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RECENT DEVEPOPMENTS IN IMPROVING THE FUEL ECONOMY AND PERFORMANCE OF A FUEL CELL HYBRID ELECTRIC VECHICLE

by

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Abstract

The transition to a sustainable mobility requires technologies capable of achieving simultaneously the reduction of greenhouse gas emissions as well as an increase in energy efficiency and providing reliable performance under real transportation applications. Fuel cell hybrid electric vehicles (FCHEVs) have emerged as a promising solution that combines the high energy density of hydrogen fuel cells with the flexibility and responsiveness of battery energy storage systems. By integrating both of these energy sources, FCHEVs provide greater driving range, faster refueling ability, and better dynamic performance to overcome many of the shortcomings of both battery electric vehicles and traditional internal combustion hybrids.

This thesis explores recent developments (2020-2025) in the improvement of fuel economy and performance of FCHEVs, focusing on both technological developments and strategies of integration in systems. It discusses the foundational concepts of electrochemistry and electrocatalysis on which the operation of fuel cells is based and the importance of electrochemical devices for the conversion and storage of energy. Important aspects of fuel consumption such as energy management strategies, regenerative braking technologies, thermal management, aerodynamic optimization and lightweight material design are reviewed in detail.

Further analysis is devoted to the advances of proton-exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs), and new hybrid architectures including batteries and supercapacitors to increase the system reliability and efficiency. Comparative analyses between FCHEVs, battery electric vehicles (BEVs), and internal combustion hybrid vehicles showcase the pros and cons in terms of sustainability, range, cost, and operational feasibility.

Finally, the thesis wraps up with a critical discussion of the prospects and challenges making up the future of FCHEVs, such as technological innovations, deployment of hydrogen infrastructure, regulatory frameworks, and market acceptance. In summary, the results highlight that FCHEVs are a feasible route to low-carbon mobility, especially in heavy duty and long-range applications, where the hybrid nature of the vehicle offers unique performance and sustainability advantages.

Keywords

Fuel Cell Hybrid Electric Vehicles (FCHEVs); Hydrogen Mobility; Fuel Economy; Energy Management; Regenerative Braking; Electrochemical Energy Storage; Sustainability; Automotive Innovation

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CHAPTER 1

Introduction

1.1. Scope and Objective of the Thesis

The challenge which international community has been struggling to address in the recent few years involves both cutting down of greenhouse gases and achieving energy security, which are the two issues which are interrelated. In this context, it is noticeably hard to mitigate carbon dioxide (CO_2) emissions based on transport means since this industry is significantly based on fossil energy. Another approach which has been suggested as a primary avenue to carbon neutrality in transport is electrification, and in this specific case, of fuel cell electric vehicle (FCEV) technology.

Current thesis focuses on recent developments geared towards surpassing fuel economy and performance in fuel cell hybrid electric vehicles (FCHEVs). The use of hydrogen is combined with the vehicles in which energy density is high with the fuel cell accompanied by the high efficiency use of energy storage in batteries, thus extending the range, performance, and reduced environmental influence. The existing research and development focuses are mainly on the technologies that place more emphasis on enhancing energy efficiency, limiting energy wastage, and improving reliability and applicability trough actual driving environments.

The major aim of the study is to give a structured overview--and critically review-- of concepts and technological advances (2020-2025) in the following topics:

1. energy management strategy development;

2. increase in fuel economy by innovating in recovery of energy and minimizing losses;

3. fuel cell material and geometrical architectural advances;

4. incorporation of intelligent control mechanism based on the application artificial intelligence (AI) and machine learning (ML) algorithms.

The research attempts to synthesize and interpret existing scientific findings on this topic by applying a literature-based research approach as opposed to systematic review methodology trying to address practical advances in current existing or prototype FCHEVs. Unlike what it has been, the research is beyond the fuel cell as an energy production aspect, but it extends to the broader design of the propulsion system, the part played by the hybrid configuration, and the overall energy architecture of the vehicle itself (Feng et al., 2023).

Moreover, this thesis also contrasts FCHEVs and the low-emission technologies, like Battery Electric Vehicles (BEVs), and Plug-in Hybrid Electric Vehicles (PHEVs). The contrast sets the conversation in the context of the present-day implications of transport, sustainability, and the continuation of the energy transition (Elgowainy et al., 2015).

Thus, the thesis gives the reader an objective, multifactorial, and current general review of the history of development of FCHEV technology regarding fuel economy and efficiency, clarifying the current issues, successes, and possible futures of the industrial activity.

1.2. Importance of Fuel Cell Technology in Hybrid Vehicles

Fuel cell (FC) technology has been considered potentially one of the most efficient transportation decarbonization pathways after the technology was developed with the potential to facilitate high energy efficiency and zero point of use emissions. Unlike the internal combustion engines, FCs spend the chemical energy of hydrogen directly to electricity by an electrochemical energy release emission, resulting in the only water and heat by-products (Barbir, 2020). The trait makes FC systems appealing to the automotive industry, particularly in a high-decimal global context that has pledged itself to fast decarbonization efforts.

Application of FC technologies in Fuel Cell Hybrid Electric Vehicles (FCHEVs) provides a number of benefits as compared to electric and traditional thermal vehicle. The hybridization of a fuel cell with a system able to store energy, usually either battery or ultracapacitors, enables the distribution of energy loads more efficiently. When there is low power demand or braking, electrical power is drawn by the energy-storage system or it would recover kinetic energy and during high-power demand, the FC would produce a stable electrical power (Yue et al., 2023).

The hybrid system is especially large since it shortens the mature power density that is inherent to hydrogen along with taking advantage of the instantaneous characteristics of electrochemical energy storage devices to offer a propulsion system that can respond to variations in power requirement. This framework reduces the use of hydrogen, improves fuel use, and extends the life length of the FC because it limits thermal stress and degradation caused by indefinite load changes (Lyu et al., 2024).

A significant benefit of FCHEVs that can be enjoyed has to do with the range of driving distance and the speed of refueling which are better than battery electric vehicles (BEVs). After typically 3 to 5 minutes, an FCHEV may fill up its hydrogen tanks and provide a range of nearing or reaching 500 kilometers regardless of the electrical charging infrastructure (Elgowainy et al., 2020). These attributes make the technology specifically suited to heavy-duty trucks, buses, long-haul trucks, and fleet.

Meanwhile, FCHEVs can support other goals of energy diversification and decentralization since hydrogen may be produced through various sources, with electrolysis, biomass, and natural gas with CO_2 capture being the three most relevant to them, and it can be transported and stocked flexibly, which allows it to match the principles of the circular economy and sustainable transition of green energy as a whole (IEA, 2023).

Overall, fuel cell technology in hybrid cars is a critical component towards building a sustainable transportation system that has high-performance results with low environmental impact. The recent breakthroughs in design, energy management, and the production of materials may mean that FCHEVs cannot be discussed as a stop-gap solution, but these are the long-term answers to the transport challenges of the twenty-first century.

1.3. Structure of the thesis

This current thesis gives a methodical description of the technology of a Fuel Cell Hybrid Electric Vehicle (FCHEV), with particular focus on fuel economics and power efficiency. It is written in bibliographic fashion; the substantive contents of one chapter form the basis upon which subsequent ones were written, and the end result is that together they provide a complete picture not only of the technological development but also of the nature and performance of the various technologies and their outlook.

In Chapter 1, the author provides the introduction to the topic, its relevance, and objectives of the research. It places FCHEV technology in the context of current trends in energy and environmental policy, justifies the reasons to select it, and determines the general direction of research. There is also talk about relevant trends on sustainable-mobility.

The second chapter forms the theoretical background of the thesis. Electrocatalysis and electrochemical principles, which form the foundation of fuel-cell behavior are discussed, and finally, electrochemical devices (in which energy is converted to and stored in electrochemical form) are explored. The interrelation between these devices and the interactions between them and within the FCHEV energy ecosystem are outlined.

Chapter 3 explores the main factors that are causing fuel consumption in fuel-cell vehicles. Strategies of energy-management, regenerative-braking systems, methods of minimizing energy and thermal losses and the impact of aerodynamic design and rolling resistance are put into consideration. The chapter is close with an overview of the more advanced materials and techniques to design that allow to exercise a weight loss on the vehicle as well as optimizing the overall performance.

The fourth chapter explains the basic working principles of the fuel cell and new technological developments observed between 2020 and 2025. The differences between the types of fuel-cells, especially PEMFCs and SOFCs, as well as the most recent hybrid configurations that combine better energy-management and storage strategies are explained. The classification of FCEVs and FCHEVs along with their energy efficiency and the benefit that hybridization has to offer is also discussed in the chapter. They include comparisons with battery-electric and hybrid internal-combustion-engine vehicles in a range, sustainability, and overall cost of ownership comparison.

Chapter 5 talks about future opportunities and issues that revolve around FCHEV development. The avenues identified in the near future technological advances such as the enhancements of fuel-cells and the associated systems needed to refuel are tested. Policies and rules that created the trend in the adoption of FCHEVs are discussed, and the chapter provides a critical analysis of recent tech trends.

Chapter 6 is the last one of the thesis, a conclusion of the main findings and a possible direction of the continuity of research in FCHEV technology. The rest of technical issues are mentioned, the possibility of FCHEV as a sustainable and innovative mobility solution in a future without fossil fuel energy is outlined.

CHAPTER 2

Theoretical Background

2.1. Principles of Electrochemistry & Electrocatalysis

Fuel cells are used to change chemical energy, typically that of hydrogen, into electrical energy through a process known as the electrochemical reaction. The process of operation resembles how a water electrolysis is driven; in this scenario, hydrogen is oxidized at the anode and oxygen is reduced at the cathode, which leads to the generation of electrical current, heat, and water as the only by-product (Barbir, 2020).

