

Key Technologies of Automotive Fuel Cells and Their Comparison with Pure Electric Batteries

Junzhe Lei^{1*}

¹School of Mechanical Engineering, Xi'an University of Architecture and Technology, Xian, Shanxi, 710000, China

Abstract. Climate change is pressing issue in the contemporary global economy, exacerbated by unsustainable development practices that adversely impact both human populations and ecosystems. Alongside these environmental challenges, the world faces an unprecedented energy crisis characterized by increasing global demand and the depletion of fossil fuel reserves, necessitating a shift towards sustainable alternatives. This paper conducts a comparative analysis of fuel cell vehicles (FCVs) and pure electric vehicles (EVs), focusing on their emission reduction and energy utilization capabilities. FCVs, using electrochemical reactions between hydrogen and oxygen, offer high energy conversion efficiency and quick refueling but face challenges related to high production costs and limited hydrogen infrastructure. EVs, powered by lithium-ion batteries, provide high efficiency, ease of charging, and strong market acceptance, though integrating solid-state lithium batteries presents technical challenges. The paper also explores advancements in catalyst and membrane technologies for FCVs, and battery performance improvements for EVs. Economic comparisons highlight the current cost advantages of EVs, while future sustainability will depend on advancements in materials, manufacturing, and recycling processes. This research aims to inform the development of next-generation transportation technologies that address both environmental and energy challenges.

1 Introduction

Climate change and global warming, exacerbated by unsustainable development, affect billions and contribute to a global energy crisis, underscoring the need for a shift towards sustainable energy alternatives [1]. The integration of green energy and the circular economy in natural resource markets is essential for achieving sustainable growth and responsible environmental management [2]. Considering well-to-wheel emissions, FCVs can achieve lower overall greenhouse gas emissions compared to ICEVs, especially with renewable hydrogen sources. Additionally, FCVs have higher energy conversion efficiencies (40-60%) compared to internal combustion engines (20-30%). Hydrogen can be produced from diverse sources, including renewables, contributing to a more sustainable energy mix. On the other hand, EVs produce no tailpipe emissions, significantly improving local air quality. They also

* Corresponding author: ljz0106@xauat.edu.cn

have lower greenhouse gas emissions than ICEVs, particularly in regions with low-carbon or renewable-heavy electricity grids. EVs' electric motors are highly efficient, converting over 90% of electrical energy into motion, and regenerative braking systems further enhance efficiency by capturing and converting kinetic energy into electricity.

Both FCVs and EVs offer substantial emission reductions compared to ICEVs. FCVs may have an edge in range and refueling times if hydrogen infrastructure advances, while EVs benefit from existing electric infrastructure and battery advancements. FCVs and EVs both significantly improve energy utilization compared to ICEVs, with FCVs efficiently converting hydrogen into motion, and EVs leveraging the high efficiency of electric motors and regenerative braking. However, integrating solid-state lithium batteries (SSLBs) into EVs involves ensuring compatibility of battery components, designing efficient battery packs, and integrating SSLBs with vehicle electrical systems. Overcoming these challenges requires advanced materials, battery management systems, and engineering solutions.

The future of SSLBs in EVs is promising, with potential breakthroughs in solid electrolyte materials, electrode design, and interface engineering. Innovations such as all-solid-state designs and solid-state lithium-metal anodes may enhance energy density, power density, cycle life, and safety. As technology and manufacturing processes mature, SSLBs are poised to play a crucial role in sustainable transportation. Developing high-performance SSLBs is crucial for the widespread adoption of EVs. Continued research and development will further integrate SSLBs into EVs, contributing to sustainable transportation solutions.

The primary objective of this paper is to conduct a comparative analysis of fuel cell vehicles (FCVs) and pure electric vehicles (EVs) to understand their advantages and challenges in emission reduction and energy utilization. The paper explores technological advancements and integration challenges, particularly focusing on the role of solid-state lithium batteries (SSLBs) in enhancing EV performance and sustainability. Ultimately, the paper proposes solutions and future prospects for these technologies to contribute to sustainable transportation and address the global energy and environmental crises.

2 Research on automotive fuel cell technology

2.1 Catalysts

Noble metals, combined with transition metals in bimetallic nanoparticles, enhance catalytic CO₂ hydrogenation by maintaining unique properties and improving reducibility and dispersion, thus reducing costs and preventing carbon deposition and agglomeration [3].

