FUEL CELL VEHICLES IN MALAYSIA: A REVIEW OF CURRENT PROGRESS, OPPORTUNITIES, AND CHALLENGES FOR A SUSTAINABLE FUTURE

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ABSTRACT: Malaysia has recently accelerated efforts to integrate hydrogen-powered transportation into its broader sustainability agenda as part of its net-zero carbon by 2050's commitment. This review paper is to focus on fuel cell vehicles (FCV) in the Malaysian context. It incorporates the most recent policy frameworks, including the 2023 Hydrogen Economy & Technology Roadmap, and synthesises insights from demonstration projects such as the 2025 Putrajaya mobile hydrogen refueling station and Sarawak's hydrogen-powered buses and autonomous trams. The review examines current technological progress, infrastructure development, and government-led initiatives, while analysing Malaysia's policy and regulatory environment in relation to FCV deployment. This review aims to provide valuable insights into the feasibility of FCV in Malaysia and offer strategic recommendations for overcoming existing barriers. The finding shows that while FCV represent a strategic initiave for Malaysia's decarbonization, it successful adoption requires stronger public–private collaboration, expanded infrastructure, clear regulatory frameworks, and targeted incentives to stimulate demand. By addressing these barriers, Malaysia can leverage hydrogen mobility as a catalyst for sustainable transport and strengthen its position as a regional leader in the hydrogen economy.

KEYWORDS: *Fuel Cell Vehicles; Sustainable Transportation*

1.0 INTRODUCTION

The automotive industry is a vital component of modern transportation, facilitating economic expansion, urbanization, and worldwide connectedness. In Malaysia, this sector is rapidly expanding, with over 700,000 vehicles sold in 2023, a record high for the second consecutive year. This growth reflects rising consumer demand and more mobility availability, but it comes at a high environmental cost [1]. Malaysia's transportation sector is one of the greatest contributors to environmental degradation, primarily through greenhouse gas emissions. As vehicle numbers increase, so does demand for gasoline and diesel, resulting in increased fossil fuel consumption. This not only raises concerns about energy security, but it also contributes to poor urban air quality and worsens the effects of climate change [2-3].

Figure 1 represents CO_2 emissions by sector in Malaysia. The figure illustrates the distribution of greenhouse gas emissions across major economic sectors in Malaysia. Electricity and heat producers account for the largest share at 48.8 %. The transport sector follows as the second largest contributor with 22.3 %, underscoring the significance of road and freight transport as key emission sources. Addressing emissions from the transport sector constitutes a critical national priority for Malaysia, necessitating systemic interventions that incorporate alternative fuel vehicles, such as fuel cell vehicles. Given the sector's significant share of national greenhouse gas emissions, advancing transport decarbonisation is essential for achieving Malaysia's climate commitments, including its net-zero target, and for ensuring a sustainable, low-carbon transition in line with global sustainability goals [4].

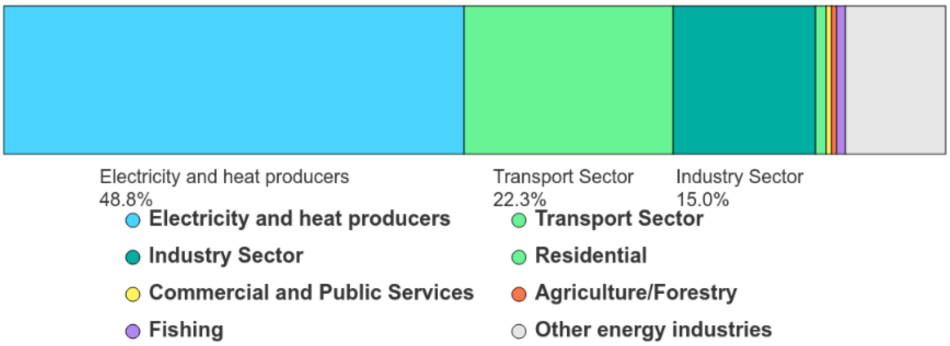

Figure 1: CO_2 emissions by sector in Malaysia (International Energy Agency, n.d.)