A basic fuel cell is a device made up of two electrodes (an anode and a cathode), an electrolyte allowing the movement of specific ions and an external circuit enabling the transport of the electrons. Hydrogen (H_2) binds to the surface of the electrocatalyst at the anode and splits into protons (H+) and electrons (e-). The protons are moved through the electrolyte to the cathode, the electrons through the external circuit which supplies the electrical power to the load. On the other side, or the cathode, the protons and the electrons react with oxygen (O_2) to give water (H_2O) to complete the electrochemical cycle.

The general switch may be symbolized as:

Anode reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

Cathode reaction:

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Overall cell reaction:

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O + \text{electricity} + \text{heat}$$

The possibility of alternative fuel pathways, like direct alcohol fuel cells, is a topic of much interest in the energy sector and has highlighted both their potential for a sustainable mix of energy sources and the technological obstacles which remain before they can be widely adopted (Song et al., 2007). Apart from alcohols, hydrocarbon utilization research has shown that methane can be activated on perovskite type oxides such as $La_{0.6}Sr_{0.4}Co_{0.8}Fe_{0.2}O_3$ and give promising catalytic and electrocatalytic performance results (Tsiakaras, et al., 1998). Earlier work on the electrochemistry of methane has also shown the feasibility of oxidative coupling on silver catalyst-electrodes supported on yttria-stabilized zirconia, which gives important information on the hydrocarbon activation pathways (Tsiakaras & Vayenas, 1993).

Three main aspects are determinant in the performance of electrochemical fuel cells: first, the kinetics of electron and ion transportation; second, the inherent chemical stability of the electrode materials; and third, the electrocatalytic activity of the catalyst that acts to reduce respective reaction barriers without being affected by them (Debe, 2012). A key idea in this field is the so-called non-faradaic electrochemical modification of catalytic activity (NEMCA effect) which has been established for reversibly promoting platinum group metal catalysts under polarization conditions (Vayenas et al., 1990).

Simulation studies also have shown that anode reaction models of direct ethanol fuel cells can be utilized to gain useful insight into the kinetics and optimization of electrocatalytic processes (Andreadis et al., 2006). It is also worth noting that the types of current commercial techniques mostly use noble metal, most significantly platinum (Pt) catalysts predominantly attributed mainly due to their high activity and stability especially in Proton Exchange Membrane (PEM) processes (Wang et al., 2019). However, the high expense and, in some cases, dwindling supply sources of these noble materials are a very tough barrier to widescale commercialize fuel-cell technology. Besides the issues associated with catalyst cost and durability, operational inefficiencies may also be caused by parasitic currents which degrade the overall electrochemical performance of PEM fuel cells.

There are studies proving that such flows can greatly decrease the efficiency and accelerate degradation mechanisms especially in direct ethanol PEMFC systems (Andreadis et al., 2008). To better illustrate the fundamental operating principles and design features of a proton exchange membrane (PEM) electrolyzer, **Figure 1** provides a schematic representation of its main components, associated processes, and research directions related to cost reduction and catalyst optimization.

Electrocatalysis is a subdiscipline of electrochemistry that is concerned with the study of the electrode processes in a systematic fashion. Its studies clarify the surfaces phenomena at atomic and molecular level, determine the exact location of the catalytic sites and fine tune reaction kinetics. The most common method to quantitatively evaluate the performance of electrocatalysts is usually through analysis of the electrochemically active surface area (ECSA), i.e., the current used to react at a fixed area, and the overpotential required to drive the desired reaction. Empirical optimization methods thus focus on maximizing a certain catalytic activity, lower the cost per kW, and maintain functionality under operational conditions that are realistic (Etesami et al., 2021).

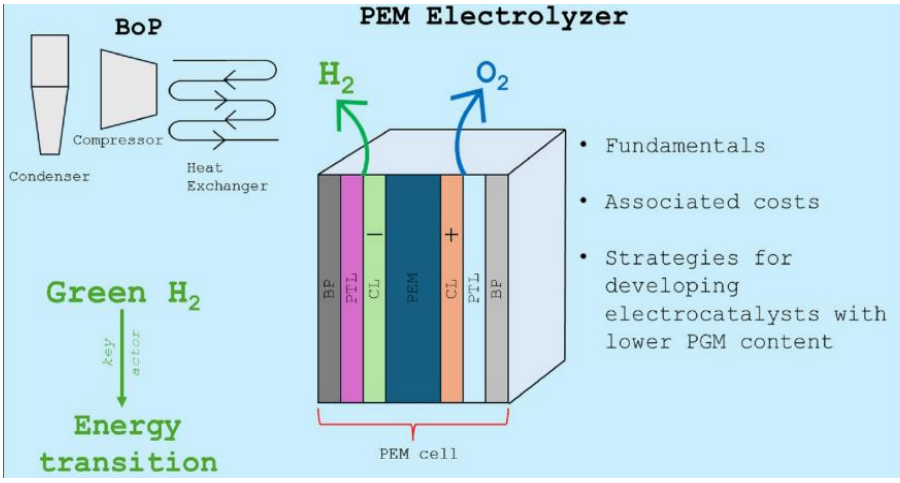

Figure 1. Schematic illustration of a Proton Exchange Membrane (PEM) electrolyzer and its balance-of-plant (BoP) components, including condenser, compressor, and heat exchanger. The PEM cell structure consists of bipolar plates (BP), porous transport layers (PTL), catalyst layers (CL), and the polymer electrolyte membrane (PEM). During operation, water electrolysis generates hydrogen (H_2) at the cathode and oxygen (O_2) at the anode. Green hydrogen, produced through this process, is recognized as a key enabler of the energy transition. The figure also emphasizes the fundamental aspects of PEM electrolysis, associated costs, and ongoing strategies to develop electrocatalysts with reduced platinum group metal (PGM) content (Araújo et al., 2024)

Recent studies confirm that new materials with nanostructuring properties, including PtCo alloys, carbon doped substrates and single-atom catalysts, are more clearly improving catalytic performance and also have significantly greater stability against poisoning by contaminants, primarily carbon monoxide (Li et al., 2025). In the light of the above, recent reviews on CO-tolerant Pt-based electrocatalysts for hydrogen-fed PEMFCs have highlighted the great progress that has been made and that, nevertheless, there are still problems to be addressed for the large-scale commercialization of this technology (Molochas & Tsiakaras, 2021). In particular, single noble metal atoms embedded in two-dimensional materials have been demonstrated to be greatly promising catalysts with high catalytic activity and stability, which paves a new pathway in high-performance electrocatalyst design (Liu et al., 2021). These advances also underscore the potential of innovative electrochemical materials more broadly, which are being explored not only for energy conversion applications but also for sensitive detection-related applications, including as biosensing platforms for viral pathogens such as the coronavirus, or in the case of the latter, a chemical agent such as carbon monoxide. These advances also highlight the potential of innovative electrochemical materials, which are currently being explored not only for energy conversion applications but also for sensitive detection-related applications, including as biosensing platforms for viral pathogens such as the coronavirus (Balkourani et al., 2021) or, in the case of the latter, a chemical Simultaneously, the deposition of nanoparticles on conductive substrates, especially carbon nanotubes and graphene, is being optimized in order to both increase the active surface area, as well as to maximize stability of catalysts over a series of operation cycles. In addition, recent comprehensive reviews highlight the cost-effective synthesis of graphene-based nanomaterials, which not only improve the electrochemical performance but also extend their application scope to non-enzymatic sensing platforms, for example, glucose sensing (Balkourani et al.,, 2022).

To highlight the diverse approaches applied in tailoring nanomaterials for enhanced energy and catalytic applications, Figure 2 presents the main strategies of chemical functionalization of carbon nanomaterials, showcasing representative examples such as graphene, carbon nanotubes, graphene nanoribbons, nanoparticles, DNA molecules, and peptides.

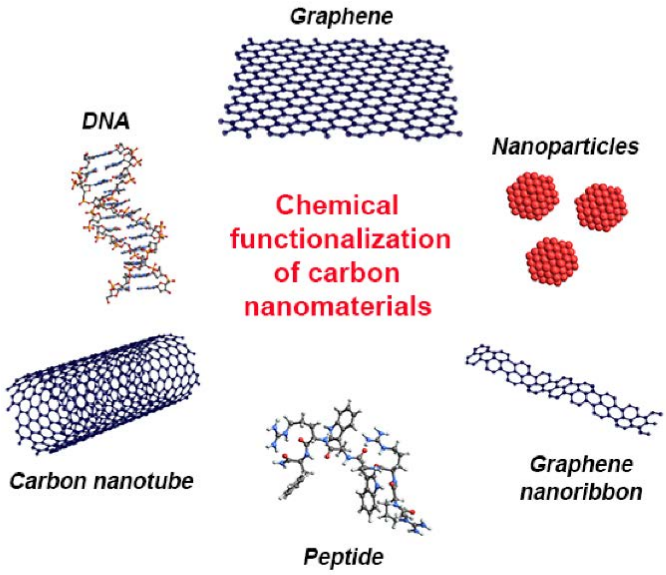

Figure 2. The main strategies of carbon nanomaterials chemical functionalization are outlined in the current illustration. The encapsulating term Chemical functionalization of carbon nanomaterials stands in the middle of the diagram yet there are peripheral blocks representing exemplars namely graphene, carbon nanotubes, graphene nanoribbons, nanoparticles, DNA molecules, and peptides. The functionalization process commonly makes these materials more water-soluble, high stability, enhances biocompatibility, and improves electrochemical functions, which expand the application field of such materials in the field of energy, electronics, and biomedicine (Burdanova et al., 2021).

