte materials with enhanced performance to ensure more reliable high-temperature operation, despite the risk of low ionic conductivity phases forming. 2) Employing thin-film deposition techniques to reduce electrolyte thickness while maintaining performance and lowering

operating temperatures. 3) Developing novel three-in-one structure fuel cells, known as electrolyte-free fuel cells or single-layer fuel cells, employing homogeneous ion-semiconductor materials to serve as the electrolyte, cathode, and anode. While the specific mechanisms remain under investigation, these approaches aim to overcome the limitations of traditional three-layer SOFC structures.

In terms of industrialization for both types of fuel cells, hydrogen fuel cell vehicles and fuel cell power stations serve as excellent examples. While hydrogen fuel cell vehicles have gained some market share, their adoption rates have been relatively slow. Bloom Energy's SOFC power station systems have already been serving numerous customers; however, they still face commercial challenges.

The development of fuel cells is currently experiencing rapid growth, driven by the ongoing pursuit of clean energy and sustainability. Although technological and industrial challenges persist, improvements and cost reductions hold the promise of widespread applications in various fields.

References

[1] Stambouli A B, Traversa E J R. Renewable and Sustainable Energy Reviews, Coastal and Ocean, 2022, 6(5): 433-455

[2] Al-Hamed K H M, Dincer I. Development and optimization of a novel solid oxide fuel cell-engine powering system for cleaner locomotives. Applied Thermal Engineering, 2021, 183: 116150.

[3] Yang Z M. Research on the total combustible amount of fossil energy to achieve the environmental protection goals of the Paris Agreement. Environmental Science & Technology (10036504), 2020, 43(9).

[4] Xu H H, Shao G P, E C L, et al. Research on the future energy system and the practical path of energy transformation in China. Electric Power Technology, 2023, 44(04): 484-491.

[5] Chen S, Zhang J C, Wei Z N, et al. Planning and operation of the electricity-gas-hydrogen integrated energy system for energy transformation. Automation of Electric Power Systems, Retrieved from: http://kns.cnki.net/kcms/detail/32.1180.TP.20230725.1525.006.html.

[6] Ge J J. Preface to the special issue, Hydrogen Energy and Fuel Cells – Hydrogen's contribution to achieving the dual carbon goals. Applied Chemistry, 2023, 40(08): 1061-1062.

[7] Tong X, Xiong Z, Gao X Y, et al. Research status and development of proton exchange membrane fuel cells. Bulletin of the Chinese Ceramic Society, 2022, 41(09): 3243-3258.

[8] Cheng D X. Preparation and performance study of a novel imidazolium anion exchange membrane for alkaline fuel cell. Beijing University of Chemical Technology, 2021.

[9] Guo X R, Guo Y M, Luo F, et al. Analysis of energy efficiency, exergy and ecological characteristics of phosphoric acid fuel cells. Power Generation Technology, 2022, 43(1): 73.

[10] Hu L, Yang Z B, Xiong X Y, et al. Research on the development strategy of solid oxide fuel cell industry in China. Chinese Journal of Engineering Science, 2022, 24(03): 118-126

[11] Li C, Wang T, Ren Y J, et al. Cathode dissolution and protection in molten carbonate fuel cells. Energy Storage Science and Technology, 2023, 12(08): 2444-2456.

[12] Li Z X, Geng Z Y, Li Y F, et al. Review of the current development of key materials for proton exchange membrane fuel cells. Commercial Vehicles, 2023(04): 93-95.

[13] Zhuo Y. Preparation and performance study of M_xO_y-8YSZ (M=Ni, Fe, Zn) solid oxide fuel cell electrolyte. Jingdezhen Ceramic University, 2023.

[14] Tian Y B, Tian C F, Li S, et al. Preparation of highly conductive biomass carbon cloth and its gas diffusion layer properties for fuel cells. Journal of Inorganic Materials, 1-10

[15] Wan W Z. Caution is needed in the development of domestic new energy vehicles to prevent the "open-concentration" strategy of foreign companies - taking the patent layout of Toyota Motor Corporation of Japan as an example. Coastal Enterprises and Technology, 2020(04): 25-31.

[16] Mao X P, Li J W, Fang D Y, et al. Current status of development of materials for solid oxide fuel cells. China Ceramics, 2023, 59(07): 10-20.

[17] Fang Y, Zhang T. A review of dynamic response research on proton exchange membrane fuel cells. Power System Technology, 2013, 37(10): 1875-1876.

[18] Wei C Q, Wu Z F. Influence of different parameters on the output characteristics of proton exchange membrane fuel cells. Modern Manufacturing Engineering, 2021(04): 62-67.

[19] Ma Y. Experimental and modeling study on the diffusion layer of proton exchange membrane fuel cells. Beijing Jiaotong University, 2010.

[20] Li T Y. Preparation and performance study of the gas diffusion layer of proton exchange membrane fuel cells. Beijing University of Chemical Technology, 2021.

[21] Zhao H, Kwak J H, Zhang Z C, et al. Studying cellulose fiber structure by SEM, XRD, NMR, and acid hydrolysis. Carbohydrate Polymers, 2007, 68(2): 235.

[22] Tian Y B, Tian C F, Li S, et al. Preparation of highly conductive biomass carbon cloth and its gas diffusion layer properties for fuel cells. Journal of Inorganic Materials, 1-10

[23] Fergus J W. Electrolytes for solid oxide fuel cells. Journal of power sources, 2006, 162(1): 30-40.

[24] Sun Y, Chen H F, Yang J, et al. Current status of solid oxide fuel cell electrolyte development. Progress in Materials Science of China, 2023, 42(05): 421-430.

[25] Latif M, Frost R, Wayen S. The Future of Hydrogen Vehicles. Climate and Energy, 2023, 40(2).

[26] Wang R, Liu K. Current development of hydrogen energy vehicles at home and abroad and thoughts on the future development of China's hydrogen energy industry. Environmental and Sustainable Development, 2022, 47(03): 44-52.

[27] Yu L Y. Multiple factors help reduce costs – China's hydrogen energy vehicle industry is on the verge of large-scale development. Shanghai Securities News, 2022-08-30(006).

[28] Singh A, Ghuman J S, Kumar R. Bloom Energy for producing electricity. International Journal of Power System Operation and Energy Management, 2014, 4(3).