This paper aims to evaluate and compare various types of alternative fuel vehicles, with a particular emphasis on hydrogen fuel cell technologies, in order to determine their suitability within the Malaysian context. While numerous studies have examined the potential of alternative fuel vehicles globally, limited research has been directed towards assessing their applicability in Malaysia, especially in alignment with the nation's long-term strategies and commitments to achieving net-zero carbon emissions by 2050.

Furthermore, despite Malaysia's growing interest in renewable energy integration and sustainable transportation, there remains a lack of comprehensive analysis that directly connects the development of hydrogen fuel cell vehicles with the country's policy objectives and emission reduction targets. Therefore, this study seeks to bridge this gap by providing an evaluation of hydrogen fuel cell types and their feasibility, offering insights that can support Malaysia's transition towards a sustainable, low-carbon transportation system.

2.0 ALTERNATIVE FUEL CELL VEHICLES

The promotion of alternative fuel vehicles (AFV), that run on electricity, gas, or a liquid other than gasoline or diesel, is one of the main initiatives to reduce greenhouse gas emissions from the transportation sector. The automotive industry is now developing more environmentally friendly AFV as part of its efforts to go beyond traditional energy-based vehicles. It is expected that the economy and environment will benefit from the increase of environmentally friendly AFV. A variety of AFV types have been suggested.

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Natural gas, hybrid, biofuel, plug-in hybrid, advanced diesel, electric vehicles (EV), and hydrogen fuel cell vehicles (HFCV) have all been the subject of earlier research [5].

Table 1 provides a comparative assessment that highlights the relative strengths and limitations of the main types of AFV. In Malaysia, the adoption of EV remains restricted, with only a small fraction of consumers considering their purchase primarily due to the high upfront cost of EV units. The development of a widespread EV culture faces numerous challenges, including inadequate charging infrastructure, the absence of comprehensive EV policies, and the lack of local EV manufacturers. Further constraints include the limited availability of affordable vehicle designs, insufficient government incentives, the incompatibility of the existing power grid with large-scale EV integration, the relatively short driving range of available EV models, and high import taxes on EVs, all of which hinder widespread adoption [6-7].

Similarly, biofuel-powered vehicles are constrained by limited production capacity, high feedstock demand that competes with food supply, and concerns over lifecycle emissions that reduce their long-term sustainability. Natural gas vehicles (NGV), while offering relatively lower emissions than conventional fossil fuels, face limitations such as inadequate refueling infrastructure, lower energy density compared to gasoline, and high conversion or purchase costs that reduce their market attractiveness [8-12].

Because of their outstanding energy efficiency (between 40 % and 70 %), extensive driving range, and zero direct emissions (only water vapor), hydrogen fuel cell vehicles (HFCV) stand out as the most promising option among them. Furthermore, HFCV provide comfort and environmental advantages while running smoothly and quietly. Even though there are obstacles like high cost and inadequate refueling infrastructure, these are mostly caused by the technology's current commercialisation stage and can be resolved with the right funding and legislative backing.

Table 1: Different types of AFV [6-12].

AFV Type	Efficiency / Fuel economy	Environmental Benefits	Challenges
Battery Electric Vehicles (BEVs)	100 – 300 miles/charge. 100 miles consuming 25 – 40 kWh.	Zero direct emissions. Smooth and quiet operation.	High upfront cost; limited charging; grid stress. Shorter driving range CO_2 formation from batteries production
Hybrid electric vehicle and plug-in hybrid electric vehicle (HEVs; PHEVS)	35 – 50 % energy efficiency 100 Miles Per Gallon equivalent (MPGe). 100 miles / 20-40 KWh	Reduction in GHG emissions. Reduction in tailpipe emissions.	Shorter driving range; higher charging time; higher purchasing cost
Hydrogen Fuel Cell Vehicles (HFCVs)	40 – 70% energy efficiency. 1.05 Kg of hydrogen for each 100 Km.	Zero Emissions. Operates quitter and smoother	High cost; sparse infrastructure; Safety considerations regarding hydrogen tanks and fueling systems.