Such trends are highlighted by nitrogen-doped hierarchical mesoporous carbon structures in which palladium nanoparticles have been demonstrated to exhibit high electrocatalytic activity and sensitivity for the simultaneous detection of biomolecules of interest such as ascorbic acid, dopamine, and glucose (Brouzgou et al., 2019). Understanding electrochemical processes and electrocatalytic reactions is also a challenging understanding that is essential not only in fundamental mechanism but also in providing the potential advantages of use in fuel-cell vehicles. Such catalytic interfaces have a major impact on numerous performance indices which include:

- the cold-start transient processes are efficient,
- The rate of propulsion system action,
- The general efficiency of the conversion of energy,

- And the robustness and extended reliability of system.

Therefore, further evolution of the electrocatalyst design, selection, and optimization will be at the heart of the further development of high-performance and sustainable FCHEV technologies.

2.2. Electrochemical Devices for Energy Conversion and Storage

The application of the electrochemical devices makes them constitute significant technological pillars of the world energy transition owing to the realization that they present the provision of sustainable and efficient means of converting and storing energy. In this field, the two primary categories are fuel cells, which convert chemical energy into electrical energy, and batteries, which store electrical energy and subsequently release it through reversible electrochemical reactions (Armand & Tarascon, 2008).

Fuel cells belong to the major electrochemical energy generators providing electric power by oxidizing fuel, which is externally supplied, most frequently a hydrogen or methanol. Through this process, fuel cells have the capability of producing power nonstop as long as there is fuel, which eliminates the need to have frequent recharging. This feature makes them especially appealing to high-autonomy usage, such as long-range vehicles (Barbir, 2020; IEA, 2023).

Another important electrochemical technology greatly relating to fuel cells is the **electrolyzers** that allow us to produce hydrogen in the form of water electrolysis. Electrolyzers generate a clean and flexible energy carrier, hydrogen, by splitting water molecules into hydrogen and oxygen through the application of an external electric current (Turner, 2004). The latest development in electrocatalysts design, for example, Mn-doped Ni_2P microstructures on nickel foam, has shown high efficiency for overall water splitting with promising ways for scalable hydrogen production (Li et al., 2020). The other research progress is also achieved with bifunctional hybrid catalysts, for example, Ni-NiO-MoNi, which shows great activity in both urea oxidation and hydrogen evolution reactions, thus expanding the range of sustainable hydrogen production technologies (Xu et al., 2020). Another development is the electronic modulation of cobalt phosphide nanosheet arrays by copper doping, which has been demonstrated to provide high-efficiency overall water splitting under the neutral-pH environment, further opening up the options for practical hydrogen production (Yan et al., 2020). Another new advancement is the one-pot synthesis of boron-doped RhFe alloys, which have shown a much higher catalytic activity in the hydrogen evolution reaction, confirming the importance of alloy engineering in electrocatalyst design (Zhang et al., 2018). This hydrogen in turn can be used in fuel cells as a fuel providing a cycle requiring no external inputs and able to contribute to both energy conversion and storage. Based on the electrolyte type, the used electrolyzers can be categorized as alkaline electrolyzer

(AEL), the proton exchange membrane electrolyzer (PEMEL), and the solid oxide electrolyzer (SOEL), with each having advantages regarding efficiency, cost, and scale (Franco & Giovannini, 2023). Recent developments in electrolyte material were the Y-doped $CaZrO_3$ thin films on porous perovskite substrates with promising ionic conductivity and structural compatibility for solid oxide fuel cell applications (Dunyushkina et al., 2016).

Further advances have been made with proton conducting ceramics such as $BaCe_{0\cdot 8}-_{x}Zr_{x}Y_{0\cdot 2}O_{3}-\delta_{n}$ which have the combined attributes of favorable thermal and transport properties which promote the operational efficiency of solid oxide fuel cell systems (Lyagaeva et al., 2015). Based on these developments, a proton-conducting electrolyte $BaCe_{0.5}Zr_{0.3}Y_{0.2}-Yb_{x}O_{3}-\delta$ has been specifically designed for intermediate temperature SOFC with a better ionic conductivity and stability for relevant operating conditions (Lyagaeva, Vdovin, Hakimova, Medvedev, Demin, & Tsiakaras, 2017).More recently, the importance of sintering additives of transition metals was also demonstrated to improve the structural and ionic conductivity properties of gadolinium doped barium cerate, further increasing the merit of this solid electrolyte material (Gorbova et al., 2008).

Hydrogen is produced through renewable-powered electrolysis and is commonly called green hydrogen, as such process excludes carbon emission and becomes essential in decarbonization plans. The International Energy Agency (2022) predicts that green hydrogen will increasingly displace both blue and grey hydrogen, based on the continuing decline in the cost of renewable energy and an enabling policy environment. The fact that it could ultimately be embedded in fuel cell hybrid electric vehicles (FCHEVs) as well as used to make steel (iron) and ammonia co-products underlines its status as an energy transition cornerstone (IEA, 2022; Staffell et al., 2019). Beyond use in energy conversion and storage, the solid oxide electrolytes are also in broad use as sensing technology, where their stability and their ionic conductivity are used to reliably detect gases and other compounds (Demin et al., 2020). A typical example is the realization of low-cost amperometric sensors to detect hydrogen, carbon monoxide and methane, proving the versatility of electrochemical devices beyond the typical energy uses (Fadeyev et al., 2015). Further contributions in this area include the design of advanced electrode configurations for solid electrolyte sensors, allowing precise monitoring of CO and H_2 concentrations in air in the case of the very important aspect of material optimization in gas-sensing technologies (Fadeyev et al., 2013). An in-depth review regarding the basics of the operating principle of solid-state electrochemical sensors for the detection of high-temperature gases has also been presented, highlighting their design principles, the material needs, and performance optimization (Gorbova et al., 2022).

The capacity of electrolyzers to supplement fuel cells is unique; it expands total energy system flexibility, as well. Electrolyzers act as an energy storage buffer when powered by intermittent renewable energy sources such as wind and solar, producing hydrogen during periods of excess electricity generation and supplying it during times of peak demand. This combination of electrolyzers and fuel cells highlights how hydrogen is the most central component of the establishment of a reliable, sustainable, and circular energy system (Dincer & Acar, 2015).

Batteries, e.g. lithium-ion, Li-ion, represent secondary electrochemical devices, which are defined by means of reversible electrochemical reactions that can be utilized in converting an electrical power into a chemical form during a charging period and back to electrical power during a discharging period. The low energy waste (usually more than 90 %) in these devices and make them potentially suited to high-rate power and applications involving high energy densities such as high-rate power delivery. However, they also come with restrictions linked to short shelf-life, relatively slow charging mechanisms, and limited supply of essential materials like cobalt which pose severe problems.

Along with lithium-ion batteries, a few alternative battery materials are under active development to overcome the material, cost and performance deficits of conventional Li-ion battery technology. Among this group, zinc-air batteries have caught the most interest with their high theoretical energy density, the abundance of zinc, and they are also environmentally friendly (Pei et al., 2014). Advantages Zinc-air systems do not require precious transition metals like cobalt or nickel as in a regular battery, and instead use oxygen dissolved in water as a cathode catalyzer. Still, poor rechargeability, unstable air electrodes, and electrolyte carbonation are some of the hindering concerns to large-scale commercialization of batteries (Li & Dai, 2014).

Solid-state batteries are another potentially promising technology, where the liquid electrolyte is replaced by solid, facilitating an increase in safety, thermal stability, and energy density (Janek & Zeier, 2016). Electric mobility is especially attractive due to their merits as far as the reduction of leakage and thermal runaway risks is concerned. However, they cannot be widely adopted because of interfacial resistance, low ionic conductivity at room temperature, and improvements are hampering scalable production (Manthiram, 2020).

Other technologies like sodium-ion batteries seem to be a potentially viable alternative, particularly in stationary energy storage. Due to the abundance of sodium resources and its low cost, such a system has the potential to reduce reliance on scarce raw materials while still providing performance comparable to Li-ion batteries in terms of lifespan and energy efficiency (Hwang et al., 2017). Their economics and sustainability props present them as serious contenders to be used as grid-scale storage and integrated by renewables (Slater et al., 2013).

As Li-ion batteries remain the dominant storage system in the electrochemical storage market, the pace of development in other battery systems including zinc-air batteries, solid-state batteries, and sodium-ion batteries exemplify the broad range of battery technologies being advanced towards manufacturing viable and better alternatives to Li-ion batteries. Their adoption into hybrid and renewable-based energy plants is likely to become crucially important in mitigating the on-going worldwide energy storage pressure (Tarascon & Armand, 2021).

Supercapacitors (or ultracapacitors) are a half-way point, making some of the same claims as both batteries and conventional capacitors. The supercapacitors have superior properties to handle this because of the ultrahigh increment and declension and the fact that they can have sufficient cycles of 100,000s or more, and they are perfect to deal with regenerative braking energy restoration and providing instant high-power energy when the fuel cell electric vehicle is operating (Szumska, 2025).

To clarify the structural and electrical characteristics of supercapacitors, Figure 3 illustrates the fundamental operating principles and equivalent models, highlighting the physical, chemical, and electrical parameters that govern their performance in energy storage and regenerative applications.