Proton exchange membrane fuel cells (PEMFCs) efficiently convert chemical energy to electrical energy using a platinum (Pt)-based catalyst on carbon supports, though Pt's high cost and centralized reserves pose commercialization and security challenges. The development of non-precious metal catalysts (NPMCs) is therefore critical to reducing reliance on Pt and enhancing the scalability and economic viability of PEMFCs, particularly those based on transition metals like iron, cobalt, and nickel, which are gaining attention. These NPMCs often incorporate nitrogen-doped carbon supports to enhance stability and conductivity.

2.2 Membrane

High-temperature proton exchange membrane fuel cells (HT-PEMFCs), operating between 120 °C and 250 °C, address traditional PEMFC challenges such as low electrode kinetics and complex water management by utilizing advanced materials like phosphoric acid-doped polybenzimidazole (PA-PBI) and composite membranes enhanced with ionic liquids for

better flexibility and thermal stability. To further improve proton conductivity and meet DOE targets, these systems incorporate functionalized nanoclays and dual interfacial proton-conducting pathways within polymer matrices, offering innovative solutions to the conductivity challenges at lower temperatures and varying humidities [4].

Recent advancements in ion exchange membrane technologies have achieved significant research results, especially as electrically driven processes replace carbon-driven ones. AEMs play a crucial role in water electrolysis, batteries, electrometallurgy, electrochemical synthesis, and CO₂ capture. However, AEMs still exhibit shortcomings such as low electrochemical performance, OH⁻ conductivity, and chemical stability. Specific issues include low selectivity, insufficient salt resistance, poor chemical corrosion resistance, and high resistance. Despite these challenges, AEMs hold great potential for future applications: efficient desalination and water quality improvement in water treatment, enhanced metal ion leaching and separation in metallurgy, and impurity removal in pharmaceutical processes. Future developments aim to create more efficient, multifunctional AEMs and integrate them with other separation technologies to expand applications, improve processing efficiency, and reduce costs.

Membrane materials are critical for the efficiency and lifespan of fuel cells, with several key attributes essential for optimal performance. High ionic conductivity facilitates rapid ion transport, enhancing power density and responsiveness while reducing energy losses. Additionally, sufficient mechanical strength and stability are required to withstand operational stresses, ensuring long-term stability without deformation or rupture. Chemical stability is also crucial, as it prevents degradation from acidic or alkaline conditions, ensuring long-term performance and reliability. Furthermore, appropriate permeability and barrier properties are necessary to prevent unintended gas or liquid permeation, maintaining reaction efficiency and safety.

Cost and manufacturing feasibility are equally important, as membrane materials must be cost-effective and feasible for large-scale production, balancing performance with economic considerations. In summary, as the core component of fuel cells, membrane materials determine the efficiency, stability, and lifespan of the cells. Future research will focus on developing advanced, economical, and stable membrane materials to advance fuel cell technology for widespread commercial applications.

2.3 Fluid flow field

PEMFCs are favored in mobility applications for their quick start-up, high power density, and dynamic operation capabilities, but they face challenges such as uneven reactant distribution and inadequate heat and water management [5]. The performance of PEMFCs heavily relies on the design of the bipolar plate (BPP) which forms the flow field, influencing reactant gas distribution, current generation, and waste removal while minimizing pressure drops across channels with various configurations like serpentine, interdigitated, and parallel patterns [6-8].

Flow field design significantly impacts fuel cell performance through various factors. Efficiently designed flow channels enhance mass transport by ensuring a steady supply of reactants (hydrogen and oxygen) to the electrode surfaces, minimizing concentration gradients that hinder reaction rates. Effective flow field designs also minimize pressure drop, maintaining optimal flow rates without excessive pumping power, thus improving energy efficiency. Proper water management is essential for maintaining ionic conductivity within the electrolyte and preventing electrode surface flooding or drying. Flow field designs that facilitate efficient water removal prevent performance degradation due to water buildup.

Uniform current density distribution across the electrode surfaces maximizes power output and minimizes localized degradation, enhancing cell durability and efficiency.

Optimized flow fields also enhance heat dissipation and regulate temperature distribution, preventing thermal gradients that can degrade performance or damage components. Improved flow field designs reduce degradation mechanisms such as catalyst poisoning, carbon deposition, and membrane degradation, leading to more reliable long-term operation. Tailoring flow field designs to specific applications, such as automotive, stationary power, and portable devices, optimizes overall system performance based on power density requirements, space constraints, and operating conditions.