Hydrogen ICE Vehicles	25 – 30% energy efficiency 1.79 kg-H_2/100 km	equipped for work in difficult weather conditions, reliable and convenient	Low efficiency. Release of nitrogen oxides, hence exhaust gas treatment is necessary to lower NOx emissions.
Natural Gas Vehicles (CNG/LNG)	25 – 30% energy efficiency. 3.5-4 kg CNG/100 Km	Reduce GHG emissions by 10–20% compared to gasoline vehicles.	Heavy tanks; limited fueling; lower driving range, high purchasing cost.
Biofuels (e.g., HVO, Ethanol blends)	20 – 25% energy efficiency. Lower fuel economy.	Reduction in exhaust emissions. Reduction in GHG emissions by 74% compared with diesel fuel.	Higher fuel cost; Increasing in NOx; cold starting problems, lower fuel economy; lower energy density

3.0 HYDROGEN FUEL CELL VEHICLES

Fuel cells are electrochemical devices that turn a reaction's chemical energy into electrical energy immediately. An electrolyte layer in contact with a porous anode and cathode on each side is the basic physical structure or building component of a fuel cell. Figure 2 represents a schematic picture of a fuel cell with the reactant/product gasses and ion conduction flow directions across the cell [13].

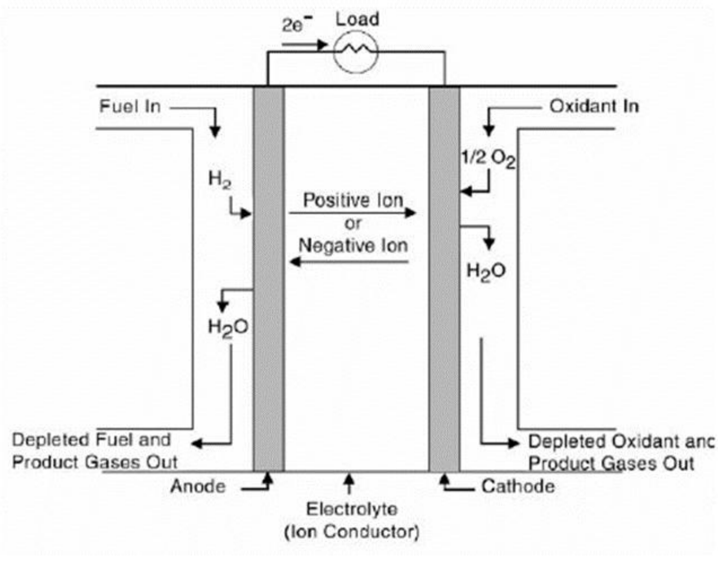

Figure 2: Schematic representation of fuel cell [13].

Gaseous fuels are continually delivered to the anode (negative electrode) compartment, and an oxidant (i.e., oxygen from the air) is continuously fed to the cathode (positive electrode) compartment in a conventional fuel cell; electrochemical reactions occur at the electrodes to create an electric current. A fuel cell varies from a standard battery in various ways, while having identical components and features. The amount of chemical reactant contained within the battery determines the maximum energy available. When the chemical reactants in the battery are depleted, the battery will stop producing electrical

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energy (i.e., discharged). Recharging, which includes injecting energy into the battery from an external source, regenerates the reactants in a secondary battery. The fuel cell, on the other hand, is an energy conversion device that may potentially produce electrical energy as long as the electrodes are supplied with fuel and oxidant. In actuality, the practical operational life of fuel cells is limited by component degradation, particularly corrosion and malfunction [8, 13].

