

Advancements and Challenges in Fuel Cell Technology for Portable, Transportation, and Stationary Applications

Nur Syafa Qahiera Abd Halim^a, Nur Syafiqah Alisa Mohd Nizam^a, Ili-Mastura Mashudi^a, Montri Luengchavanon^b, Umira Asyikin Yusop^{a,c}, Wan Nor Anasuhah Wan Yusoff^a, Lim Bee Huah^a & Nurul Akidah Baharuddin^{a*}

^a*Solid Oxide Fuel Cell Group, Fuel Cell Institute,
Universiti Kebangsaan Malaysia, UKM Bangi, 43600, Selangor, Malaysia*

^b*Sustainable Energy Management Program, Wind Energy and Energy Storage Systems Centre,
Faculty of Environmental Management, Prince of Songkla University, Songkhla 90110, Thailand,*

^c*Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia,
86400 Parit Raja, Batu Pahat, Johor, Malaysia*

**Corresponding author: akidah@ukm.edu.my*

*Received 17 June 2025, Received in revised form 3 June 2026
Accepted 3 July 2026, Available online 30 September 2026*

ABSTRACT

Fuel cell technology has emerged as a promising clean energy conversion technology for support the transition towards low-carbon and sustainable energy systems. Unlike conventional combustion-based technologies, fuel cells directly convert the chemical energy of fuels into electricity through electrochemical reactions, offering high energy efficiency, low emissions, and fuel flexibility. This review examines recent advances in fuel cell technologies and evaluates their suitability for portable, transportation, and stationary applications. For portable applications, Proton Exchange Membrane Fuel Cells (PEMFCs) and Direct Methanol Fuel Cells (DMFCs) are highlighted because of their low operating temperatures, compact design, and high energy density, making them suitable for portable electronic devices and military equipment. In the transportation sector, PEMFCs have demonstrated significant potential for fuel cell electric vehicles, trains, and unmanned aerial vehicles owing to their rapid start-up capability and high-power density. For stationary applications, Solid Oxide Fuel Cells (SOFCs), Molten Carbonate Fuel Cells (MCFCs), and PEMFC-based Combined Heat and Power (CHP) systems provide high electrical efficiency and effective waste heat recovery for residential, commercial, and industrial power generation. Despite these advantages, commercialization remains constrained by high capital costs, durability limitations, hydrogen infrastructure, and regulatory challenges. Continued advances in catalyst and membrane materials, hydrogen production and storage, system integration, manufacturing processes, and supportive government policies are essential to improve the economic competitiveness and long-term reliability of fuel cell systems. Overall, fuel cell technology represents a key enabling technology for achieving a sustainable hydrogen economy and accelerating the transition towards low-carbon energy systems.

Keywords: Fuel cells applications; portable applications; transportation applications; stationary applications; hydrogen economy

INTRODUCTION

The global energy landscape is undergoing a rapid transformation, driven by the urgent need to decarbonize economies and secure sustainable energy supplies. The transition towards clean energy systems has become increasingly urgent as the global population is projected to increase from 7.8 billion in 2020 to 9.9 billion by 2050,

requiring approximately 80% more energy to support socioeconomic development and industrial activities (Attanayake et al. 2024). While renewable energy sources such as solar and wind offer immense promise, their inherent intermittency necessitates efficient energy conversion, storage, and management technologies to ensure a stable and reliable electricity supply (Dr. Clara Anderson 2020).

Among the available clean energy technologies, fuel cells have emerged as one of the most promising solutions because they convert the chemical energy of a fuel directly into electricity through electrochemical reactions without combustion. During operation, hydrogen is electrochemically oxidized at the anode, while oxygen is reduced at the cathode to generate electricity, water, and, depending on the fuel cell type, heat as a by-product. Unlike conventional thermal power generation, which is constrained by the Carnot efficiency limit, fuel cells convert chemical energy directly into electricity through electrochemical reactions, enabling higher electrical efficiencies and lower CO₂ and SO_x emissions than conventional combustion-based systems (Gruber et al. 2024). Fuel cells offer several advantages, including high energy conversion efficiency, fuel flexibility (including renewable hydrogen), combined heat and power (CHP) capability, and broad applicability across portable, transportation, and stationary applications (Malik et al. 2026).

Fuel cells are generally classified according to their electrolyte materials into several major types, including Proton Exchange Membrane Fuel Cells (PEMFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs). Each technology exhibits distinct operating temperatures, electrolyte materials, performance characteristics, and application domains. Among these technologies, PEMFCs have attracted considerable research interest because of their high-power density, rapid start-up capability, relatively low operating temperatures, and excellent dynamic response, making them particularly suitable for portable and transportation applications.

Within PEMFC technology, the development of intermediate-temperature PEMFCs (IT-PEMFCs, approximately 100–200 °C) and high-temperature PEMFCs (HT-PEMFCs, approximately 120–200 °C) has emerged as an effective strategy to overcome the limitations of conventional low-temperature PEMFCs, particularly Nafion membrane degradation, poor high-temperature performance, and complex water management requirements. Nevertheless, these higher-temperature systems continue to face challenges related to long-term performance stability. In HT-PEMFCs, increasing phosphoric acid doping levels to enhance proton conductivity may compromise membrane mechanical stability. Recent studies have shown that incorporating Ce-based metal–organic frameworks (Ce-MOFs) into sulfonated poly (ether ether ketone) (SPEEK) membranes improves proton conductivity, thermal stability, mechanical properties, and chemical durability (Theerthagiri et al. 2025). Similarly, phosphoric acid-doped imidazolium polysilsesquioxane-

crosslinked poly (vinyl chloride) membranes exhibit high proton conductivity, enhanced phosphoric acid uptake, and improved dimensional stability for HT-PEMFC applications (Jin et al. 2022). These material innovations are expected to improve long-term fuel cell durability and accelerate the commercialization of PEMFC technology. Collectively, such advances contribute to greenhouse gas emission reduction and support pathways consistent with the IEA Net Zero by 2050 Scenario, which aligns with the Paris Agreement objective of limiting global warming to 1.5°C above pre-industrial levels (Ministry of Economy 2023).

The versatility of fuel cells enables their deployment across portable, transportation, and stationary applications owing to their scalable power output and adaptable operating characteristics. Portable systems emphasize compactness, lightweight design, high energy density, and rapid start-up for consumer electronics, military equipment, and auxiliary power units. Transportation applications require high power density, rapid dynamic response, long operating lifetimes, and fast refuelling for fuel cell electric vehicles (FCEVs), buses, trains, and unmanned aerial vehicles (UAVs). In contrast, stationary applications prioritize long-term durability, fuel flexibility, high electrical efficiency, and effective waste heat recovery through combined heat and power systems. Hybrid PEMFC/supercapacitor devices utilizing reduced graphene oxide/Nafion/Pt electrodes further improve performance by simultaneously enhancing energy density and power density (Fu et al. 2023).