In summary, flow field design is critical in determining the efficiency, reliability, and longevity of fuel cell systems. Advances in optimizing flow field configurations are instrumental in advancing fuel cell technology towards broader commercialization and practical applications.[5] Advanced simulation techniques, including computational fluid dynamics (CFD), multiphysics field coupling simulation, and optimization algorithms, are widely used to optimize flow field design, improving fluid dynamics performance and system efficiency.

2.4 Cooling technology

2.4.1 Cooling system

Cooling technologies for fuel cells encompass various methods, including liquid cooling, forced air cooling, heat pipe cooling, radiators, and phase change cooling. Each of these technologies has unique advantages and limitations that make them suitable for different applications.

Liquid cooling offers high heat conduction performance, effectively absorbing and transferring heat while enabling precise temperature control through flow management [9]. This method is commonly used in high-power density equipment or applications requiring efficient heat removal, such as computer CPUs, GPUs, and engine cooling. However, liquid cooling systems are complex, requiring a cooling medium and pump for circulation, which introduces risks of leakage and corrosion. Forced air cooling is simpler, as it does not require liquids or pumps, resulting in lower maintenance costs and broad environmental suitability. Its heat dissipation efficiency, however, is generally lower than that of liquid cooling and is significantly affected by ambient temperature and airflow. This method is often used in light-loaded electronic devices, low-power servers, and mobile devices. Heat pipe cooling provides efficient heat transfer with low heat resistance, making it ideal for small spaces without the need for external power. Despite its high cost and limitations related to the length of the heat pipe and the properties of the heat transfer medium, it is used in compact spaces such as laptops, LED lights, and aerospace equipment where efficient heat dissipation is critical [9].

Radiators are characterized by their simple structure, high reliability, and suitability for long-term stable operation. They are widely used in electronic equipment, vehicle engines, and industrial equipment that require substantial heat dissipation. However, radiators are highly dependent on environmental conditions, and their heat conduction performance is generally limited. Phase change cooling absorbs a large amount of latent heat during the phase change process, offering significant heat capacity and temperature stabilization. This method is particularly useful for critical heat dissipation in high-power density equipment, such as peak load heat dissipation in electronic devices and temperature control in space cabins. Nonetheless, its application is limited by the phase transition temperature, and temperature control near the phase transition point can be challenging.

2.4.2 Heat management system

Tian et al. presented an improved Deep Deterministic Policy Gradient (DDPG) algorithm for Energy Management Systems (EMS), integrating Fractional-order Total Active Disturbance Rejection Control (FTADRC) for fuel cell thermal regulation. However, there are still several existing issues of the area. Fuel cells face durability issues during long-term operation, such as material degradation and performance decline. To enhance fuel cell durability, it is essential to develop new materials and technologies. These include improving catalyst activity and stability, optimizing electrode structures, and enhancing corrosion and oxidation resistance. Further, the high production costs of fuel cells limit their scalability for commercial applications. Reducing these costs requires a thorough cost-effectiveness analysis and exploring new production technologies and processes. Seeking cheaper raw materials and improved component designs are also critical approaches to make fuel cells more economically viable. Current technologies face several bottlenecks, including low catalyst activity, challenges in hydrogen storage and distribution, and the complex integration of fuel cell systems. Addressing these challenges involves enhancing catalyst efficiency, optimizing hydrogen handling technologies, and simplifying system designs and integration. Future research should focus on developing new materials, intelligent control systems, and more efficient fuel cell stack designs to overcome these technological limitations.

In summary, advancing fuel cell technology requires addressing issues of durability, cost, and technological bottlenecks through innovative research and development. By improving materials, production processes, and system designs, the scalability and commercial viability of fuel cells can be significantly enhanced [9].

3 Research on battery technology for electric vehicles

Lithium-ion batteries, one of the three dominant types used in EVs alongside Lead-Acid and Nickel Metal Hydride, are favored for their high energy density and long cycle life but require advanced management systems due to risks of thermal runaway. These batteries function through the movement of lithium ions between the anode and cathode via a liquid electrolyte, making them suitable for portable electronics, EVs, and other applications, yet their susceptibility to overheating necessitates careful monitoring of temperature and voltage. Solid-state batteries use a solid rather than liquid electrolyte, offering advantages such as enhanced safety and stability, reduced flammability, and the potential for higher energy density and longer life cycles compared to traditional lithium-ion batteries. Despite their higher production costs and complex manufacturing processes that have hindered widespread adoption, ongoing research aims to refine these technologies and establish solid-state batteries as a viable option for future energy storage solutions [10].