A number of distinct fuel cells are at various phases of development. They can be divided into various categories based on the type of fuel and oxidant used, whether the fuel is processed outside (external reforming) or inside (internal reforming) the fuel cell, the type of electrolyte used, the operating temperature, and whether the reactants are fed to the cell through internal or external manifolds, among other factors [14].

Table 2 below presents a comparative overview of the main types of fuel cell technologies currently applied or considered for use in fuel cell vehicles. Each type of fuel cell—such as Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel Cells (SOFC), and others—differs in terms of the fuel they use, the electrolyte material, operating temperature, and system efficiency. These differences affect their suitability for specific applications ranging from passenger cars to heavy-duty vehicles and portable power devices. The table also outlines the key advantages, such as energy efficiency and environmental performance, along with notable technical or infrastructural challenges that may hinder widespread adoption. This comparison provides essential insights for policymakers, researchers, and industry stakeholders looking to support the development and deployment of FCV in various sectors [14-17].

Table 2: Different types of fuel cells [14-17].

Type of Fuel Cell	Fuel	System Efficiency	Output power range	Suitability for Vehicles	Advantages	Challenges
PEMFC (Proton Exchange Membrane Fuel Cell)	Pure hydrogen	40–60%	Up to 250 KW	Passenger cars (e.g., Toyota Mirai, Honda Clarity); buses; unmanned aerial vehicles	Lightweight; Small size; Fast startup and load times	Sensitive to impurities; requires high-purity hydrogen; costly platinum catalyst
SOFC (Solid Oxide Fuel Cell)	Hydrogen, natural gas, biogas	45–65% up to 85% with combined Heat and Power (CHP)	From 5 up to 3000 KW	Trucks, maritime.	fuel flexibility, and high efficiency Fit for CHP	High operating temperature (600–1000°C); long start-up time
PAFC (Phosphoric Acid Fuel Cell)	Hydrogen methanol	~40 - 50%	From 50 up to 1000 W	Rarely used in vehicles; more suitable for stationary applications	Increased tolerance to fuel impurities	Moderate efficiency; acid management; slow start-up; sulfur sensitivity

AFC (Alkaline Fuel Cell)	Hydrogen	45–60%	From 10 up to 100 KW	space vehicles; niche military	Low operating temperature; quick startup	CO_2 sensitivity; electrolyte degradation
DMFC (Direct Methanol Fuel Cell)	Methanol (liquid)	~ 30%	Up to 100 KW	Can be used in light-duty electric vehicles	Low cost and operational temperature; high power density	Lower efficiency; methanol crossover; slow kinetics
MCFC (Molten Carbonate Fuel Cell)	Hydrogen, natural gas, biogas, CO	50-60%	Up to 1000 KW	Heavy-duty transport, marine.	Fuel variety; High efficiency	Very high operating temperature (~650°C); complex system design; CO_2 management

PEMFC dominate vehicular hydrogen applications due to low operating temperature, rapid cold- and hot-starts, high power density, and compatibility with transient duty cycles typical of urban buses and mixed-traffic logistics. Malaysia's tropical climate eliminates extreme cold-start penalties and favors the thermal management envelope of PEM stacks. Moreover, the occurrence of stop-start urban bus routes, airport shuttles, and port drayage creates duty cycles where fast refueling and high uptime are decisive. Local universities and research institutes have concentrated on PEMFC stack diagnostics, humidification control, degradation mitigation in humid conditions, and hydrogen quality assurance, topics directly relevant to Malaysian operating environments where moisture, heat, and particulate exposure are non-trivial (18-19].

4.0 MALAYSIA'S PROGRESS IN FELL CELL DEVELOPMENT

Malaysia is progressively embracing hydrogen fuel cell vehicles as part of its broader alternative fuel vehicle strategy to achieve net-zero carbon emissions by 2050. This commitment is reflected in national frameworks such as the National Energy Policy 2022–2040 and the forthcoming National Hydrogen Economy and Technology Roadmap (HETR), which identify hydrogen as a strategic low-carbon energy carrier [20-21].