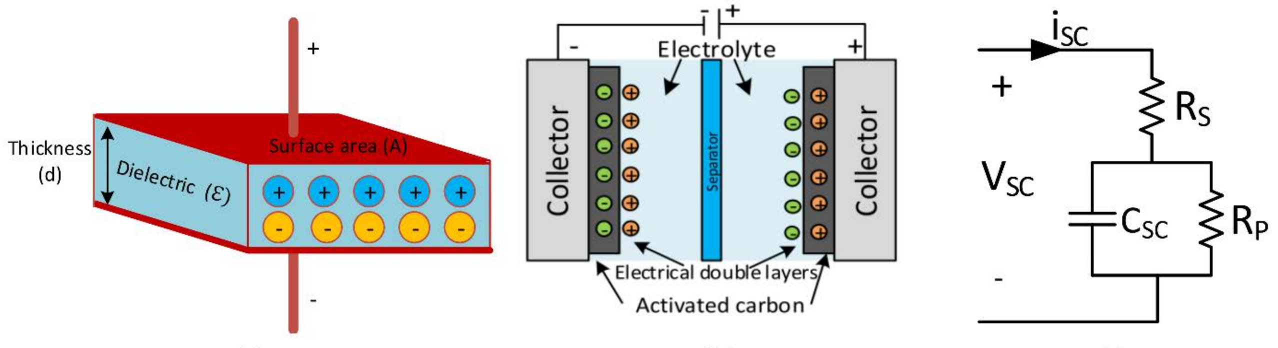

Figure 3. Representation of the fundamental operating principles and electrical models of a supercapacitor. In image (a), the schematic of a traditional capacitor with a dielectric material is shown, where the capacitance depends on the relative dielectric constant (ε), the thickness (d), and the surface area (A). Image (b) presents the internal structure of an electric double-layer capacitor (EDLC), featuring activated carbon electrodes, an electrolyte, and a separator, where ion layers form at the electrode–electrolyte interfaces. Image (c) illustrates the equivalent electrical circuit of the supercapacitor, which includes the internal resistance (Rs), the ideal capacitance (Csc), and the parallel leakage resistance (Rp). Together, the three parts of the figure highlight the physical, chemical, and electrical parameters that determine the performance and behavior of supercapacitors in energy storage and recovery applications (Şahin et al., 2022).

In modern discussion of low-emission transport and hybrid propulsion, electrochemical equipment is commonly implemented in hybrid systems, such as:

- Fuel cell-battery hybrid systems, with energy provided by the fuel cell and power needs in short-term supplied by the battery, or energy regenerated through braking.
- Fuel cell supercapacitor (FCCS) systems, which are designed to provide the best power responsiveness in such application with high and fast-changing loads (Wang et al., 2023).
- Use of triple hybrid systems (FC + Battery + Supercapacitor), that utilizes the relative benefits of the individual technology when it comes to multimodal mobility settings (Li et al., 2025).

Such hybrid systems require advanced Energy Management Strategies (EMS) that can dynamically distribute the loads, track the operating conditions, and prolong the life of the devices making up the hybrid (Tella et al., 2024). The process of the reverse conversion using electrolysis is of special importance: passing electrical energy into chemical energy: hydrogen. The use of this "power-to-gas-to-power" strategy is the basis of the new Power-to-X systems and creates a circular application of renewable energy (IEA, 2023).

As a category, electrochemical devices form a key technological component of an intelligent, clean and resilient energy system. Their specifications, performance improvements, and efficient insertions into complicated systems of energy and automobiles require a sophisticated insight to speed up the transition to energy. To illustrate the integration of multiple energy sources in a hybrid propulsion configuration, Figure 4 presents the schematic of a PEM fuel cell hybrid electric vehicle (FCHEV), highlighting the interaction between the fuel cell, battery, and supercapacitor through their respective converters and the common DC bus.

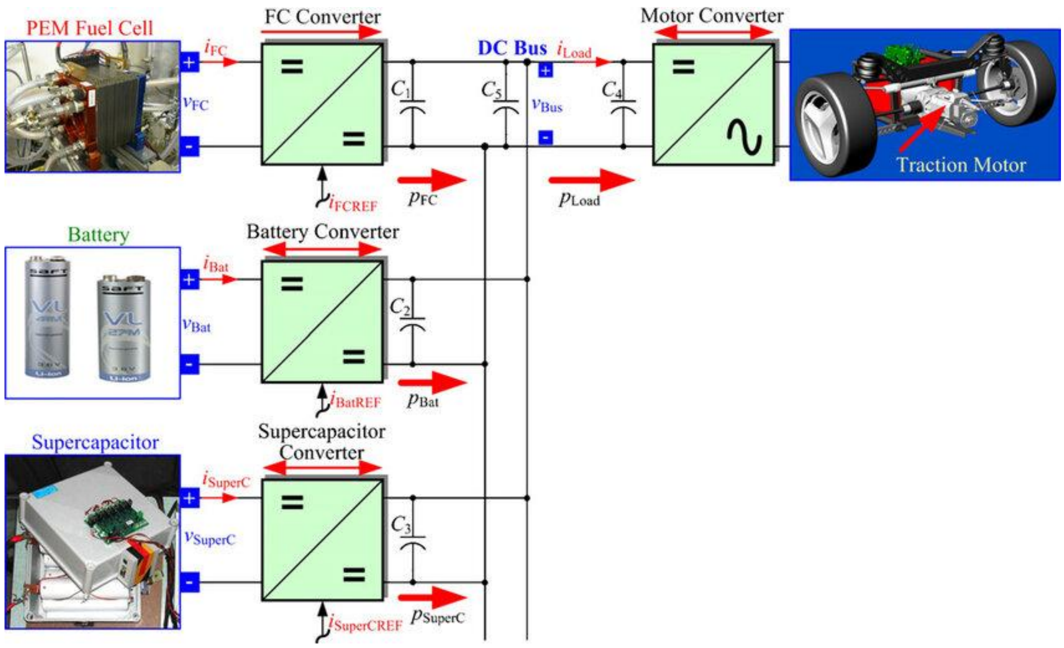

Figure 4. An illustrative design of a hybrid propulsion system inside a PEM fuel cell electric vehicle (FCHEV) is demonstrated, and it has merged three main energy sources: a PEM fuel cell, a battery and a supercapacitor. The output of each source is tied together at a common DC bus by its own converter (FC Converter, Battery Converter, Supercapacitor Converter), and each converter drives out to the final consumer which is the traction motor via the Motor Converter. The diagram exhibits the voltage power and current data of the available sources, the smoothing filters (capacitors C1-C4) and the energy control lines. The schematic shows collaborative efforts between these sources and is aimed toward the optimal distribution of power, minimized hydrogen utilization, and the critical positive reaction to varying loads in the propulsion system (Thounthong et al. 2009).

Table 1. Comparison of Fuel Cell Technologies

Fuel Cell Type	Operating Temperature	Efficiency (%)	Start-Up Time	Fuel	Advantages
PEMFC	60–80°C	40–60	Fast	H_2	High responsiveness
SOFC	700–1000°C	50–65	Slow	CH_4/H_2	High efficiency

CHAPTER 3

Factors Affecting Fuel Consumption

3.1. Energy Management Strategies (EMS)

Energy-management strategy (EMS) constitutes a critical system in ensuring maximum utilization of fuel in fuel-cell hybrid electric vehicles (FCHEVs). Its core aim is to decide in real-time, how and when each energy storage or generation source, the fuel cell, battery, supercapacitor and regenerative braking will need to feed in the energy or absorb it. In this way, EMS aims at achieving peak performance, reducing the amount of hydrogen used, and increasing the service life of all the parts of the hybrid system (Wang et al., 2023).

FCHEV energy management is an active process that needs to accommodate simultaneously the following parameters:

(1) immediate vehicle power demands,

(2) battery State of Charge (SoC),

(3) Fuel-cell temperature and efficiency,

(4) braking-energy recovery efficiency,

(5) future power demands including acceleration, deceleration and uphill drive conditions.

EMS, in general, in literature is normally categorized into (a) rule-based and (b) the optimized strategies. Rule-based strategies assume that, when the specific condition threshold has been reached--such as low or high SoC--the fuel cell or battery is disabled or enabled. These methodologies are fairly simple in theory, but they do not, in most cases, deliver on the performance versus consumption balancing required in modern hybrid powertrains (Lee & Kim, 2021).

Dynamic-programming (DP) algorithms, model predictive control (MPC), or artificial-intelligence methods, including reinforcement learning (RL) are used in optimized EMS and thus improves predictive ability and real-time responsiveness. These methodologies allow these approaches to perform one of the hubris roles more successfully than others by maximizing the usage of said energy sources under a certain criterion (e.g., under its mathematical criteria that might include but are not limited to, minimum fuel consumption or minimum degradation) (Tella et al., 2024; Tian et al., 2024).

One modern example of such is the power-split planning where the necessary power of the vehicle is dynamically divided between the fuel cell and the battery with the aim of minimizing the use of hydrogen. As an example, the fuel cell keeps to the high-efficiency modes, whereas the battery reduces the spikes of energy or accumulates braking-energy recovery (Li et al., 2025).

Cooperation between EMS and eco-driving is also great. Eco-driving is about changing one driving behaviour to suit the performance of the hybrid system, say by simply accelerating smoothly or doing advance braking to spend even less on fuel (Elgowainy et al., 2020). To highlight the role of smart energy management in integrated renewable systems, Figure 5 presents a schematic of a microgrid architecture combining photovoltaic generation, a diesel unit, and a battery energy storage system (BESS), all coordinated by a central Energy Management System (EMS).

