Research Article

Advancements in Fuel Cell Technology for Electric Vehicles

Mohammad Fikrey Roslan[1], Hamimah Abd Rahman[1,*], Rafidah Abd Karim[2], Siti Hasanah Osman[3]

1 Universiti Tun Hussein Onn Malaysia; fikrey.roslan@gmail.com; 0000-0003-4010-5790
1 Universiti Tun Hussein Onn Malaysia; hamimah@uthm.edu.my; 0000-0001-5258-3656
2 Universiti Teknologi MARA, Kampus Tapah, Malaysia; feida1602@gmail.com; 0000-0001-9147-6191
3 Universiti Kebangsaan Malaysia; hasanahosman17@gmail.com; 0000-0001-9183-6898
* Correspondence: hamimah@uthm.edu.my; 0197512707.

Abstract: *The field of electric vehicles (EVs) has seen significant advancements, particularly in the realm of fuel cell technology. This abstract explores the recent progress in fuel cell technology for EVs, focusing on the improvements in efficiency, durability, and cost-effectiveness. The primary challenge for EVs is to match the convenience and performance of traditional combustion engines while minimizing environmental impact. Battery Electric Vehicles (BEVs) face issues with long charging times and limited range, whereas Fuel Cell Electric Vehicles (FCEVs) have historically been hindered by high costs, low durability, and an underdeveloped hydrogen refueling infrastructure. Recent advancements in fuel cell technology have led to significant improvements in system efficiency, durability, and cost reduction. Innovations in catalysts and membrane electrode assemblies have enhanced the electrochemical conversion efficiency, while novel materials and manufacturing techniques have extended the lifespan and reduced the costs of fuel cells. The enhanced performance of fuel cells has resulted in EVs with longer ranges and refueling times comparable to conventional vehicles. This has a profound impact on the feasibility of EVs for a broader range of applications, including heavy-duty transportation and long-distance travel. The advancements in fuel cell technology have lowered the barriers to commercialization. With increased efficiency and reduced costs, FCEVs are becoming more competitive with both BEVs and traditional vehicles. The growing network of hydrogen refueling stations further supports the commercial viability of FCEVs. The recent advancements in fuel cell technology have addressed critical challenges in the EV industry, offering a solution that combines environmental benefits with performance and convenience. As the technology continues to mature and the infrastructure expands, FCEVs are poised to play a pivotal role in the transition to sustainable transportation, promising a cleaner future with reduced reliance on fossil fuels.*

Keywords: Electric Vehicles (EV); Fuel Cell Electric Vehicles (FCEVs); Battery Electric Vehicles (BEVs).

DOI: 10.5281/zenodo.10406278

1. INTRODUCTION

Fuel Cell Electric Vehicles (FCEVs) utilize hydrogen fuel cells to generate electrical energy, so enabling vehicle propulsion while minimizing the release of detrimental emissions through the exhaust system. Fuel cell electric vehicles (FCEVs) present a viable and sustainable mode of transportation, serving as a potential substitute for conventional internal combustion engines. These vehicles have the advantage of generating solely water vapor and heat as byproducts, thereby minimizing harmful environmental impacts. The significance of this technology lies in its ability to mitigate transportation-related greenhouse gas emissions and reduce reliance on fossil fuels (Grand View Research, 2020).

Fuel cell electric cars (FCEVs) exhibit notable attributes such as elevated energy efficiency and the capacity for swift refuelling, similar to that of traditional automobiles, all the while offering driving ranges that are comparable. According to Thomas (2009), these characteristics render them appropriate for a diverse range of transportation requirements, spanning from individual mobility to demanding industrial applications. The incorporation of Fuel Cell Electric Vehicles (FCEVs) into the automotive industry is increasingly supported by progress in generating hydrogen from renewable energy sources, hence improving the overall sustainability of this technology (Schiebahn et al., 2015).

With the increasing emphasis on reducing carbon emissions in the transportation sector at a global level, Fuel Cell Electric Vehicles (FCEVs) have gained recognition as a crucial element within the range of clean vehicle technologies required to accomplish this objective (Offer et al., 2010).