Fuel cell capacity therefore varies according to application requirements, ranging from portable kilowatt-scale systems to stationary multi-megawatt power plants (İnci & Aydemir 2025). Among the various fuel cell technologies, SOFCs and MCFCs are particularly suitable for medium- and large-scale stationary power generation because of their high electrical efficiencies, excellent fuel flexibility, and efficient waste heat recovery. In contrast, PEMFCs are more suitable for portable and transportation applications owing to their rapid start-up, relatively low operating temperatures, and excellent dynamic response. Recent advances in PEMFC technology have centred on the development of perfluorosulfonic acid (PFSA)-based composite membranes with improved proton conductivity, durability, and stability under low-humidity and elevated-temperature operating conditions, thereby enhancing the overall performance and commercial viability of PEMFCs (Maiti et al. 2022). Nevertheless, the high catalyst cost and limited long-term durability remain the two major barriers to the widespread commercialization of PEMFC technology (Borup et al. 2020).

Although numerous review articles have discussed individual fuel cell technologies or specific application sectors, a comprehensive review integrating portable,

transportation, and stationary applications while simultaneously addressing the associated technological and commercialization challenges remains limited. Therefore, this review critically examines recent advances in fuel cell materials, operating principles, and system design across portable, transportation, and stationary applications. In addition, the technological, economic, infrastructural, and regulatory challenges affecting large-

scale commercialization are comprehensively discussed together with future research directions that may facilitate the widespread deployment of fuel cell technologies. Figure 1 presents the conceptual framework of this review, illustrating the operating principles, major fuel cell technologies, application sectors, material innovations, and commercialization challenges discussed throughout this paper.

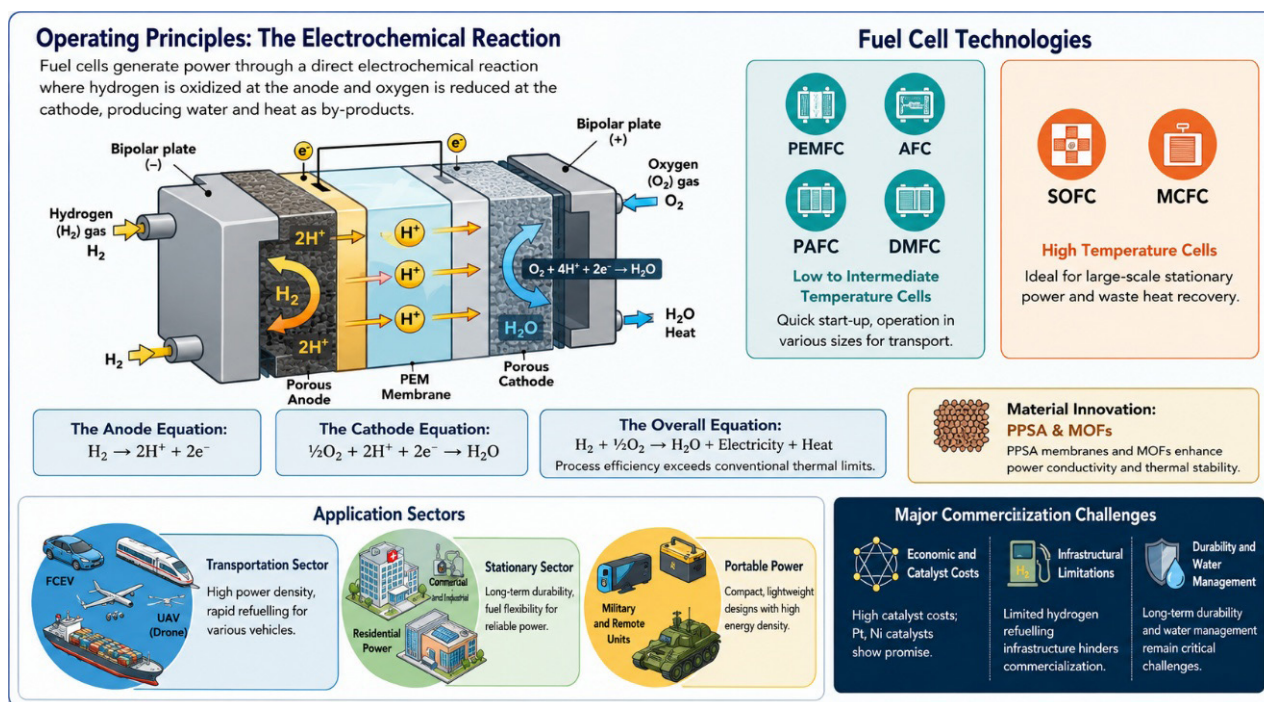


FIGURE 1. An overview of the key topics discussed in this review, including fuel cell operating principles, application sectors, and commercialization challenges

PORTABLE APPLICATION

Technological advancements have substantially increased the demand for compact, lightweight, and high-energy-density power sources for portable electronic devices, military equipment, medical devices, and auxiliary power systems. Portable fuel cell applications generally require power outputs below 100 W while emphasizing long operating duration, rapid start-up, lightweight design, low noise, and high energy density for consumer electronic devices (Hassan et al. 2023). Compared with conventional rechargeable batteries, fuel cells provide higher energy densities and continuous power generation as long as fuel is supplied, making them promising alternatives for next-generation portable power systems.

Among the available fuel cell technologies, PEMFCs and DMFCs have emerged as the leading candidates for portable applications. PEMFCs are well suited for portable systems because of their high-power density, rapid start-up capability, and high electrical efficiency. In contrast,

DMFCs are particularly attractive for low-power portable applications because liquid methanol is easier to store, transport, and refuel than compressed hydrogen (Santiago et al. 2024). Unlike hydrogen-fed PEMFCs, DMFCs do not require high-pressure hydrogen storage tanks or complex fuel delivery infrastructure, thereby simplifying system design and improving operational safety. Furthermore, their high energy density enables prolonged operating duration with convenient fuel replenishment, making DMFCs attractive power sources for portable electronic devices and other low-power application (Osman et al. 2025). Nevertheless, PEMFCs remain the preferred technology for applications requiring higher power density, rapid transient response, and greater electrical efficiency, particularly in portable auxiliary power units and defence systems.