Energy density and power density are pivotal metrics that influence a battery's performance, with energy density determining the battery's runtime and application range, such as in electric vehicles, and power density affecting its ability to meet high-demand scenarios like vehicle acceleration. Lithium-ion batteries, with energy densities between 150 to 250 Wh/kg, are optimal for portable electronics and electric vehicles, though their power density may restrict performance in some contexts, whereas solid-state batteries, using solid electrolytes, promise even higher energy densities by enabling the use of high-capacity electrode materials. Additionally, they can achieve better safety and stability, which could enable more aggressive optimization of power density. Several strategies are being explored to enhance both energy and power densities in batteries. For lithium-ion batteries, advancements include the development of high-capacity anode materials such as silicon and the use of advanced cathode materials like nickel-rich layered oxides. Enhancing the electrolyte formulation and employing nanotechnology to create more efficient electrode

structures also contribute to these improvements. For solid-state batteries, the focus is on developing solid electrolytes with high ionic conductivity and stable interfaces between the electrolyte and electrodes. These advancements aim to maximize the energy stored while allowing rapid energy discharge when needed. Several factors influence the cycle life of batteries, including the type of electrode materials used, the nature of the electrolyte, operating temperatures, and the depth of discharge cycles. For instance, high-capacity materials such as silicon in lithium-ion batteries tend to undergo significant volume changes during cycling, leading to mechanical degradation and reduced cycle life. Similarly, high temperatures can accelerate side reactions within the battery, further diminishing its longevity. Recent research has focused on mitigating the factors that limit battery cycle life. For lithium-ion batteries, strategies include the development of more stable electrode materials that can accommodate volume changes, the use of advanced coatings to protect electrode surfaces, and the incorporation of additives in electrolytes to suppress unwanted side reactions. Solid-state batteries benefit from the inherent stability of solid electrolytes, but ongoing research is aimed at improving the interface stability between the solid electrolyte and electrodes to prevent degradation over time. Additionally, advanced diagnostic tools and predictive modeling are being used to understand degradation mechanisms better and to design batteries that can withstand more cycles without significant performance loss.

In summary, enhancing the energy density, power density, and cycle life of batteries involves a combination of material innovations, advanced manufacturing techniques, and comprehensive understanding of battery chemistry and physics. These improvements are crucial for the development of next-generation batteries that meet the growing demands of various high-performance applications.

4 Comparison of fuel cell and battery technologies

4.1 Technical comparison

4.1.1 Working principles of fuel cells and pure electric batteries

Fuel cells operate through electrochemical reactions, using hydrogen (or other fuels like methanol and ethanol) and oxygen from the air to generate electricity and water. The energy conversion efficiency of fuel cells ranges from 40% to 60%, depending on the type of fuel and cell technology used [11]. Hydrogen fuel cells, which react hydrogen with oxygen, are particularly efficient and environmentally friendly, producing only water as a byproduct. Fuel cells offer stable power output, making them suitable for long-distance driving and high-speed operations. They also allow for quick refueling, similar to traditional fuel vehicles, and have strong cold-start capabilities in low-temperature environments.[11]

Pure electric vehicles (EVs) use lithium-ion batteries and other energy storage devices to store electrical energy, which is then converted into electrical power to drive the electric motor. The energy conversion efficiency of lithium-ion batteries is typically between 80% and 90%, resulting in minimal energy loss from the power grid to the vehicle [12]. EVs are easy to charge, with extensive infrastructure available, making them ideal for urban and short-distance driving. They offer excellent acceleration performance, fast instant torque response, and high energy recovery efficiency through systems like regenerative braking. Additionally, EVs provide a quieter and more comfortable driving experience compared to fuel-cell vehicles [12].

Fuel cells are more efficient than traditional internal combustion engines, with almost no exhaust emissions, contributing to better environmental protection. They provide stable power output suitable for long-distance driving and rapid hydrogen refueling, similar to the

convenience of traditional fueling. Fuel cells also perform well in cold starts, offering advantages over battery electric vehicles in low-temperature conditions. Lithium-ion batteries used in EVs have high energy conversion efficiency, easy charging, and extensive infrastructure. They excel in urban and high-density traffic environments due to their excellent acceleration performance and fast torque response. Energy recovery systems in EVs enhance efficiency, particularly during braking and slow driving. EVs are also quieter, providing a more comfortable driving experience.