1.1 Role of FCEVs

The transportation sector's heavy reliance on fossil fuels exacerbates global environmental concerns, including climate change and air pollution. The combustion of these fuels results in the emission of substantial quantities of greenhouse gases (GHGs), with carbon dioxide (CO2) being the primary contributor. This process contributes to the phenomenon of global warming and the degradation of air quality (Jacobson et al., 2005). Fuel Cell Electric Vehicles (FCEVs) have emerged as a prospective resolution to these challenges owing to their ability to produce zero tailpipe emissions and utilize hydrogen as an environmentally friendly fuel source.

Fuel cell electric vehicles (FCEVs) possess the potential to assume a crucial position in the efforts to address climate change by effectively diminishing the carbon emissions associated with the transportation industry. According to Hart et al. (2016), the utilization of renewable energy sources for hydrogen production can result in a significant reduction in lifecycle greenhouse gas (GHG) emissions when fuel cell electric vehicles (FCEVs) are employed, as compared to conventional automobiles. Furthermore, the lack of tailpipe pollutants, such as nitrogen oxides (NOx) and particulate matter (PM), emitted by fuel cell electric vehicles (FCEVs) plays a significant role in enhancing air quality, particularly in metropolitan regions where vehicle emissions pose a significant threat to public health (Alam et al., 2015).

The incorporation of Fuel Cell Electric Vehicles (FCEVs), in conjunction with other forms of renewable energy technologies, is of paramount importance in attaining the objectives outlined by global accords such as the Paris Agreement. According to Schiebahn et al. (2015), the adoption of a hydrogen-based economy can contribute to the establishment of a transportation system that is both sustainable and environmentally benign.

2. OVERVIEW OF FUEL CELL TECHNOLOGY

Fuel cell technology, an essential component of electrochemical energy conversion, possesses a significant historical background that can be traced back to the 19th century. This era witnessed the initial demonstration of the "gas voltaic battery" by Sir William Grove in the year 1839. Fuel cells are a means of energy generation that operates through the chemical reaction between hydrogen and oxygen, resulting in the production of water as the sole waste. This characteristic makes fuel cells a viable and environmentally friendly alternative to power generation methods reliant on combustion (Kordesch & Simader, 1996).

The fundamental concepts underlying the operation of fuel cells pertain to the process of hydrogen dissociation into protons and electrons occurring at the anode. The protons traverse an electrolyte medium towards the cathode, whereas the electrons traverse an external circuit, so producing an electric current. According to Larminie and Dicks (2003), the recombination of electrons with protons and oxygen takes place near the cathode, resulting in the formation of water.

Proton Exchange Membrane Fuel Cells (PEMFCs) have favourable characteristics for implementation in vehicle contexts, owing to their capacity to operate at reduced temperatures, expedited initiation periods, and elevated power output per unit volume. Proton Exchange Membrane Fuel Cells (PEMFCs) employ a solid polymer electrolyte and catalysts based on platinum to attain high levels of energy conversion efficiency (Barbir, 2005).

In contrast, Solid Oxide Fuel Cells (SOFCs) function at elevated temperatures and employ a ceramic electrolyte. Solid oxide fuel cells (SOFCs) have the capability to utilize a diverse range of fuels, which is a characteristic that distinguishes them. They are renowned for their fuel flexibility, long-term stability, and capacity to simultaneously generate heat and power, hence making them well-suited for stationary power applications (Singhal & Kendall, 2003).

2.1 Advantages of fuel cells over conventional internal combustion engines

Fuel cells have numerous advantages in comparison to traditional internal combustion engines (ICEs) and battery-powered electric vehicles (BEVs). In comparison to internal combustion engines (ICEs), fuel cells exhibit superior energy conversion efficiency and generate no tailpipe emissions. This characteristic is of utmost importance in the context of mitigating greenhouse gas emissions and enhancing air quality (Wang et al., 2010). Fuel cells are devices that facilitate the conversion of hydrogen's chemical energy into electricity via an electrochemical reaction. This process circumvents the comparatively less efficient combustion method employed in internal combustion engines (ICEs), which is frequently associated with the emission of pollutants like nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter.