Despite these advantages, both PEMFCs and DMFCs continue to face several technical challenges that limit their widespread commercialization. In PEMFCs, approximately 45–60% of the chemical energy of hydrogen is converted

into heat during operation, making effective thermal and water management essential for maintaining stable electrochemical performance. Conventional PEMFCs therefore typically operate at relatively low temperatures (60–80 °C) to maintain adequate membrane hydration and high proton conductivity while minimizing performance degradation. Recent advances in thermal management have demonstrated that recovering waste heat through CHP systems can increase the overall energy efficiency of PEMFC systems to approximately 60–90%, depending on system configuration and heat utilization (Farhat et al. 2022; Najmi et al. 2025)

Beyond commercial electronics, portable fuel cells have attracted increasing interest in military and defence applications, where silent operation, lightweight construction, high reliability, and extended mission endurance are essential operational requirements. Recent research has focused on the development of compact PEMFC-based power supply systems for mobile applications, particularly unmanned ground vehicles (UGVs), supported by embedded monitoring technologies to improve system performance, operational reliability, and energy management (Matejček et al. 2025). Compared with conventional diesel generators, fuel cells generate minimal

acoustic noise, lower thermal signatures, and reduced environmental emissions, making them attractive for military applications requiring enhanced operational stealth and reliability.

Figure 2 summarizes the principal portable fuel cell technologies and compares the key characteristics, advantages, and application suitability of PEMFCs and DMFCs. As illustrated, DMFCs are particularly suitable for low-power portable electronics because of their high energy density and convenient liquid fuel storage, whereas PEMFCs are better suited for applications requiring higher power output, rapid start-up, and continuous operation, such as portable auxiliary power units and military systems.

Overall, portable fuel cell technologies demonstrate considerable potential as next-generation power sources because of their high energy density, extended operating duration, and environmentally friendly operation. Nevertheless, further improvements in fuel storage, catalyst durability, thermal management, and system cost are required before large-scale commercialization can be achieved. The technological advances realized in portable fuel cell systems have also provided a foundation for the development of larger-scale transportation applications, which are discussed in the following section

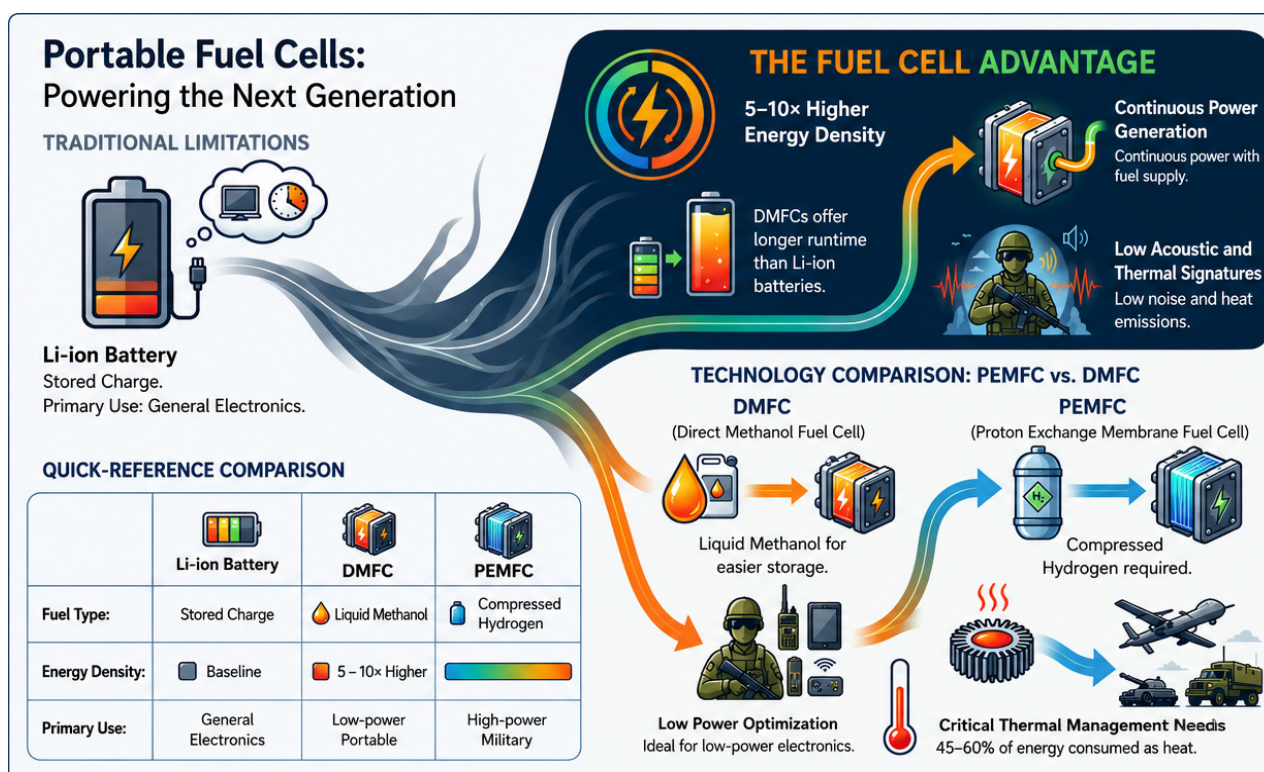


FIGURE 2. Overview of portable fuel cell technologies, key advantages, and application suitability of PEMFCs and DMFCs

TRANSPORTATION APPLICATIONS

Fuel cell technology is regarded as one of the most promising alternatives for decarbonizing the transportation sector because of its high energy conversion efficiency, rapid refuelling capability, and near-zero tailpipe emissions. Compared with conventional BEVs, FCEVs offer significantly shorter refuelling times and longer driving ranges, making them particularly attractive for applications requiring continuous operation and extended travel distances. Consequently, PEMFCs have emerged as the dominant fuel cell technology for transportation owing to their relatively low operating temperatures, high power density, rapid start-up capability, and excellent dynamic response under varying operating conditions (Yue et al. 2026).

Transportation applications require energy systems that provide high energy density for extended driving range

together with high power density to satisfy rapid acceleration and regenerative braking requirements (Aghmadi & Mohammed 2024). Conventional propulsion systems, including lithium-ion batteries and internal combustion engines (ICEs), continue to dominate the automotive industry. Despite their widespread adoption, lithium-ion batteries remain limited by relatively low energy density and long charging times, while internal combustion engines continue to produce greenhouse gas emissions and rely on fossil fuels (Rout et al. 2026). These limitations have accelerated interest in hydrogen-powered fuel cell technologies as practical alternatives for future low-carbon transportation systems.