4.1.2 Working principles of fuel cells and pure electric batteries

Fuel cell systems face durability challenges and high maintenance costs, particularly for hydrogen supply and storage facilities. Despite recent improvements, the durability and cost of fuel cell systems remain significant hurdles. The charging cycle life of lithium-ion batteries ranges from thousands to tens of thousands of cycles, depending on usage and charging management. Technological advancements continue to improve battery life and energy density, with future developments expected to yield batteries with longer life spans and higher efficiency. The degradation rate of fuel cells is shown in Fig. 1.

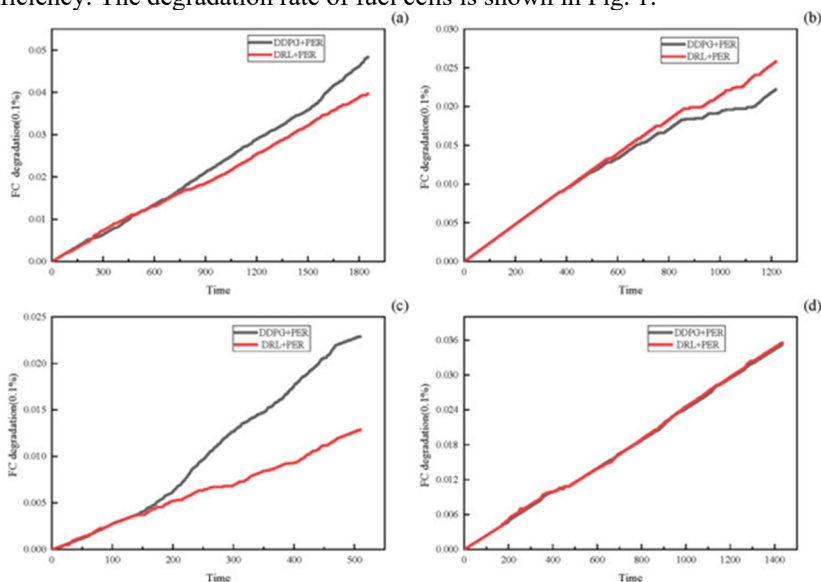


Fig. 1. Cumulative degradation rate of fuel cell for DDPG+PER and DRL+PER algorithms under four driving cycles: (a) FTP75; (b) NEDC; (c) US06-2; (d) LA92-2 [12]

In conclusion, both fuel cells and pure electric batteries offer unique advantages and face specific challenges. Fuel cells provide stable power and quick refueling, making them suitable for long-distance travel, while pure electric batteries excel in energy efficiency, acceleration, and urban driving conditions. Ongoing advancements in both technologies aim to address current limitations and enhance their overall performance and viability for widespread adoption in the transportation sector.

4.2 Economic comparison

The production costs of fuel cells and pure electric batteries differ significantly. Fuel cells, particularly those using platinum-based catalysts, are expensive to produce due to the high cost of materials and complex manufacturing processes. The cost of hydrogen production and storage infrastructure further adds to the overall expense. In contrast, lithium-ion

batteries, while still costly, benefit from economies of scale as the technology matures and manufacturing processes become more efficient. The materials used in lithium-ion batteries, such as lithium, cobalt, and nickel, are also relatively expensive, but ongoing research aims to reduce reliance on these critical materials and lower production costs.

In terms of operational costs, pure electric vehicles (EVs) generally have an advantage over FCVs. The cost of electricity for charging EVs is typically lower than the cost of hydrogen fuel. Additionally, EVs have fewer moving parts and require less maintenance compared to FCVs, which need regular maintenance of hydrogen supply and storage systems. However, FCVs may have an edge in specific scenarios where rapid refueling and longer driving ranges are critical, potentially reducing downtime and operational inefficiencies in certain applications.

Market acceptance of EVs is currently higher than that of FCVs. The extensive charging infrastructure and the availability of various EV models cater to a broad consumer base, from urban commuters to long-distance travelers. Government incentives and growing environmental awareness further boost EV adoption. FCVs, while promising in terms of performance and environmental benefits, face challenges due to the limited hydrogen refueling infrastructure and higher initial costs. However, ongoing investments in hydrogen production and distribution, coupled with technological advancements, may improve the market prospects for FCVs in the future.