The state of Sarawak has positioned itself as a hydrogen pioneer, having launched Asia's first hydrogen-powered buses in Kuching and built Southeast Asia's first integrated green hydrogen production and refueling station. Sarawak aims to expand this fleet to over 100 hydrogen buses by 2030 as part of its green mobility and smart city initiatives [22].

On a national level, PETRONAS established a dedicated Hydrogen Business Unit and is working toward scaling both green and blue hydrogen production, with mobility applications included in its long-term plans. The Ministry of Science, Technology and Innovation (MOSTI) has also been promoting local hydrogen research and development, emphasizing collaborations between industry and academia to boost FCV deployment. Malaysia's future roadmap includes expanding hydrogen refueling infrastructure in urban and industrial hubs, integrating FCV into public and commercial fleets, and leveraging hydrogen exports to fund domestic hydrogen mobility growth. Although still emerging, hydrogen FCV is expected to play a crucial role in decarbonizing Malaysia's transport sector, particularly where efficiency, refueling speed, and long-range capabilities are critical [23].

Malaysia aims to introduce hydrogen as a key alternative fuel in the transport sector to support its Net Zero GHG emissions goal by 2050. The roadmap identifies hydrogen-powered mobility, especially FCEV and hydrogen buses, as early-use applications due to their zero-emission profile and suitability for long-range, heavy-duty transport. The strategy envisions Malaysia becoming both a hydrogen producer and user, starting with domestic demand, particularly in the public transport sector (buses and rail) before expanding to private FCEV and eventually exporting green hydrogen technologies [21,24]. Table 3 summarizing the strategic phases for hydrogen in transportation in Malaysia.

Table 3: Different types of fuel cells [21-23].

Phase	Timeframe	Description	Stakeholders
Short-Term	2021–2030	- Focus on pilot projects (e.g., hydrogen buses in Sarawak and mobile refueling in Putrajaya). - Develop early hydrogen refueling infrastructure. - Promote local R&D and component manufacturing (e.g., PEMFC development). - Begin integrating hydrogen use in fleet and public transport systems.	• MOSTI (policy and innovation support) • PETRONAS (hydrogen production & infrastructure) • Sarawak Energy & SEDC Energy (regional hydrogen pilot projects) • MGTC (coordination of low-carbon mobility) • Local universities (UKM, UTM, IIUM) (R&D and prototype development)
Medium-Term	2031–2040	- Scale up hydrogen production (including green hydrogen via electrolysis). - Deploy more extensive hydrogen refueling networks across key transport corridors. - Encourage local manufacturing of FCEVs, including buses and light-duty vehicles. - Foster public-private partnerships for technology transfer and investment.	• PETRONAS & TNB (scaling green hydrogen production and grid integration) • MIDA & MITI (industrial investment and incentives) • Automotive OEMs (PERODUA, PROTON, TOYOTA, HYUNDAI) (local manufacturing and assembly) • PPP initiatives (domestic & international investors) • MOF & EPU (financing and policy alignment)
Long-Term	2041–2050	- Achieve mass commercialization of hydrogen vehicles. - Integrate hydrogen into the national mobility and logistics framework. - Leverage Malaysia's position as a regional hydrogen hub to support fuel cell vehicle exports.	• PETRONAS (regional hydrogen exports and infrastructure leadership) • MITI & MATRADE (export promotion and trade facilitation) • TNB & National Grid Operators (energy supply and system integration) • Private sector (automotive, logistics, energy companies) (mass commercialization and global partnerships)

Despite recent advancements in Malaysia's hydrogen roadmap, such as the 2023 Hydrogen Economy & Technology Roadmap (HETR), which identifies hydrogen as a pivotal "transition lever" for reaching net-zero by 2050, substantial gaps remain, particularly in the transportation sector's decarbonization strategy. Notably, there is a critical absence of a comprehensive life cycle assessment (LCA) for hydrogen production and FCV deployment in the Malaysian context, which hinders understanding of the full environmental trade-offs across the hydrogen value chain from generation to storage, distribution, and vehicle operation. While international studies have developed LCA frameworks for hydrogen-fueled buses and vehicles in other jurisdictions (e.g., comparisons of hydrogen, electric, and diesel buses; and cradle-to-gate and well-to-wheel analyses) [25-26].