Figure 3 summarizes the key performance advantages of PEMFCs for transportation applications, highlighting their rapid refuelling capability, high electrical efficiency, low emissions, and suitability for diverse transportation modes, including passenger vehicles, railways, and UAVs.

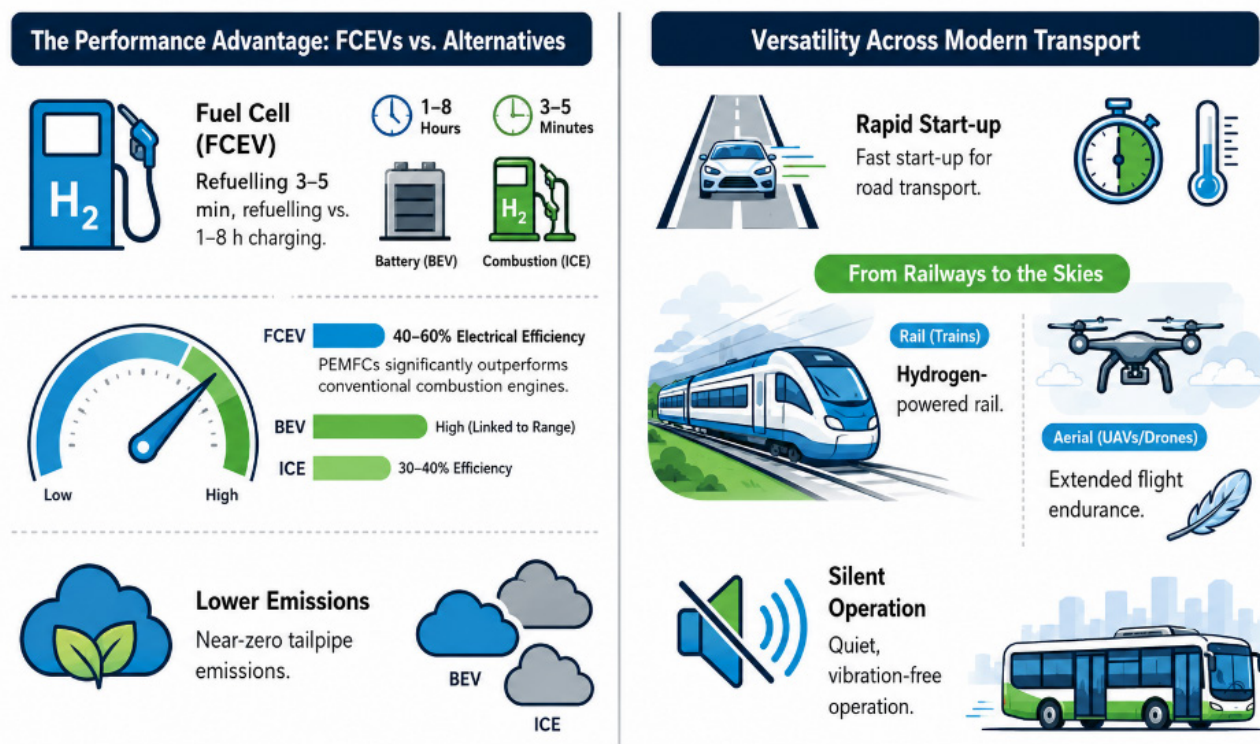


FIGURE 3. Performance advantages and transportation applications of PEMFCs

The practical viability of PEMFC technology has been demonstrated through numerous commercial and pilot-scale FCEV deployments. The hydrogen-powered MobyPost fuel cell vehicle (FCV) represents a promising application of fuel cell technology in postal transportation, where system-level modelling and simulation have been employed to evaluate vehicle performance, optimize energy management, and support powertrain development

(Bai et al. 2021; Fandi, Novák & Chyský 2024). These studies demonstrate that although PEMFC technology has reached practical deployment, durability under dynamic operating conditions remains an important engineering challenge. High cell voltages during start-up, shut-down, and idle operation accelerate catalyst degradation and membrane ageing, highlighting the need for effective energy management strategies to improve fuel cell

durability and extend system lifetime (Dong et al. 2026). Nevertheless, PEMFCs continue to offer several advantages over conventional propulsion technologies, including higher electrical efficiency than ICEs, start-up times of less than 30 s, low operating temperatures, and rapid dynamic response, making them highly suitable for road transportation applications.

Unlike battery electric vehicles, whose driving range and charging duration remain constrained by battery capacity and charging infrastructure, hydrogen fuel cell vehicles can typically be refuelled within several minutes while providing competitive driving ranges. BEVs require charging times ranging from less than 30 minutes using fast chargers to several hours with conventional charging systems, whereas commercial FCEVs can be refuelled within approximately 3–5 minutes (Togun et al. 2025). Furthermore, HEVs continue to emit pollutants, including carbon monoxide, hydrocarbons, and nitrogen oxides, while consuming fossil fuels (Bagheri et al. 2021). FCEVs are therefore expected to play an increasingly important role in sustainable transportation. Fuel cells convert hydrogen directly into electricity with electrical efficiencies of approximately 40–60%, substantially higher than the less than 20% energy conversion efficiency of conventional gasoline internal combustion engines under typical driving conditions (Dash et al. 2022). Economic analyses further suggest that the operating costs of FCEVs are expected to become increasingly competitive as hydrogen production scales up, green hydrogen prices decline, and fuel cell manufacturing costs continue to decrease through advances in materials, large-scale production, and supply chain optimization (Thorat & Dhamal 2026). These developments indicate a promising commercial outlook for fuel cell-powered transportation systems, particularly as technological advancements, cost reductions, and hydrogen infrastructure continue to improve (Wang et al. 2025).

Beyond passenger vehicles, PEMFC technology has expanded into rail transportation, where rapid start-up capability, high efficiency, and zero tailpipe emissions provide significant environmental and operational advantages. Hydrogen-powered trains employing PEMFCs generate electricity through the electrochemical conversion of hydrogen and oxygen, with water as the only reaction by-product (Ding & Wu 2024). The relatively low operating temperature of PEMFCs (below 100°C) reduces thermal management complexity while enabling system efficiencies approaching 61%, making them well suited for railway applications. In contrast, SOFCs typically operate at elevated temperatures between 500°C and 1000°C, resulting in prolonged start-up times and increased thermal management requirements. Consequently, despite their superior electrical efficiency, these characteristics currently

limit their widespread application in transportation systems (Zhang et al. 2025).