When comparing battery electric vehicles (BEVs) to fuel cells, it is evident that fuel cells offer advantages in terms of extended driving ranges and quicker refuelling times. These benefits are comparable to those observed in conventional vehicles, so effectively eliminating two significant constraints commonly associated with battery-powered transportation (Khan & Martin, 2015). Battery electric vehicles (BEVs) face limitations due to the energy density of batteries and the extended time required for charging. In contrast, fuel cells may be rapidly refuelled with hydrogen, rendering them more appropriate for heavy-duty and long-distance purposes.

In addition, it should be noted that fuel cells exhibit a remarkable ability to sustain constant performance across a diverse spectrum of operating conditions. This stands in stark contrast to batteries, which are prone to experiencing substantial performance degradation when subjected to high temperature variations. According to Ahluwalia et al. (2017), the utilization of fuel cells becomes more dependable across a wide range of climatic conditions and for more rigorous usage situations.

3. ADVANCES IN FUEL CELL MATERIALS AND DESIGN

Fuel cells have numerous advantages in comparison to traditional internal combustion engines (ICEs) and battery-powered electric vehicles (BEVs). In comparison to internal combustion engines (ICEs), fuel cells exhibit superior energy conversion efficiency and generate no tailpipe emissions. This characteristic is of utmost importance in the context of mitigating greenhouse gas emissions and enhancing air quality (Wang et al., 2010). Fuel cells are devices that facilitate the conversion of hydrogen's chemical energy into electricity via an electrochemical reaction. This process circumvents the comparatively less efficient combustion method employed in internal combustion engines (ICEs), which is frequently associated with the emission of pollutants like nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter.

When comparing battery electric vehicles (BEVs) to fuel cells, it is evident that fuel cells offer advantages in terms of extended driving ranges and quicker refuelling times. These benefits are comparable to those observed in conventional vehicles, so effectively eliminating two significant constraints commonly associated with battery-powered transportation (Khan & Martin, 2015). Battery electric vehicles (BEVs) face limitations due to the energy density of batteries and the extended time required for charging. In contrast, fuel cells may be rapidly refuelled with hydrogen, rendering them more appropriate for heavy-duty and long-distance purposes.

In addition, it should be noted that fuel cells exhibit a remarkable ability to sustain constant performance across a diverse spectrum of operating conditions. This stands in stark contrast to batteries, which are prone to experiencing substantial performance degradation when subjected to high temperature variations. According to Ahluwalia et al. (2017), the utilization of fuel cells becomes more dependable across a wide range of climatic conditions and for more rigorous usage situations.

3.1 Research on nanostructured catalysts, non-platinum catalysts, and high-temperature materials

The investigation of nanostructured catalysts has played a crucial role in enhancing the efficiency of fuel cells and mitigating expenses. The utilization of nano structuring techniques on platinum-based catalysts leads to an augmentation in the available surface area for electrochemical reactions. Consequently, this results in an elevation of the catalytic activity per unit of platinum and a concomitant reduction in the total quantity of precious metal necessary. According to Wu et al. (2011), empirical evidence suggests that the utilization of nanostructured catalysts, specifically platinum-cobalt nanoparticles, might yield substantial enhancements in the operational efficiency of proton exchange membrane fuel cells (PEMFCs).

The investigation of non-platinum catalysts has garnered significant attention in research due to their potential as a financially viable substitute for platinum-based materials. Transition metal-nitrogen-carbon (M-N-C) catalysts have exhibited considerable potential in terms of both activity and stability for the oxygen reduction process (ORR) in fuel cells. The synthesis of these catalysts commonly involves the pyrolysis of a combination of transition metal salts, nitrogen-containing polymers, and carbon supports, leading to the formation of a remarkably efficient catalyst for the oxygen reduction reaction (Cheng et al., 2014).

Efforts are currently underway to develop high-temperature materials for fuel cells, specifically in the context of solid oxide fuel cells (SOFCs), with the aim of achieving optimal performance at elevated temperatures. The utilization of improved ceramics and perovskite oxides in solid oxide fuel cells (SOFCs) allows for their resilience under challenging operational circumstances. This characteristic contributes to the improvement of fuel cell system efficiency and the expansion of fuel options (Fabbri et al., 2010).

The progress made in the field of nanostructured catalysts, non-platinum catalysts, and high-temperature materials plays a pivotal role in the improvement of fuel cell technology, enabling enhanced efficiency and reduced costs.