Secondly, an impractical timespan is proposed for the hydrogen go-to-market plan. This is because Malaysia still has abundant reserves of fossil fuels, and it requires a high cost for current hydrogen production and utilization [26]. In addition, the absence of clear and consistent policies, coupled with fragmented guidance from relevant stakeholders, creates significant uncertainty in the hydrogen transition pathway and consequently slows down the progress of decarbonization efforts in the transportation sector [27].

5.0 CHALLENGES AND BARRIERS

The development of the fuel cell market in Malaysia faces several significant challenges that could delay its growth and widespread adoption. A primary obstacle is the high initial cost associated with fuel cell technology and the necessary hydrogen infrastructure development, which limits large-scale implementation. This financial barrier is compounded by the lack of a comprehensive hydrogen refueling network, particularly in regions outside major urban centers, affecting the confidence in vehicle range and complicating fleet planning. In addition to economic challenges, there are technical issues that need to be addressed. These include concerns related to hydrogen storage safety, the durability of fuel cells in Malaysia's tropical climate, and the standardization of vehicle components. Furthermore, regulatory and policy uncertainties pose risks, as inconsistent incentives and delays in implementing supportive frameworks can diminish investor confidence and hinder market development [28].

Several significant obstacles must be addressed to enable widespread adoption, including public perception and acceptance, inadequate infrastructure, competition from other vehicle technologies, regulatory limitations, vehicle performance, and user costs. While innovation and technological progress in hydrogen fuel cell vehicles (FCV) indicate that they are ready for deployment in Malaysia, these advancements alone are not enough to drive a rapid transition. In contrast, developed nations have accelerated adoption by pairing strong government backing with evolving societal values toward environmental sustainability [29].

Understanding consumer preferences and demand is recognized as an essential factor. Although Malaysian consumers express concern for environmental issues, this concern does not consistently influence their purchasing decisions regarding alternative fuel

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vehicles. As a result, the government's role becomes even more critical in facilitating the shift toward renewable energy sources like hydrogen. For developing nations, the challenge of encouraging consumer behavior that supports environmentally friendly vehicles is notably more difficult. This is why energy-importing countries often take the lead in pursuing alternative energy solutions. In Malaysia's case, the situation is further complicated by its recent status as a net energy importer, highlighting the urgent need for innovation and a transition toward a sustainable energy system, one that demands focused attention from policymakers [29-31].

6.0 CONCLUSION

Fuel cell vehicles, particularly proton exchange membrane fuel cell (PEMFC) vehicles, present Malaysia with a strategic pathway to decarbonize transport and achieve its 2050 net-zero target. PEMFC is well-suited for Malaysia's climate and transport needs due to their low operating temperature, rapid start-up, and high efficiency. Malaysia has taken steps through the Hydrogen Economy and Technology Roadmap (HETR) and the National Energy Transition Roadmap (NETR), supported by initiatives such as Sarawak's hydrogen buses and refueling stations. However, progress is constrained by high technology costs, limited infrastructure, and evolving regulatory frameworks. To overcome these gaps, Malaysia must strengthen policies, foster public–private partnerships, and incentivize adoption to scale up infrastructure and reduce costs. With targeted support and alignment to long-term energy goals, hydrogen FCV can shift from niche projects to mainstream mobility solutions, positioning Malaysia as a regional leader in hydrogen transportation.

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