Recent advances have expanded fuel cell applications to UAVs, where high specific energy, lightweight energy systems, extended flight endurance, rapid refuelling, and low acoustic signatures are essential operational requirements. Compared with battery-powered UAVs, hydrogen PEMFC systems provide significantly longer flight endurance, faster refuelling, and zero tailpipe emissions, making them well suited for infrastructure inspection, environmental monitoring, precision agriculture, aerial surveillance, emergency response, and other long-duration missions (Menicou, Karagiorgis & Christodoulou 2025).

In addition to PEMFCs, AFCs have also demonstrated potential for transportation applications because they employ an alkaline electrolyte, typically potassium hydroxide (KOH), and operate at moderate temperatures between 60°C and 100°C (Qasem & Abdulrahman 2024). AFCs offer relatively low material costs and excellent electrochemical performance when supplied with high-purity hydrogen and oxygen. However, their sensitivity to carbon dioxide significantly limits practical deployment because carbonate formation degrades electrolyte performance. Consequently, PEMFCs remain the dominant fuel cell technology for transportation applications owing to their high-power density, rapid start-up capability, operational flexibility, longer durability, and greater technological maturity (Wu et al. 2025).

Hydrogen storage remains another critical consideration for transportation applications. Currently, compressed gaseous hydrogen stored in high-pressure cylinders represents the most mature hydrogen storage technology and is readily integrated with PEMFC systems. However, challenges related to storage density, refuelling infrastructure, and hydrogen distribution networks continue to hinder its widespread adoption (Scarpati et al. 2024). Continued advances in hydrogen storage technologies, hydrogen production, distribution infrastructure, and fuel cell durability are therefore expected to accelerate the commercialization of fuel cell transportation systems across passenger vehicles, railways, unmanned aerial vehicles, maritime transport, and heavy-duty mobility.

STATIONARY APPLICATIONS

Stationary fuel cell systems have emerged as promising technology for distributed power generation in residential, commercial, institutional, and industrial sectors, where high electrical efficiency, continuous operation, and low environmental impact are essential. In contrast to transportation applications, stationary systems emphasize

long-term durability, fuel flexibility, and efficient waste heat recovery rather than rapid start-up and transient response. Consequently, SOFCs and MCFCs have become the dominant fuel cell technologies for stationary power generation owing to their high efficiency and fuel flexibility (Sebbani, Ettouhami & Boulakhbar 2025).

Among these technologies, SOFCs have attracted considerable attention owing to their high electrical efficiency (>50%), low emissions, fuel flexibility, and suitability for stationary and distributed power generation (Talebizadehsardari et al. 2026). Their high operating temperatures also enable internal fuel reforming and the utilization of non-precious metal catalysts, further improving system efficiency and fuel flexibility. A typical SOFC stack consists of multiple planar single cells connected electrically to achieve the desired power output. Each cell comprises an anode, cathode, and dense ceramic electrolyte arranged in a multilayer sandwich structure. Tape casting remains one of the most widely adopted ceramic processing techniques owing to its scalability, cost-effectiveness, and capability for continuous, large-scale manufacturing (Touidjine et al. 2026).

Commercial stationary fuel cell systems have been deployed in a wide range of applications, including residential micro-combined heat and power (micro-CHP) systems, hospitals, commercial buildings, data centres, telecommunication facilities, and distributed power generation networks. Their ability to provide continuous electricity with high efficiency and low emissions makes them particularly attractive for applications requiring reliable and uninterrupted power supply.

The integration of fuel cells with renewable energy systems has further enhanced the attractiveness of stationary applications. Hydrogen produced using surplus renewable electricity can be stored and later reconverted into electricity through fuel cells during periods of low renewable energy availability, thereby improving grid stability and energy security. Previous techno-economic assessments have consistently shown that hybrid energy systems integrating photovoltaic (PV) arrays, electrolyzers, hydrogen storage, and fuel cells improve renewable energy utilization, reduce dependence on fossil-fuel-derived electricity, and enhance overall system sustainability (Babatunde & Olanrewaju 2026; Reza et al. 2026). For example, a photovoltaic (PV)–fuel cell–battery cogeneration system could reliably supply electrical power to hospitals in Malaysia while reducing operating costs and enhancing energy resilience (Sarker et al. 2024). Similarly, comparative analyses of off-grid PV–electrolyser–fuel cell systems have shown that appropriately sized fuel cell systems can effectively satisfy residential electricity demand while maximizing renewable energy utilization and improving long-term energy reliability.

One of the greatest advantages of stationary fuel cells is their ability to simultaneously generate electricity and useful thermal energy through CHP, combining cooling, heating and power (CCHP), and trigeneration systems. Unlike conventional thermal power plants, which reject a substantial fraction of input energy as waste heat, fuel cells facilitate the recovery and utilization of thermal energy for domestic hot water production, space heating, cooling, and industrial applications, thereby improving overall energy efficiency (Chen, Huang & Chua 2022). For example, proton exchange membrane fuel cells (PEMFCs) typically exhibit electrical efficiencies of approximately 50%; however, integration into CHP systems enables overall energy utilization efficiencies exceeding 80% by recovering and utilizing waste heat (Alam Rimon, Mourshed & Kibria 2025). Figure 4 illustrates a typical integrated stationary fuel cell system combining renewable energy sources, an electrolyser, hydrogen storage, and a battery bank to provide reliable power for residential applications.

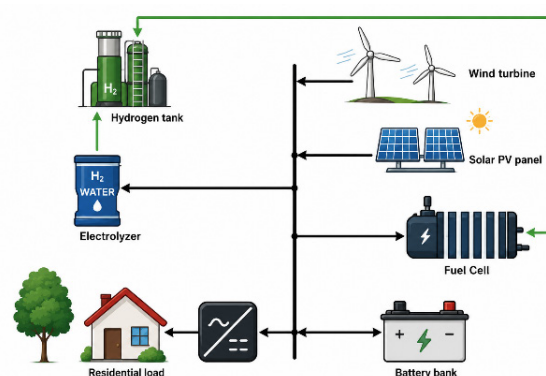


FIGURE 4. Schematic of an integrated stationary fuel cell system incorporating renewable energy sources, an electrolyser, hydrogen storage, and a battery bank for residential power generation

Despite these advantages, the widespread commercialization of stationary fuel cell systems remains constrained by economic barriers. Capital costs remain relatively high due to the use of expensive catalyst materials, complex balance-of-plant (BoP) components, and specialized installation and integration requirements (Sebbani et al. 2025). Compared with conventional stationary energy systems such as diesel generators, gas-fired combined heat and power plants, and utility grid electricity, current fuel cell systems generally require higher initial investment despite offering lower operational emissions and greater long-term energy efficiency. Despite significant technological advances, fuel cell technologies, including DMFCs, SOFCs, and PEMFCs, remain more expensive than conventional energy technologies because their continued development and optimization rely on

costly materials, advanced manufacturing processes, and complex system integration (Sazali et al. 2020). Nevertheless, continued advances in catalyst development, manufacturing technologies, and large-scale production are expected to lower system costs and accelerate the commercialization of fuel cell technologies (Shi, Shen & Wei 2025).