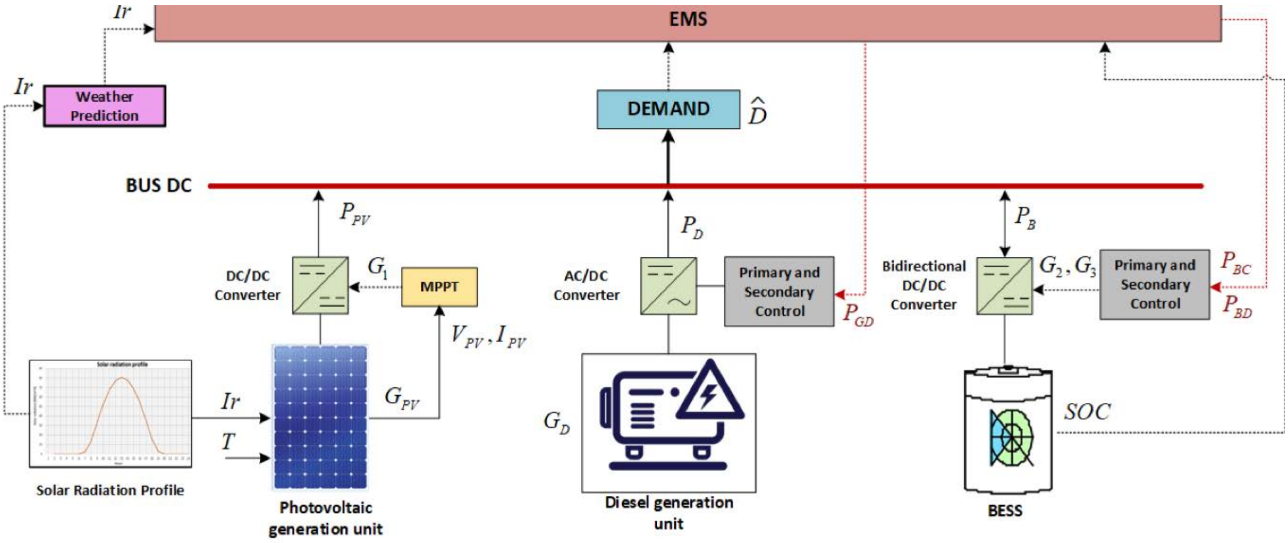

Figure 5. The submitted microgrid design includes photovoltaic (PV) unit, a diesel generation system, and a battery Energy storage system (BESS), with a central Energy Management System (EMS). The PV unit is meant to supply power to the DC bus through which it is converted by the use of a converter which has maximum power point tracking (MPPT) algorithm which adjusts to solar irradiance and ambient temperature. The diesel generator provides power via a separately supplied AC/DC converter but the BESS is connected via a bidirectional DC/DC converter, capable of providing charging and discharging in response to the energy balance of the system and battery state of charge (SoC). The EMS balances demand predicts generation and distributes power in real time thereby optimizing load sharing and stabilizing the microgrid (Basantes et al., 2023).

Recent developments demonstrated that the simultaneous usage of GPS followed by LIDAR sensors and AI-based prediction of motion can provide a possibility of EMS streamlining not only on the fly but also in regard to the predictions of the route ahead including its inclines, turns, and traffic patterns along the path as well as stops. This forward predictive EMS approach also adds more economy and better fuel consumption.

One of the most important mechanisms of FCHEVs energy management is to ensure they achieve fuel economy. It is therefore expected that the combination of high control algorithms, maturing smart EMS, and the inclusion of predictive technologies would become the foundation of the future generation of energy-efficient fuel cell vehicles.

3.2. Regenerative Braking Technologies

Regenerative braking is a critical energy-recovery system in fuel-cell hybrid-electric vehicles (FCHEVs) where it enables vehicle kinetic energy to be converted into electrical energy during vehicle braking. Most of this energy has been lost as waste heat in brakes in the typical internal-combustion-engine-powered vehicle but is recoverable to be restored to the electric system in the FCHEV (Wang et al., 2023).

Regenerative braking is based on the central idea of bi-directional functionality of the electric motor as both an engine and a generator. When the car driver brakes, the direction in which the motor works is changed back and the mechanical energy is changed to the electrical energy. Such electric power is transferred to the battery or supercapacitor of the vehicle to be stored there and reused (Zhang et al., 2018).

Depending on the structure of the hybrid system, and the presence or absence of storage units, the implementation of regeneration may result in a number of different, but not exclusive, configurations:

Battery-based replenishment: Rechargeable batteries are set up to store electrical energy, often in the form of lithium-ion batteries; since energy density is high, bursts of electricity can easily be stored, but short braking distances generate cooling power losses because charging current is relatively low.

Supercapacitor systems: Supercapacitors possess fast absorptions/ discharges and recharging capabilities hence they are appropriate supercapacitor-based systems suitable in FCHEVs where power fluctuations are frequent (Li et al., 2025).

Hybrid recovery: The combination of both the batteries and the supercapacitors enables the division of expendable energies to be distributed with a balance between immediate and long-term (Tella et al., 2024).

Distribution of braking strategy is a key factor of the system efficiency and safety. The electronic motor-control system should determine in real time, the optimal quantity of electric braking to ensure maximum energy recovery, prioritizing safety. Such a decision is made depending on vehicle speed, rate of deceleration, and condition of charge of the storage devices (Zhao et al., 2020). It is a very prevalent strategy to use a mixed strategy which can mean that the braking load is combined between the mechanical and the electric brakes.

The efficacy of regeneration depends on a number of factors and they include:

- driver profile-city-type which involve a lot of jamming to and for and highway driving at constant speed;
- the highest amount of charging of the storage devices;

- operating temperature that affects battery circuit design and chemical behavior of batteries/super capacitors (Lee & Kim, 2021).

To illustrate the integration of braking and propulsion in fuel cell electric vehicles, Figure 6 presents a schematic of a combined braking and drive system architecture that highlights the interaction between electrical, hydraulic, and control subsystems.

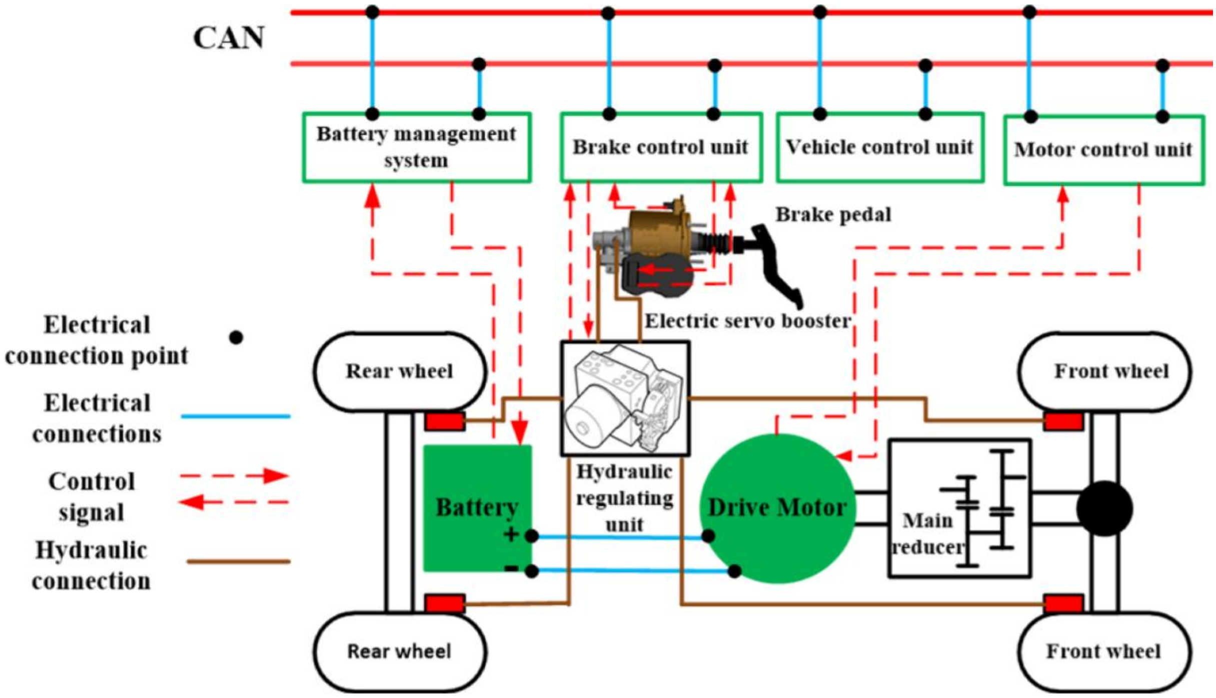

Figure 6. The diagram shows a combined braking and propulsion system on an electric car paying attention to the interaction between the elements of electrical, hydraulic, and control subsystems. Its architecture will have four control units, Battery Management System (BMS), Brake Control Unit (BCU), Vehicle Control Unit (VCU) and Motor Control Unit (MCU), connected through a CAN bus. Brake pedal action switches on an electrically powered brake booster and sends a signal to the Hydraulic Regulating Unit, as well as the hydraulic systems on the wheels. At the same time, the electric connection between the battery and the drive motor allows the propulsion through Main Reducer with coordination and braking control and energy recovery through interaction of all subsystems. The colors of the lines are used to specify the type of each connection: electrical, control signal, or hydraulic. (Liu et al., 2023)

Modern research shows that simultaneous use of predictive EMS, GPS sensors and traffic-prediction models can increase regenerative braking efficiency by up to 10-15 percent, and the vehicle can adjust its energy behavior long before the start of braking (Tella et al., 2024). The reuse of this energy further provides a number of strategic choices: pre-charging of fuel cell, auxiliary loads (e.g. HVAC) and increasing power during peak demand. The combination of these measures can not only achieve considerable improvement in overall vehicle efficiency, but can also mitigate the consumption of hydrogen, hence emphasizing that regenerative braking can be seen as more than an add-on to FCHEVs, paying dividends not only in terms of greater autonomous control, less energy loss and the progressive achievement of sustainable mobility.