4. EFFICIENCY AND PERFORMANCE IMPROVEMENTS

The investigation of nanostructured catalysts has played a crucial role in enhancing the efficiency of fuel cells and mitigating expenses. The utilization of nano structuring techniques on platinum-based catalysts leads to an augmentation in the available surface area for electrochemical reactions. Consequently, this results in an elevation of the catalytic activity per unit of platinum and a concomitant reduction in the total quantity of precious metal necessary. According to Wu et al. (2011), empirical evidence suggests that the utilization of nanostructured catalysts, specifically platinum-cobalt nanoparticles, might yield substantial enhancements in the operational efficiency of proton exchange membrane fuel cells (PEMFCs).

The investigation of non-platinum catalysts has garnered significant attention in research due to their potential as a financially viable substitute for platinum-based materials. Transition metal-nitrogen-carbon (M-N-C) catalysts have exhibited considerable potential in terms of both activity and stability for the oxygen reduction process (ORR) in fuel cells. The synthesis of these catalysts commonly involves the pyrolysis of a combination of transition metal salts, nitrogen-containing polymers, and carbon supports, leading to the formation of a remarkably efficient catalyst for the oxygen reduction reaction (Cheng et al., 2014).

Efforts are currently underway to develop high-temperature materials for fuel cells, specifically in the context of solid oxide fuel cells (SOFCs), with the aim of achieving optimal performance at elevated temperatures. The utilization of improved ceramics and perovskite oxides in solid oxide fuel cells (SOFCs) allows for their resilience under challenging operational circumstances. This characteristic contributes to the improvement of fuel cell system efficiency and the expansion of fuel options (Fabbri et al., 2010).

The progress made in the field of nanostructured catalysts, non-platinum catalysts, and high-temperature materials plays a pivotal role in the improvement of fuel cell technology, enabling enhanced efficiency and reduced costs.

.

4.1 Advancements in system integration and control strategies

Recent advancements in system integration and control strategies for optimizing fuel cell performance under different operating conditions have been a focus of several studies.

One study assessed control strategies for improving the efficiency of proton exchange membrane (PEM) fuel cell systems in hybrid vehicles. The research compared constant power, baseline rule-based, and optimal mode-based control strategies, finding that the optimal mode-based strategy increased fuel cell system efficiency by 33% in low-load drive cycles and 12% in high-load drive cycles. This strategy also led to a decrease in energy consumption, demonstrating the potential for significant improvements in fuel economy (Energies, 2022).

Another paper reviewed various topologies and energy management strategies for fuel cell hybrid electric vehicles (FCHEVs). It highlighted the importance of energy management systems (EMS) that can dynamically adjust the power split between the fuel cell and the battery to optimize efficiency and performance. The review suggested that advanced control strategies, including fuzzy logic and adaptive control, could lead to better system integration and performance under varying conditions (World Electric Vehicle Journal, 2022).

These studies indicate that the integration of advanced control strategies into fuel cell systems can lead to more efficient operation, reduced fuel consumption, and improved overall performance, especially when tailored to specific drive cycles and load demands.

5. FUTURE PROSPECTS AND CHALLENGES

Significant progress has been made in the domain of fuel cell technology for electric vehicles, with notable gains observed in the realms of safety, dependability, and energy efficiency. Fuel cell electric vehicles (FCEVs) have exhibited superior operational durations and distances in comparison to pure electric vehicles, hence suggesting heightened levels of durability and reliability. The overall cost of ownership during the lifespan of Fuel Cell Electric Vehicles (FCEVs) is considerably cheaper compared to both conventional vehicles and pure electric vehicles. This is mostly due to the drastically reduced fuel expenses associated with FCEVs, which is in line with societal objectives of conserving energy and reducing emissions. According to a study published in the World Electric Vehicle Journal in 2023, the expected energy conversion efficiency of fuel cell stacks in fuel cell electric vehicles (FCEVs) is reported to be 62%. Furthermore, the overall efficiency from the fuel tank to the wheels, commonly referred to as "tank to wheel" efficiency, is calculated to be 37.7%. It is worth noting that these figures indicate a significantly greater efficiency compared to conventional gasoline and diesel-powered vehicles.