In addition to economic considerations, regulatory compliance plays a critical role in the successful deployment of stationary fuel cell systems. The widespread deployment of fuel cells in residential and commercial applications necessitates strict compliance with national building regulations and relevant safety standards governing gas handling, pressure vessels, electrical systems, ventilation, refrigerant management, and environmental protection (Jørgensen & Ma 2025). Such regulatory frameworks ensure safe installation, mitigate operational hazards associated with hydrogen handling and high-temperature operation, and strengthen public confidence in fuel cell technologies. As governments continue to strengthen decarbonization policies and building energy regulations, harmonized technical standards and standardized installation guidelines are expected to play an increasingly important role in accelerating the large-scale commercialization of stationary fuel cell systems.

Overall, stationary fuel cells represent one of the most technologically mature application sectors because they integrate high electrical efficiency, fuel flexibility, renewable energy compatibility, and waste heat recovery within a single energy platform. Continued advances in system durability, catalyst development, manufacturing technologies, hydrogen infrastructure, and regulatory harmonization are expected to further improve their economic competitiveness and accelerate widespread commercialization for residential, commercial, and industrial power generation.

HEAVY-DUTY TRANSPORTATION APPLICATIONS

Heavy-duty transportation has emerged as one of the most promising sectors for hydrogen fuel cell deployment because it demands long driving range and rapid refuelling, where battery-electric technologies continue to face practical limitations, particularly in long-haul freight applications (Luo et al. 2026). Compared with conventional

diesel-powered heavy-duty vehicles, hydrogen fuel cell systems can substantially reduce greenhouse gas emissions while providing a technically viable solution for long-haul freight and other heavy-duty transport applications (Genovese et al. 2023). Unlike passenger vehicles, heavy-duty transportation requires continuous high-power output, extended operating range, high payload capacity, and minimal operational downtime. These operational requirements make hydrogen fuel cells particularly attractive for commercial freight transport, where rapid refuelling and high energy density help maximize fleet utilization and logistics efficiency.

Unlike battery-powered heavy-duty vehicles, whose payload capacity and operational range are constrained by battery weight and charging duration, hydrogen fuel cell systems benefit from the high gravimetric energy density of hydrogen, enabling extended driving ranges with considerably shorter refuelling times. Therefore, hydrogen has emerged as a promising low-carbon energy carrier for hydrogen internal combustion engines (H_2 ICEs) and FCEVs, offering a viable pathway for decarbonizing transportation, particularly in applications where battery electrification remains less practical (Wallington et al. 2025; Liu et al. 2026). Among the available fuel cell technologies, PEMFCs are regarded as the most suitable for heavy-duty transportation owing to their high power density, low operating temperature, rapid start-up capability, and excellent dynamic response under variable operating conditions (Wallington et al. 2025).

Figure 5 compares the overall performance of conventional and alternative transportation technologies based on key evaluation criteria, including energy efficiency, greenhouse gas emissions, fuel consumption, driving range, and operating cost. The comparison indicates that hydrogen fuel cell vehicles achieve the highest overall performance across the selected evaluation criteria. According to a comparative assessment, hydrogen fuel cell vehicles achieved the highest overall performance ranking, followed by H_2 ICE vehicles, biofuel vehicles, hybrid electric vehicles, and battery electric vehicles (Acar & Dincer 2020). Conventional fossil-fuel-powered vehicles recorded the lowest overall performance because of their poor environmental performance and lower overall energy efficiency. These findings demonstrate the considerable potential of hydrogen fuel cell technology as a long-term solution for decarbonizing heavy-duty transportation.

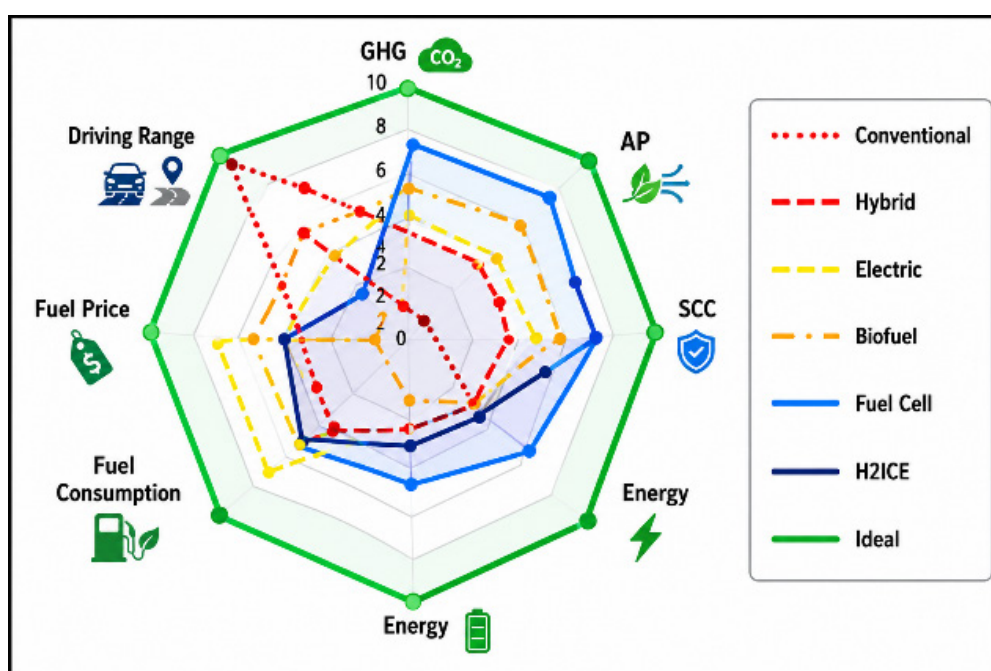


FIGURE 5. Comparative performance assessment of conventional and alternative transportation technologies based on key operational and environmental criteria. Adapted from Acar & Dincer (2020)

Beyond heavy-duty road transportation, hydrogen fuel cell technology is increasingly being developed for rail, maritime, and aviation applications, where long operating ranges, high energy demand, and rapid refuelling requirements reduce the practicality of battery-electric systems (Nyangon & Darekar 2024). These sectors are among the most challenging to decarbonize because of their demanding operational requirements and the limitations of current battery technologies. These advantages are particularly important for heavy-duty vehicles (HDVs), where battery-electric trucks face significant trade-offs between battery mass, driving range, and payload capacity, whereas hydrogen fuel cell HDVs

provide longer driving ranges and shorter refuelling times (Khosravi et al. 2026). Fuel cell systems are inherently modular and can be scaled to satisfy different power requirements by increasing stack size or combining multiple stacks. Furthermore, high-volume manufacturing is expected to substantially reduce system and stack costs through economies of scale (Lal et al. 2023).