3.3. Minimization of Losses and Thermal Management

Reduction of energy losses on one hand and adequate thermal management are related yet very important pillars in the effort to improve the total efficiency of a fuel cell hybrid electric vehicle (FCHEV). Seeking the enhanced fuel economy, the effective use of energy within each subsystem which constitutes the fuel cell, the power electronics modules, and auxiliary systems among others becomes especially significant. To provide a clearer view of the main pathways and losses within fuel cell hybrid electric vehicles, Figure 7 illustrates the energy-flow diagram of an FCHEV, showing how energy is transferred from the hydrogen tank to the wheels while highlighting the key points of efficiency loss across different subsystems.

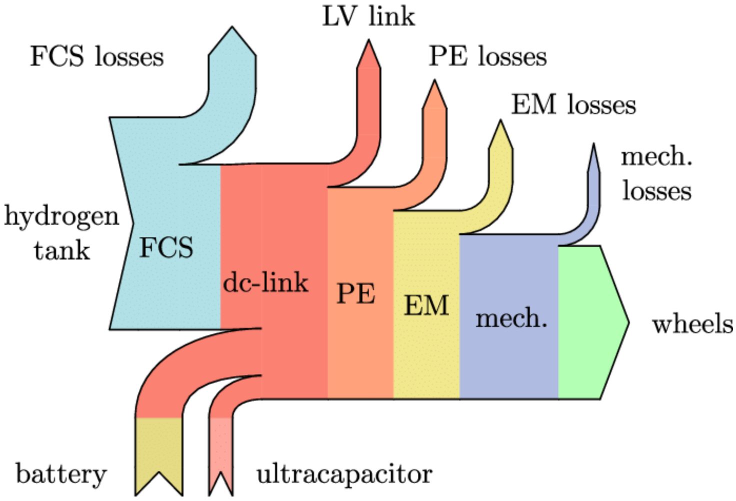

Figure 7. Energy-flow diagram of fuel-cell hybrid electric vehicle (FCHEV) The flow of energy through a car includes the main paths through which the energy flows and the energy losses at every position. In the tank, the hydrogen stored electrochemically is burnt up (oxidized) in the fuel cell stack (FCS), as further energy is provided by the battery and the supercapacitor. Once converted into direct-current electricity in the intermediate dc-link, the energy goes out to the power electronics (PE), the electric motor (EM), the associated electromechanical elements (mech.) and, last but not least, the wheels. Simultaneously, there are losses at every point-fuel-cell losses (FCS losses), power-electronics losses (PE losses), electric-motor losses (EM losses), and mechanical losses (mech. losses) and discharge to low-voltage auxiliary circuits (LV link). The diagram, therefore, indicates the path of energy that runs between its generation and kinetic output, and the key spots of energy loss on its way (Rudolf et al., 2021).

The energy losses in a fuel-cell hybrid electric vehicle (FCHEV) occur because of operating the fuel cell stack in non-ideal conditions (including conversion losses), as well as through thermal losses due to over-heating, resistance to the flow of materials and temperature-related performance degradation. Most of the chemical energy contained in hydrogen is never released as electricity in the fuel cell because a relatively large percentage, maybe 40-50 % in a conventional system, is discharged as heat that has to be actively managed to prevent wastage and the premature failure of materials (Pourrahmani et al., 2022).

The fuel cell is not the only thermal management consideration in FCHEVs; battery, power electronics, electric motor and the vehicles climate control system are also subjects of thermal management. All its parts dictate distinct thermal conditions and operation limits. In the event of failure in controlling the temperature, rapid performance loss, harmful responses, thermal deterioration, or unsafe activities like battery thermal runaway may happen (Hwang et al., 2023).

To overcome such problems, new cooling and heat-distribution architectures have been worked out based on liquid-cooled mechanisms, air-cooled ones or upon two-phase methods. Fuel cells commonly use liquid-cooled heat exchangers since they can eliminate heat quickly and keep the stack around a steady 60-80 ^{o} C temperature range. Lithium-ion ones also require very tight temperature regulation in the range of 20-40 ^{o} C to be both safe and highly efficient (Alawi et al., 2025).

Such innovative technologies of the active control of the heat flows are integration of thermoelectric (TE) materials and intelligent control sensors allowing dynamically to control the heat flows and the redistribution of the power based on the real thermal conditions in the subsystems. With the use of thermoelectric generator (TEGs), it is possible to convert waste heat to electricity and hence achieve greater efficiency of the overall vehicle (Sanin-Villa, 2022).

Parallel methods include phase-change materials (PCMs) as thermal buffers, to store heat temporarily when there are peak demands, stabilizing the temperature reduce thermal fluctuation and have the ability to extend operating lifetimes of fuel cells and batteries. During phase transition between the solid and the liquid state, a PCM extracts heat, which helps maintain stable temperatures in the event of critical vehicle functions (Buonomo et al., 2024).

The overall concept of minimized energy losses in FCHEVs is also aimed at power-electronic converter design (DC/DC or DC/AC), aimed at reduced thermal losses in the converter due to energy conversion between voltage and current, and the use of more advanced semiconductors, e.g. SiC and GaN, with higher voltages and less thermal losses in general (Baba et al., 2021).

Management of thermal and minimization of energy loss, thus, becomes structural of FCHEV energy architecture. According to the efficient use of generated and dissipated energy can contribute to better fuel economy, less environmental impact and to the goal of a technologically dependable and commercially appealing propulsion scheme.

3.4. Aerodynamic Design and Rolling Resistance Minimization

Both aerodynamic design and rolling resistance reduction are two key areas of focus in fuel cell hybrid electric vehicles (FCHEVs) in the drive to achieve greater fuel economy. In on-ground use especially at medium and high speeds, a significant percentage of its energy budget is utilized in order to deal with the aerodynamic drag which increases exponentially with the movement speed. Meanwhile, rolling resistance or mechanical energy that measures the efforts needed to evolve the tires over the road leads to decisive effects on the total consumption of energy specifically at lower velocities when in urban traffic conditions (Zhang, 2025).

Four main parameters determine the magnitude of the aerodynamic drag; these are drag coefficient (Cd), frontal area (A), air density and velocity of the vehicle. Modern FCHEV design practices aim to minimize Cd by streamlining body shapes, using active aero--such as variable flaps or moveable air-intake grilles--and promising full underbody covering to preclude repeating local flow separation vortices (Huang et al., 2025). The ensuing aerodynamic efficiency does not only reduce power loading to the fuel cell and, hence, limiting hydrogen usage, but it also assists in temperature control by circulating air over the key parts, such as the fuel-cell stack and the cooling circuits. Empirical evidence proves that a 0.02 decrease of Cd can produce up to a 5 % increase of driving range, depending on velocity profile and ambient conditions (Mansouri et al., 2024).

Rolling resistance on the other hand is due to the mechanical and material characteristic of tires when in contact with the road surface. Despite the fact that this is mostly felt at low speeds, its effect on energy consumption becomes salient throughout the whole range of operations, especially in congested settings or even commuting in the urban areas. The reduction measures include improvements in tire design, the use of new bonding rubber and minimization of deformation and tire pressure maintenance on a rigorous basis. In FCHEVs, reduced rolling friction decreases the energy requirement on the battery pack and fuel cell and increases range and does not increase hydrogen use.

To counter this, equipment producers are incorporating complete regulated electronic tire-pressure regulation systems, active suspension, and load-equalization devices in a bid to reduce losses caused by weight imbalances or poor selecting of tire deformation. Simultaneously, there are prospects of positive results in terms of micro-particle and nanoparticle reinforced composite polymers to achieve the optimum trade-off between grip properties and their rolling resistance properties (Wei et al., 2021).

Recent work also presents AI-based predictive models that constantly update with the values of exterior factors-wind speed, temperature, the condition of the road surface-and adapt the energy-management policy irrespective of the future variance in aerodynamic drag or rolling resistance. These strategies herald future directions of efficient FCHEV design, which are at the core of informing how hydrogen is used in terms of gas consumption, range, performance, and sustainability of FCHEV in an energy and environmentally constrained environment.

3.5. Materials and Design for Efficiency Improvement and Weight Reduction

The contemporary concurrent energy efficiency and mass reduction of vehicle design are one of the main design considerations of fuel cell hybrid electric vehicles (FCHEVs). Mass decrease reduces hydrogen use since lighter cars need less propulsive power and forces to accelerate and to preserve the speed, and it also increases the efficiency of radiant breaks. At the same time, the integrated use of sophisticated components grants improved structural rigidity, reduced thermal transmissions, and a greater efficiency under working and climatic pressures (Hassan et al., 2023).

Fuel-cell module research currently focuses on optimization of individual component materials, namely, the electrolyte membrane, the electrodes, electrocatalysts and the bipolar plates. The standard Nafion membrane, which is used in proton exchange membrane fuel cells (PEMFC) application, has excellent ionic conductivity but is prone to dehydration and limited thermal stability. As of late, new technologies are offering composited membranes of inorganic oxide nanoparticles (e.g., SiO_2, TiO_2), thusly increasing thermal stability and moisture sensitivity tolerance (Parekh, 2022). To illustrate the structural components and catalytic processes within a proton exchange membrane fuel cell (PEMFC), Figure 8 presents the catalyst layer and its architecture, highlighting the role of platinum-based nanoparticles, carbon supports, and the PEM electrolyte membrane in enabling proton conduction and electrochemical reactions.