The advancement of fuel cell systems, which serve as the primary power source for fuel cell electric vehicles (FCEVs), is of utmost importance for the evolution and growth of these automobiles. Fuel cell stack technology has made significant progress in several areas. These advancements encompass system power that exceeds 100 kW, power density that surpasses 3.1 kW/L, the ability to start at cold temperatures as low as -30 °C, decreased platinum loading, and enhanced durability spanning from 5,000 to 20,000 hours. According to a study published in the World Electric Vehicle Journal in 2023, the implementation of these enhancements is crucial for facilitating the widespread manufacturing and achieving commercial viability of Fuel Cell Electric Vehicles (FCEVs).

Notwithstanding these technological breakthroughs, the commercial viability of fuel cell electric vehicles (FCEVs) continues to be impeded by legal and regulatory impediments. The broader implementation of Fuel Cell Electric Vehicles (FCEVs) necessitates the resolution of various concerns, such as the presence of imprecise hydrogen dispensing alternatives and the absence of standardized safety rules (Sustainability, 2021).

5.1 Potential of FCEVs

Fuel cell electric vehicles (FCEVs) possess the capacity to exert a substantial influence in the process of revolutionizing the transportation industry towards achieving zero emissions. Fuel cell electric vehicles (FCEVs) are propelled by hydrogen and generate solely water as a byproduct, rendering them an environmentally friendly energy alternative characterized by the absence of carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions. Electric vehicles (EVs) possess several benefits, including extended driving ranges and rapid refuelling capabilities that are comparable to those of internal combustion engine vehicles (ICEVs). These attributes render EVs an appealing choice for personal transportation, as well as for commercial and public transport applications (Cleaner Engineering and Technology, 2022).

Previous studies have investigated the integration of Fuel Cell Electric Vehicles (FCEVs) into interconnected transportation and energy systems, enabling them to function autonomously as mobile power generators, thereby eliminating the need for external power supply. This exemplifies the adaptability of fuel cell electric vehicles (FCEVs) in their contribution to an economically viable and environmentally sustainable energy system, particularly when integrated with renewable energy resources (Cleaner Engineering and Technology, 2022).

Efforts are underway to formulate policies and laws that facilitate the widespread acceptance of fuel cell electric vehicles (FCEVs) and other cars with zero-emission capabilities. As an example, California has established aggressive targets to attain carbon neutrality throughout the entire state by the year 2045. These objectives are accompanied by executive orders mandating that all newly manufactured automobiles and commercial trucks must be zero-emission vehicles by the years 2035 and 2045, respectively. According to a study published in the International Journal of Transportation Science and Technology in 2023, the implementation of such laws plays a vital role in facilitating the shift towards a transportation sector that produces zero emissions.

6. CONCLUSION

The future of fuel cell technology for electric cars (FCEVs) appears promising, since it is anticipated to experience substantial expansion. This growth can be attributed to breakthroughs in technology and the implementation of favourable policies. The future outlook for Fuel Cell Electric Vehicles (FCEVs) appears to be favourable owing to its notable attributes such as their significant energy-conversion efficiency, extended operational durations, and expedited refuelling capabilities. According to a recent publication in the World Electric Vehicle Journal (2023), fuel cell electric vehicles (FCEVs) have demonstrated an energy conversion efficiency of up to 62% in fuel cell stacks. This notable efficiency makes FCEVs a viable and efficient alternative to conventional combustion engines. Moreover, FCEVs are particularly suitable for heavy-duty applications such as buses and trucks, where the ability to cover long distances and refuel rapidly are crucial factors.

The exploration of incorporating Fuel Cell Electric Vehicles (FCEVs) into intelligent transportation systems and renewable energy infrastructures is also underway. According to research findings, it has been shown that Fuel Cell Electric Vehicles (FCEVs) have the capability to function inside an interconnected energy system, hence potentially fulfilling the role of mobile power plants and making a valuable contribution towards ensuring stability in the electrical grid (Cleaner Engineering and Technology, 2022). This observation underscores the multifaceted function of Fuel Cell Electric Vehicles (FCEVs) within both the transportation and energy domains.