Figure 6 illustrates the relationship between average vehicle mileage, power requirements, and the suitability of hydrogen fuel cell systems across different transportation sectors, highlighting the transition from light-duty vehicles to medium- and heavy-duty applications, including trucks, trains, and ships.

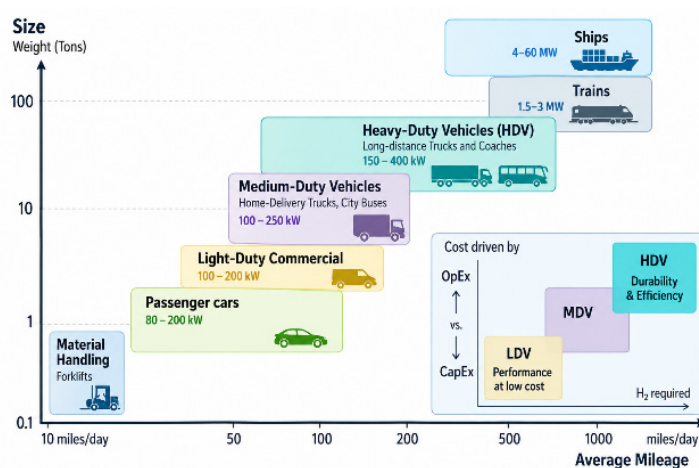


FIGURE 6. Relationship between vehicle power requirements, daily mileage, and the suitability of hydrogen fuel cell systems across light-, medium-, and heavy-duty transportation applications. Adapted from R. Borup et al. (2021)

Despite these promising developments, several challenges continue to limit the large-scale deployment of hydrogen fuel cell systems in heavy-duty transportation. These challenges include the high capital cost of fuel cell stacks, insufficient hydrogen refuelling infrastructure, stringent durability requirements under demanding operating conditions, and the need for large-scale production of low-carbon hydrogen. Continued advances in catalyst development, hydrogen storage technologies, manufacturing processes, and fuel cell durability are therefore essential to improve system performance, reduce costs, and strengthen the commercial competitiveness of heavy-duty fuel cell systems.

Overall, hydrogen fuel cells represent one of the most promising long-term solutions for decarbonizing heavy-duty transportation because they combine long driving range, rapid refuelling capability, operational flexibility, and low greenhouse gas emissions. Continued improvements in hydrogen production, refuelling infrastructure, fuel cell durability, and manufacturing technologies are expected to further accelerate the commercialization of hydrogen-powered trucks, trains, ships, aircraft, and other heavy-duty transportation systems.

CHALLENGES

Despite significant technological advances, the widespread commercialization of fuel cell technology continues to be constrained by interconnected technological, economic, infrastructural, environmental, and regulatory challenges. Although fuel cells offer high energy conversion efficiency, fuel flexibility, and low emissions, overcoming these barriers requires coordinated efforts among researchers, industry, policymakers, and energy providers. Progress in one area is often dependent on advances in another, highlighting the need for integrated strategies to establish a sustainable hydrogen economy.

From an environmental perspective, prospective life cycle assessment (LCA) indicates that future SOFCs are expected to exhibit substantially lower global warming potential (GWP) than current SOFC designs, supporting the development of more environmentally sustainable stationary fuel cell systems (Spreafico 2023). Nevertheless, the overall environmental performance of fuel cell technologies remains strongly dependent on the hydrogen production pathway. Green hydrogen produced through renewable-powered water electrolysis offers substantially lower environmental impacts, whereas hydrogen generated through fossil-fuel reforming significantly reduces these benefits because of associated carbon emissions. Furthermore, inconsistencies in LCA methodologies,

including differences in functional units, system boundaries, geographical assumptions, and allocation methods, complicate direct comparisons among published studies. Future sustainability assessments should therefore adopt standardized life cycle assessment methodologies that integrate environmental, economic, and social dimensions to provide more comprehensive, transparent, and consistent evaluations of fuel cell technologies (ElAgouz et al. 2026).

Economic competitiveness remains one of the principal barriers to large-scale commercialization. High capital costs are primarily associated with expensive catalyst materials, particularly platinum-group metals, sophisticated BoP components, hydrogen storage systems, and specialized manufacturing and installation requirements. Compared with mature energy technologies such as internal combustion engines, diesel generators, and conventional grid electricity, fuel cell systems continue to require substantially higher initial investment despite offering higher energy efficiency and lower operational emissions. Consequently, the high upfront cost remains a major factor limiting market penetration and industrial adoption. Although recent advances in non-platinum catalysts, automated manufacturing technologies, and economies of scale are expected to reduce production costs, achieving cost competitiveness with established energy technologies remains a significant challenge. In addition, fluctuations in hydrogen production costs, fuel prices, and maintenance requirements continue to influence the overall life-cycle cost of fuel cell systems.

Long-term durability and operational reliability represent equally important technical challenges. Material degradation resulting from prolonged operation, thermal cycling, catalyst sintering, membrane degradation, and corrosion progressively reduces system lifetime while increasing maintenance and replacement costs. In PEMFCs, membrane dehydration, catalyst poisoning by carbon monoxide and sulfur compounds, and repeated start-up and shutdown cycles accelerate performance degradation. Conversely, high-temperature fuel cells such as SOFCs experience thermal stress, mechanical degradation, and material incompatibility arising from prolonged exposure to elevated operating temperatures. These degradation mechanisms reduce electrical efficiency, shorten service life, and ultimately increase the total cost of ownership. Continued research is therefore required to develop advanced catalyst materials, durable membrane technologies, and intelligent control strategies capable of extending operational lifetime while minimizing degradation under dynamic operating conditions.