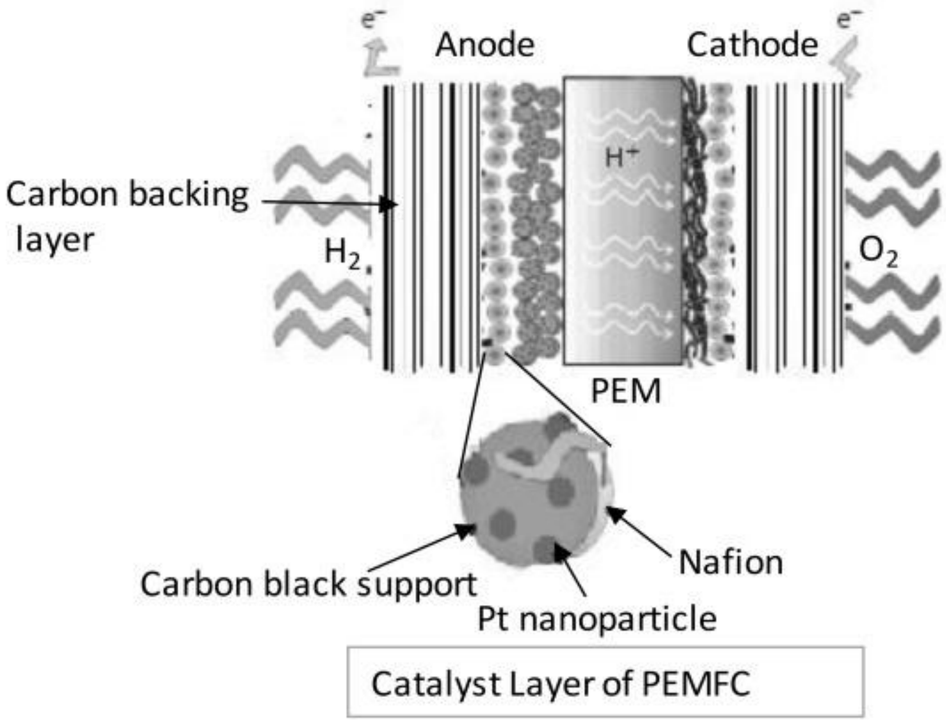

Figure 8. Illustration of the catalytic layer and the basic architecture of a proton exchange membrane fuel cell (PEMFC). The image depicts the flow of hydrogen (H_2) to the anode, where it is dissociated into protons (H^+) and electrons (e^-) by a catalyst consisting of platinum (Pt) nanoparticles supported on carbon black. The protons pass through the PEM electrolyte membrane (often Nafion), while the electrons travel through an external circuit. At the cathode, the protons combine with the electrons and oxygen (O_2) to produce water. The structure also includes carbon backing layers for gas and electron transport (Okonkwo et al., 2021).

Drastic progress has been made in reducing use of precious metal in electrocatalysts. Though platinum is extremely effective, it is expensive and limited by scarce supply. Other catalysts, such as alloyed PtCo and PtNi and nitrogen and iron-based non-precious metal catalysts (FeN-C), as well, have gained significant traction and could be used in fuel cells processes that tend to limit the work of fuel cells (Chen et al., 2023). A representative example is the development of nitrogen-doped hierarchically mesoporous carbon derived from interpenetrated MOF which has demonstrated highly effective catalytic activity for oxygen reduction reaction further advancing the field of non-precious metal electrocatalysts (Tan et al., 2017). Also, the easy synthesis of symmetry-broken concave Pt-Pd nanocubes has been demonstrated to highly improve the catalytic activity toward the ORR, demonstrating the great benefits of controlled bimetallic nanostructures (Wu et al., 2019). Similar improvements have been made with palladium-tin based alloys supported on carbon which show more electrocatalytic activity and stability during electrooxidation of glucose in alkaline medium, further demonstrating the versatility of bimetallic catalysts in electrochemical applications (Brouzgou et al., 2014). Another representative example is the fabrication of ordered mesoporous carbon/tungsten carbide composites which are characterized by high surface area and have shown excellent performance for methanol electrooxidation, indicating the potential of hybrid catalyst architecture (Wang et al. 2012). Furthermore, ordered mesoporous WC/C composites have also been used as promoters for Pt catalysts with the resultant high activity and durability for methanol electrooxidation, which further validates the importance of synergistic catalyst designs (Wang et al., 2014).

Moreover, the use of graphite-polymer composites and thin metallic sheets of stainless steel or titanium alloy (which are insulated with carbon coating) have been useful in bipolar plates-components that serve as conductors of electricity among adjacent cells in bipolar cells besides being structural parts as well. The decision has significantly lowered weight and increased corrosion properties and electrical conductivity (Hai et al., 2022).

It is also important to make peripheral systems as well as the weight of the vehicle body light. Using aluminum and magnesium alloys and carbon-fiber-reinforced plastics (CFRPs) to replace steel parts can realize large reductions in mass with no loss in structural integrity. The use of composite materials in the floors, suspension system, door panels, and roof leads to a reduction of 15 25 % of the overall weight, which is directly proportional to reduced energy consumption to propel such a vehicle (Sellali et al., 2022).

FEM (computational finite-element simulations) have the potential of allowing local reinforcement where it is desired and optimize structural design resulting in lighter geometries. At the same time monocoque composite platforms enhance passive safety and reduce the amount of parts, which also contributes to a decreased total mass.

Incorporation of lightweight, thermally conductive materials also enhances cooling and ventilation systems functioning, therefore reducing the thermal mass of the vehicle and allows its quick adjustment to changes in temperature. It will be essential to fuel-cell electric vehicles (FCHEVs), in which the ability to control the operating temperatures of the fuel cell and batteries is key to performance and durability.

Also, weight minimization in all subsystems consuming energy (motors, gear reducers, wiring, and power electronics) should be done with a holistic design philosophy that places emphasis on high energy-density parts, as well as integrated control systems to minimize overall components count and system infrastructure complexity.

Together, such design and material usage innovations make FCHEVs run more efficiently, lighter, safer and more sustainably over their life cycle. The mechanical and chemical synergy makes the role of FCHEVs a frontrunner in the transportation-sustainable technology.

Table 2. Comparison of Materials for Lightweight Vehicles

Material	Density (g/cm³)	Strength-to-Weight Ratio	Cost ($/kg)	Recyclability	Application
Aluminum	2.70	Moderate	1.5–2.5	Yes	Chassis, panels
Carbon fiber	1.75	High	>15	Limited	Sports vehicles
HSS steel	7.85	Good	0.5–0.9	Yes	Frame

CHAPTER 4

Basic Operating Principles of the Fuel Cell

4.1. Recent Technological Developments (2020–2025)

Materials, cell/stack and in-system innovations made over the past five years have fueled the effort to achieve fuel-cell powertrains that are more efficient, durable and affordable. In PEMFCs, the prevailing trend has been to develop devices with even higher power density at reduced loading of the precious metals, when accompanied by an acceptable water/thermal management, and the ability to operate stably through very transient automotive profiles. Meanwhile, solid-oxide fuel cells (SOFCs) have been in their turn advancing to lower operating temperatures and metal-support structures to reversible operation to match electricity generation with high-efficiency electrolysis. Taken together, these advancements support the viability of FCHEVs to achieve range/refueling/life-cycle goals in accordance with the energy transition as a whole (Barbir, 2020; IEA, 2023). The selection of fuel is a crucial factor in overall system efficiency, especially in the case of solid oxide fuel cells, where different kinds of fuel can have a major impact on the system's performance and the amount of energy produced (Coutelieris et al., 2003).

In PEMFC electrodes, the use of platinum-group metal (PGM) has been continuously minimized without compromising kinetics of oxygen reduction reaction (ORR). Advanced Pt-alloy catalysts-commonly Pt-Co or Pt-Ni with ordered or shape-controlled nanostructures- exhibit enhanced specific and mass activities, compared with Pt/C and improved ability to sustain high-current operation when paired with graphitized or corrosion-resistant supports (Chen et al., 2023). Development has also been achieved on PGM-free Fe-N-C catalysts with half-cell activities now promising and stability enhanced through heteroatom doping and defect engineering; durability at start-stop and high-potential excursions is still the key corrosive of automotive implementation, but the sustained maturity, suggests a plausible route to further reduction of stack cost (Chen et al., 2023). Such catalyst developments are being complemented by catalyst layers that have been re-engineered to include ultralow ionomer levels, swept down porosity, and thinner active layers, all to reduce transport distances and reduce local oxygen and water constraints at high current densities (Barbir, 2020).

Membrane/ionomer design has been developed to broaden the thermal and humidity operating window. Hydrocarbon membranes (including inorganic nanofillers, such as SiO_2 or TiO_2) have demonstrated enhancement of dimensional stability as well as reduced gas crossover and maintenance of proton conductivity during dry-hot tests and freeze thaw cycles (conditions common in vehicles) (Ying et al., 2024). In the stack level, bipolar plates made of coated stainless steel or graphite polymer composite could have low weight, volume with interfacial contact resistance and lifetime requirements, contributing to the greater volumetric power density in the stack and ease of heat management hardware (Li, 2024).

Other areas of innovation include water and heat management, the twin factors that all too frequently are considered to limit real-world PEMFC performance. MPLs and PTLs are now being designed with customized pore size distributions as well as wettability gradients and microchannels to enhance the rinsing of liquid-water and to sustain membrane hydration during broad loads swings. Design of flow fields is also being optimized through topology and bio-inspired design, metal foams, and additive manufacturing to maximize the pressure drop and flooding and homogenize the current density to reduce local hot spot, and therefore extend the component life (Barbir, 2020; Pourrahmani et al., 2022). System: Integrated compressor-expander stacks, low-parasitic humidifier stacks, model-predictive thermal control systems structure coolant, air and hydrogen lines to ensure stacks stay within narrow bands of temperature under transient drive cycles, minimizing the proportion of waste heat and limiting the voltage variation (Pourrahmani et al., 2022).