In addition, the promotion of zero-emission mobility is being facilitated through the implementation of legislation, such as California's requirement for all newly manufactured automobiles and commercial vehicles to operate with zero emissions by the years 2035 and 2045, respectively. According to a study published in the International Journal of Transportation Science and Technology in 2023, it is anticipated that these laws will facilitate the rapid integration of Fuel Cell Electric Vehicles (FCEVs) into the market and stimulate additional advancements in this domain.

To promote the adoption of fuel cell electric vehicles (FCEVs), policymakers, researchers, and industry stakeholders should focus on several key areas:

1. Infrastructure Development: Expanding the hydrogen refuelling infrastructure is critical for the widespread adoption of FCEVs. Policymakers can incentivize the construction of hydrogen refuelling stations and collaborate with industry partners to develop standardized safety regulations for hydrogen fuel (Sustainability, 2021).

2. Technological Advancements: Researchers should continue to improve fuel cell technology, focusing on increasing the durability and reducing the cost of fuel cell stacks. Efforts to decrease the reliance on rare materials like platinum and to enhance the cold start capabilities of fuel cells are also important (World Electric Vehicle Journal, 2023).

3. Policy and Incentives: Policymakers should create favourable regulatory frameworks and financial incentives for FCEVs. This includes tax credits, subsidies for vehicle purchase, and support for research and development. Policies that mandate a certain percentage of zero-emission vehicles in public and private fleets can also drive adoption (International Journal of Transportation Science and Technology, 2023).

By addressing these areas, stakeholders can create a conducive environment for FCEVs, aligning with global efforts to reduce greenhouse gas emissions and transition to a sustainable transportation system.

Acknowledgments: The authors would like to express their gratitude to the Malaysian Ministry of Higher Education (MOHE) for supporting this research through Fundamental Research Grant Scheme (FRGS/1/2020/TK0/UTHM/02/15).

References

Saxena, S., Kapoor, A., & Horowitz, K. (2013). Analysis of hydrogen fuel cell electric vehicles' potential to reduce US petroleum consumption and greenhouse gas emissions. International Journal of Hydrogen Energy, 38(20), 8499-8514.

Eberle, U., & von Helmolt, R. (2010). Sustainable transportation based on electric vehicle concepts: a brief overview. Energy & Environmental Science, 3(6), 689-699.

International Energy Agency (IEA). (2019). The Future of Hydrogen – Seizing today's opportunities. Report prepared by the IEA for the G20, Japan.

Grand View Research. (2020). Fuel Cell Vehicle Market Size, Share & Trends Analysis Report By Region (North America, Europe, APAC, LATAM, MEA), And Segment Forecasts, 2020 - 2027.

Thomas, C. E. (2009). Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy, 34(15), 6005-6020.

Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., & Stolten, D. (2015). Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. International Journal of Hydrogen Energy, 40(12), 4285-4294.

Offer, G. J., Howey, D., Contestabile, M., Clague, R., & Brandon, N. P. (2010). Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy, 38(1), 24-29.

Jacobson, M. Z., Colella, W. G., & Golden, D. M. (2005). Cleaning the Air and Improving Health with Hydrogen Fuel-Cell Vehicles. Science, 308(5730), 1901-1905.

Hart, D., Lehner, F., & Soto, A. (2016). Analysis of the potential for hydrogen-powered FCEVs to reduce CO2 emissions. International Journal of Hydrogen Energy, 41(19), 8144-8153.

Alam, F., Mamat, R., Masjuki, H. H., & Zainulabidin, M. H. (2015). Emission reduction potential of using hydrogen-enriched compressed natural gas in a spark ignition engine. Energy Conversion and Management, 105, 328-337.

Kordesch, K., & Simader, G. (1996). Fuel Cells and Their Applications. VCH Publishers.

Larminie, J., & Dicks, A. (2003). Fuel Cell Systems Explained. John Wiley & Sons.

Barbir, F. (2005). PEM Fuel Cells: Theory and Practice. Elsevier Academic Press.

Singhal, S. C., & Kendall, K. (Eds.). (2003). High-temperature solid oxide fuel cells: fundamentals, design, and applications. Elsevier.

Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2010). A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research. Applied Energy, 87(4), 981-1007.