Recycling and reuse present distinct challenges and opportunities for both fuel cells and lithium-ion batteries. Lithium-ion batteries can be recycled to recover valuable metals like lithium, cobalt, and nickel, which can be reused in new batteries. However, the recycling process is complex and energy intensive. Efforts are underway to develop more efficient and cost-effective recycling methods. Fuel cells, particularly those with platinum-based catalysts, also offer recycling potential, as platinum can be recovered and reused. The recycling infrastructure for fuel cells is less developed compared to lithium-ion batteries, but advancements in this area could enhance the sustainability and economic viability of fuel cell technology.

In summary, while EVs currently have an economic advantage over FCVs in terms of production and operational costs, the future development of both technologies will depend on advancements in materials, manufacturing processes, and infrastructure. Recycling and reuse strategies will also play a crucial role in improving the sustainability and cost-effectiveness of both fuel cell and lithium-ion battery technologies.

5 Conclusion

In conclusion, both FCVs and pure EVs present viable pathways toward sustainable transportation, each with distinct advantages and challenges. FCVs, with their high energy conversion efficiency and quick refueling capabilities, are well-suited for long-distance travel and high-speed operations, particularly in scenarios where rapid refueling and stable power output are crucial. However, they face significant hurdles in terms of production costs, durability, and the development of hydrogen infrastructure.

On the other hand, EVs offer high energy efficiency, ease of charging, and excellent performance in urban environments. Their established technology, extensive charging infrastructure, and lower operational costs make them more widely accepted in the current market. Despite this, the integration of solid-state lithium batteries (SSLBs) into EVs remains challenging, requiring advances in materials and battery management systems to fully realize their potential.

Economic comparisons reveal that while EVs currently have an advantage in both production and operational costs, the future success of both technologies will rely on ongoing advancements in materials science, manufacturing processes, and infrastructure development.

Additionally, improving recycling and reuse strategies for both fuel cells and lithium-ion batteries will be crucial for enhancing the sustainability and economic viability of these technologies.

Overall, the future of sustainable transportation lies in the continued research and development of both fuel cell and battery technologies, addressing their respective challenges and leveraging their strengths to achieve broader commercialization and practical application.

References

1. E. Dogan, T. Luni, M. T. Majeed, P. Tzeremes. The nexus between global carbon and renewable energy sources: A step towards sustainability. *Journal of Cleaner Production*, 416, 137927 (2023).
2. R-A Corbos, O-I Bunea, D-C Jiroveanu, The effects of the energy crisis on the energy-saving behavior of young people. *Energy Strategy Reviews*, 49, 101184 (2023).
3. C. Wei, H. Ding, Z. Zhanget al. Research progress of bimetallic catalysts for CO₂ hydrogenation to methane. *International Journal of Hydrogen Energy*, 58, 872-91 (2024).
4. H. Kahrman, Y. Akin, Recent studies on proton exchange membrane fuel cell components, review of the literature. *Energy Conversion and Management*, 304, 118244 (2024).
5. K. Lim, C. Kim, R. Park, et al. Enhancing PEMFC performance through orifice-shaped cathode flow field designs: A multiscale, multiphase simulation study on oxygen supply and water removal. *Chemical Engineering Journal*, 475,146147 (2023).
6. J. Hao, T. Hao, Z. Lu, et al. Cross-scale modeling and optimization analysis of the solid oxide fuel cell cogeneration system based on the heat current method. *Energy Conversion and Management*, 280, 116828 (2023).
7. P. Yang, Y. Zhang, C. Yang, et al. Thermodynamic performance comparison of a SOFC system integrated with steam reforming and dry reforming by utilizing different fuels. *Energy Conversion and Management*, 300, 117981 (2024).
8. Q. Yang, T. Zeng, C. Zhang, et al. Modeling and simulation of vehicle integrated thermal management system for a fuel cell hybrid vehicle. *Energy Conversion and Management*, 278, 116745 (2023).
9. M. R. Islam, B. Shabani, G. Rosengarten, et al. The potential of using nanofluids in PEM fuel cell cooling systems: A review. *Renewable and Sustainable Energy Reviews*, 48, 523-39 (2015).
10. F. Mohammadi, M. Saif. A comprehensive overview of electric vehicle batteries market. *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, 3, 100127 (2023).
11. M. Shen. Solid oxide fuel cell-lithium battery hybrid power generation system energy management: A review. *International Journal of Hydrogen Energy*, 46, 32974-94 (2021).
12. J. Wen, D. Zhao, C. Zhang. An overview of electricity powered vehicles: Lithium-ion battery energy storage density and energy conversion efficiency. *Renewable Energy*, 162, 1629-48 (2020).