Hydrogen infrastructure development remains another major obstacle to the widespread deployment of fuel cell technologies. Unlike conventional fossil fuels, hydrogen requires dedicated production, storage, transportation,

distribution, and refuelling infrastructure, much of which remains underdeveloped in many countries. This situation creates the well-known “chicken-and-egg” dilemma, whereby limited hydrogen infrastructure discourages fuel cell adoption, while insufficient market demand discourages investment in new infrastructure. Additional technical challenges include hydrogen liquefaction, compression, long-distance transportation, storage safety, and refuelling station availability. These issues become even more significant in heavy-duty transportation, maritime applications, and aviation, where large hydrogen storage capacities and specialized refuelling facilities are required. Addressing these challenges will require coordinated investment in renewable-powered hydrogen production, storage technologies, distribution networks, and refuelling infrastructure to establish a reliable and economically sustainable hydrogen supply chain.

In addition to technological and economic considerations, comprehensive regulatory frameworks and internationally harmonized technical standards are essential for the safe and widespread deployment of fuel cell technologies. Although many countries have introduced national hydrogen strategies and decarbonization policies, regulatory requirements governing fuel cell installation, hydrogen handling, safety certification, and operational standards remain inconsistent across different regions. In residential and commercial buildings, compliance with building codes governing ventilation, electrical systems, energy efficiency, fire safety, and indoor air quality is essential to ensure the safe and reliable operation of stationary fuel cell systems (Anireddy 2024). The absence of globally harmonized standards increases certification costs, complicates international technology deployment, and slows market expansion. Consequently, stronger collaboration among governments, standards organizations, regulatory agencies, and industrial stakeholders is required to establish consistent regulatory frameworks that facilitate commercialization while maintaining high safety standards.

Despite these challenges, continued advances in catalyst development, membrane materials, hydrogen production technologies, manufacturing processes, and digital system optimization are expected to substantially improve the commercial viability of fuel cell technologies. Coupled with supportive government policies, expanding renewable energy deployment, and sustained investment in hydrogen infrastructure, these technological

developments are expected to accelerate the transition toward a sustainable hydrogen economy. Nevertheless, achieving large-scale commercialization will ultimately require integrated solutions that simultaneously address technological, economic, infrastructural, environmental, and regulatory barriers, rather than treating these challenges as independent issues.

CONCLUSION

Fuel cells have emerged as a key electrochemical energy conversion technology capable of supporting the global transition towards sustainable and low-carbon energy systems owing to their high energy conversion efficiency, fuel flexibility, and low environmental impact. This review demonstrates that the suitability of fuel cell technologies is highly application-dependent, with PEMFCs and DMFCs being particularly suitable for portable applications, PEMFCs representing the preferred technology for transportation because of their high power density, rapid start-up capability, and excellent dynamic response, and SOFCs together with MCFCs offering significant advantages for stationary power generation through their high electrical efficiency, fuel flexibility, and CHP capability. Despite these advantages, the large-scale commercialization of fuel cells continues to be constrained by interconnected technological, economic, infrastructural, environmental, and regulatory challenges, including high capital costs, material degradation, hydrogen production and distribution, limited refuelling infrastructure, and the lack of internationally harmonized standards. Continued advances in catalyst and membrane materials, hydrogen production and storage technologies, manufacturing processes, system integration, and digital control strategies, together with supportive government policies and coordinated investment in hydrogen infrastructure, will be essential to improve the durability, reliability, and economic competitiveness of fuel cell systems. Overall, sustained collaboration among researchers, industry, policymakers, and energy providers will be crucial to accelerating the commercialization of fuel cell technologies, enabling their widespread deployment across portable, transportation, and stationary applications, and supporting the global transition towards a sustainable hydrogen economy.

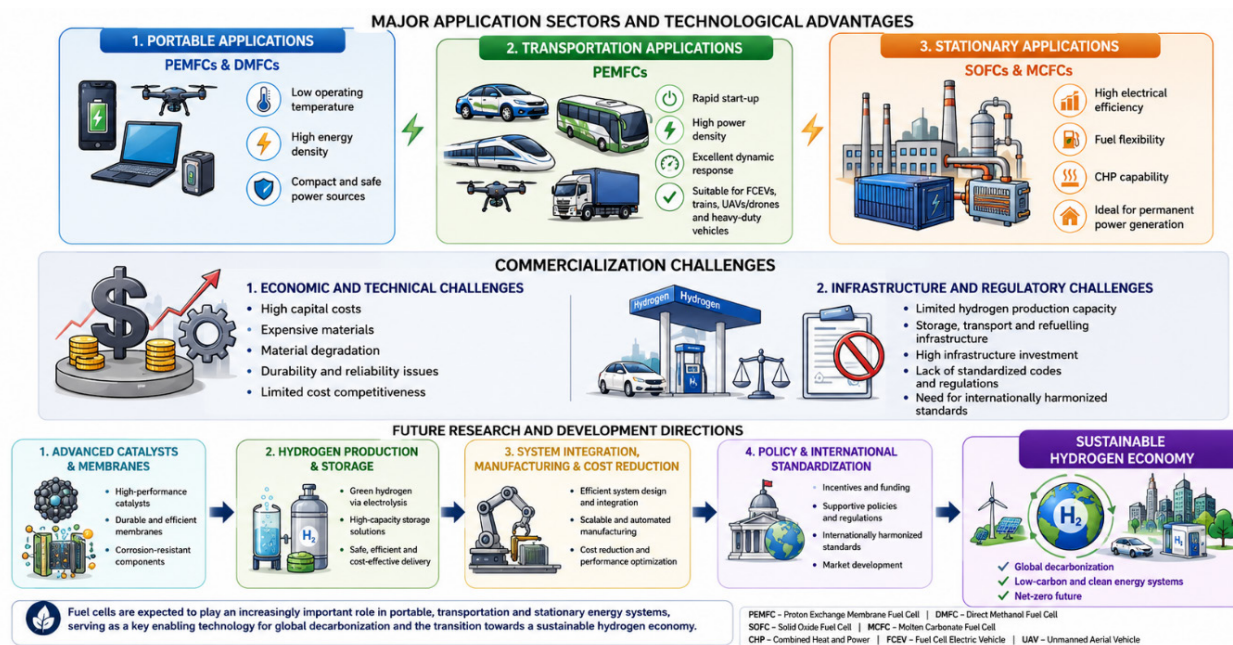


FIGURE 7. Schematic overview of fuel cell application sectors, commercialization challenges, future research directions, and the pathway towards a sustainable hydrogen economy

ACKNOWLEDGEMENT

This work was supported by the Ministry of Higher Education (MoHE), Malaysia through the research sponsorship under Prototype Development Research Grant Scheme (PRGS): PRGS/1/2024/TK08/UKM/02/1.

DECLARATION OF COMPETING INTEREST

None.

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