Khan, M. A., & Martin, D. (2015). Review of energy storage systems for electric vehicle applications: Issues and challenges. Renewable and Sustainable Energy Reviews, 52, 1309-1321.

Ahluwalia, R. K., Wang, X., Steinbach, A. J., & Rousseau, A. (2017). Fuel cell electric vehicles and hydrogen infrastructure: status 2017. Energy Policy, 106, 431-440.

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. International Journal of Hydrogen Energy, 38(12), 4901-4934.

Peighambardoust, S. J., Rowshanzamir, S., & Amjadi, M. (2010). Review of the proton exchange membranes for fuel cell applications. International Journal of Hydrogen Energy, 35(17), 9349-9384.

Proietti, E., Jaouen, F., Lefèvre, M., Larouche, N., Tian, J., Herranz, J., & Dodelet, J. P. (2011). Iron-based cathode catalyst with enhanced power density in polymer electrolyte membrane fuel cells. Nature Communications, 2, 416.

Wu, J., Yang, H. (2011). Platinum-based oxygen reduction electrocatalysts. Accounts of Chemical Research, 46(8), 1848-1857.

Cheng, N., Banis, M. N., Liu, J., Riese, A., Li, R., Sun, X. (2014). Advanced nitrogen-doped carbon-supported cobalt-iron oxygen reduction catalyst. ACS Catalysis, 4(10), 3663-3670.

Fabbri, E., Pergolesi, D., Traversa, E. (2010). Materials challenges toward proton-conducting oxide fuel cells: A critical review. Chemistry of Materials, 22(3), 519-534.

Electronics. (2022). Energy Management Strategy of Fuel-Cell Backup Power Supply Systems Based on Whale Optimization Fuzzy Control. https://doi.org/10.3390/electronics11152325

Sustainability. (2022). Design, Modelling, and Thermodynamic Analysis of a Novel Marine Power System Based on Methanol Solid Oxide Fuel Cells, Integrated Proton Exchange Membrane Fuel Cells, and Combined Heat and Power Production. https://doi.org/10.3390/su141912496

Energies. (2022). Control Strategy Assessment for Improving PEM Fuel Cell System Efficiency in Fuel Cell Hybrid Vehicles. https://doi.org/10.3390/en15062004

World Electric Vehicle Journal. (2022). Fuel Cell Hybrid Electric Vehicles: A Review of Topologies and Energy Management Strategies. https://doi.org/10.3390/wevj13090172

World Electric Vehicle Journal. (2023). Advantages and Technological Progress of Hydrogen Fuel Cell Vehicles. https://doi.org/10.3390/wevj14060162

Sustainability. (2021). Fuel Cell Electric Vehicles (FCEV): Policy Advances to Enhance Commercial Success. https://doi.org/10.3390/su13095149

Cleaner Engineering and Technology. (2022). Design for shared autonomous vehicle (SAV) system employing electrified vehicles: Comparison of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). https://doi.org/10.1016/j.clet.2022.100505

International Journal of Transportation Science and Technology. (2023). Emerging technologies and policies for carbon–neutral transportation. https://doi.org/10.1016/j.ijtst.2022.09.002

World Electric Vehicle Journal. (2023). Advantages and Technological Progress of Hydrogen Fuel Cell Vehicles. https://doi.org/10.3390/wevj14060162

Cleaner Engineering and Technology. (2022). Design for shared autonomous vehicle (SAV) system employing electrified vehicles: Comparison of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). https://doi.org/10.1016/j.clet.2022.100505

International Journal of Transportation Science and Technology. (2023). Emerging technologies and policies for carbon–neutral transportation. https://doi.org/10.1016/j.ijtst.2022.09.002

Sustainability. (2021). Fuel Cell Electric Vehicles (FCEV): Policy Advances to Enhance Commercial Success. https://doi.org/10.3390/su13095149

World Electric Vehicle Journal. (2023). Advantages and Technological Progress of Hydrogen Fuel Cell Vehicles. https://doi.org/10.3390/wevj14060162

International Journal of Transportation Science and Technology. (2023). Emerging technologies and policies for carbon–neutral transportation. https://doi.org/10.1016/j.ijtst.2022.09.002