Durability has been made a major theme In FCHEVs, where carbon corrosion and Pt dissolution/aggregation are accelerated by carbon and Pt loss in start-stop events; air starvation; and high-voltage holds, mitigation strategies have evolved to include stable supports, alloy-dealloying resistance, and soft-landing controls, which reduce the potential spikes produced via battery and supercapacitor buffering. Battery-assisted hybridization will also mitigate load transients that the stack has to bear, which empirically retards voltage decay and increases practical life span, an aspect actively exploited by current energy management systems (Ye et al., 2025; Wang, Zhang, Xie, & Wang, 2022). Stack purging schemes and membranes with reduced water uptake have increased freeze starts, upstream filtration and an intelligent control scheme that identifies and responds to air-side impurities like NOx or SO_2 and to trace CO present in fuel supplied upstream (Barbir, 2020) have given longer tolerance to contamination.

The fabrication and cost savings have been following the advancements in materials. Roll-to-roll process of membrane-electrode assemblies (MEAs), reduced thickness of gaskets and seals and in-situ diagnostics to control quality have increased yields and standardization. On the stack level, there have been part count reductions and modular designs reducing the time required to assemble and simplify the integration of BoP. At a system level the long-term declining trend in PGM loading, replacement of uncoated metal plates by coated metal plates, and maturation of higher-volume technologies are also noted in projected reduction in $/kW of automotive stacks (IEA, 2023). There are also recycling streams of spent stacks, more so closed-loop Pt recovery, to minimize the costs and environmental impact during the life cycle (IEA, 2023). To provide a comprehensive view of the internal structure and functional layers of a proton exchange membrane fuel cell (PEMFC), **Figure 9** illustrates a schematic diagram detailing the major components—including the hydrogen inlet, terminal plate, bipolar plate, gas diffusion layer, catalyst layer, proton exchange membrane, and oxygen inlet—together with the microstructure of the catalyst layer where platinum nanoparticles are supported on carbon and ionomer binder.

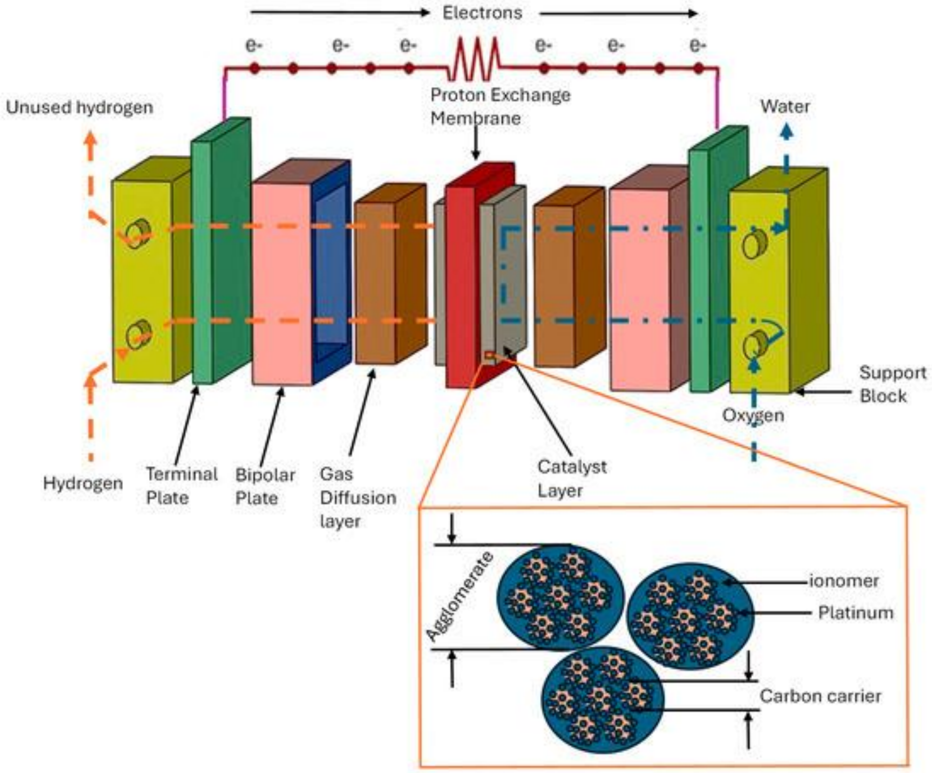

Figure 9. A Proton Exchange Membrane Fuel Cell (PEMFC) schematic diagram showing the principal components (hydrogen inlet, terminal plate, bipolar plate, gas diffusion layer, catalyst layer, proton exchange membrane and oxygen inlet). The inset presents nanoarchitectured microstructure of a catalyst layer covered with platinum nanoparticles impregnated on a carbon carrier and ionomer binder. (Okonkwo, 2025)

The developments of Hydrogen production and quality control is closely associated with the fuel-cell advances. Electrolyzers driven by renewable energy sources are transitioning to higher current density operation with iridium-sparsely loaded anodes and resilient porous transport layers, providing specific capital cost reduction and delivering hydrogen vesselisation suitable as a feedstock to automotive PEMFCs; the escalating convergence of electrolyzer and fuel-cell component supply chains (ionomers, PTLs, titanium hardware) should yield both cross-recognition and further cost leverage (Araujo et al., 2024; IEA, 2023). On the vehicle side, storage innovation, 700-bar Type IV tanks designed with better liner and carbon wrapping, has made ongoing refinements to gravimetric capacity and shorter necessary refueling times, hence plausible long-range applications of FCHEVs (IEA, 2023).

One trend in SOFC technology has been towards lower operating temperatures (800 to 1000 ^{o}C to 500 to 700 ^{o}C), making thermal stress tolerance more lenient, allowing a wider selection of materials and providing faster warm-up to operating temperatures. A plan would be thin electrolyte layers with an increased ionic conductivity, improved surface exchange with oxygen in the cathodes, and metal supported cells that combines resilience with faster thermal cycling. It is especially interesting that reversible solid-oxide systems (rSOC) operating as SOFCs during power generation and as SOECs in storage mode (where its round-trip efficiency due to the low operating temperature potentially exceeds those of carbon-based fuels) can address sector coupling between transportation, power and industry generating hydrogen becoming possible (IEA, 2023; Wang, Zhang, Xie, & Wang, 2022).

Diagnostics and control has greatly improved. Optimized tools-X-ray/neutron imaging, high-speed impedance spectroscopy, and data-driven observer, now resolve distributions of water, oxygen, and heat in working stacks that can be used to inform physics-based and hybrid "digital-twin" models applied in design and control tuning. In vehicles, predictive information and machine learning predicts power flows between the fuel cell, battery, and supercapacitor and manages them to ensure the stack operates in its high-efficiency region, to limit the transients, and to capture the available energy-recoupling opportunities-these, in turn, translate to minimized hydrogen usage at the drive-cycle level (Ye et al., 2025; Wu et al., 2021).

Safety and thermal resilience are two ongoing activities. In hybrid systems, battery thermal management systems are being developed simultaneously with fuel-cell cooling systems to share heat exchangers and pumps with phase-change materials, or dedicated chillers used to stabilize thermal variations and minimize parasitic loads and potentially improve reliability (Xie et al., 2023; Pourrahmani et al., 2022). The switch to power electronics using wide band-gap semiconductors like SiC and GaN has reduced conversion losses and facilitated higher frequencies of switching that reduces passive component sizes and the cooling demands placed on the BoP (Yin et al., 2021).

In the coming decade of 2020-2025, all the innovations described above have a practical implication the gradual reduction in the gap between research metrics and in-use performance. Synergies between higher stack power density at lower PGM loadings, enhanced durability to aggressive cycling, more effective thermal/water management, and intelligent hybrid energy control is enabling FCHEVs with greater range, faster transients, and reduced hydrogen intensity per kilometer. Together with the accelerated deployment of low-carbon hydrogen and ongoing drop in system cost according to the projections by international organizations, these developments make fuel-cell powertrains a viable option as a complementary technology that could sit alongside battery-electric platforms across light-, medium-, and heavy-duty mobility categories (IEA, 2023; Barbir, 2020; Ye et al., 2025; Chen et al., 2023; Chen et al., 2023).

4.2. Advances in Fuel Cells (PEMFC, SOFC)

Fuel cell technologies have experienced great advancements in the past few years, notably on proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs). Each cell type retains a central role in research, and industry due to the complementary nature of their strengths: PEMFCs are ideal to use in transportation and portable applications given their low operating temperature and rapid dynamic response whereas SOFCs are commonly found in stationary power generation applications given their greater efficiencies and having the capacity to accept a wide variety of fuels (Barbir, 2020; O'Hayre et al., 2016).

In the case of PEMFCs, the development has occurred more in terms of durability, cost and ideal performance under extreme working conditions. The most important field of innovation is the chemic development of new membranes that could maintain protons conductivity under low-humidity conditions (or even high temperature) and solve the traditional drawbacks of the Nafion-based membranes (Ying et al., 2024). Moreover, catalyst research has focused on minimizing usage of platinum-group metals (PGMs) which have long been a cost and supply limitation. The efficiency of alloy catalysts, core-shell nanostructure, and non-PGM alternatives, platinum loading needs have been reduced by a significant margin, down to only below 20% of the necessary load whilst still retaining the same catalytic activity (Zhao et al, 2022). In conjunction with the design of catalysts, there has been an increase in durability owing to the reduction of degradation mechanisms including the agglomeration of catalyst particles, corrosion of carbon supports and thinning membranes (Shi et al., 2025).

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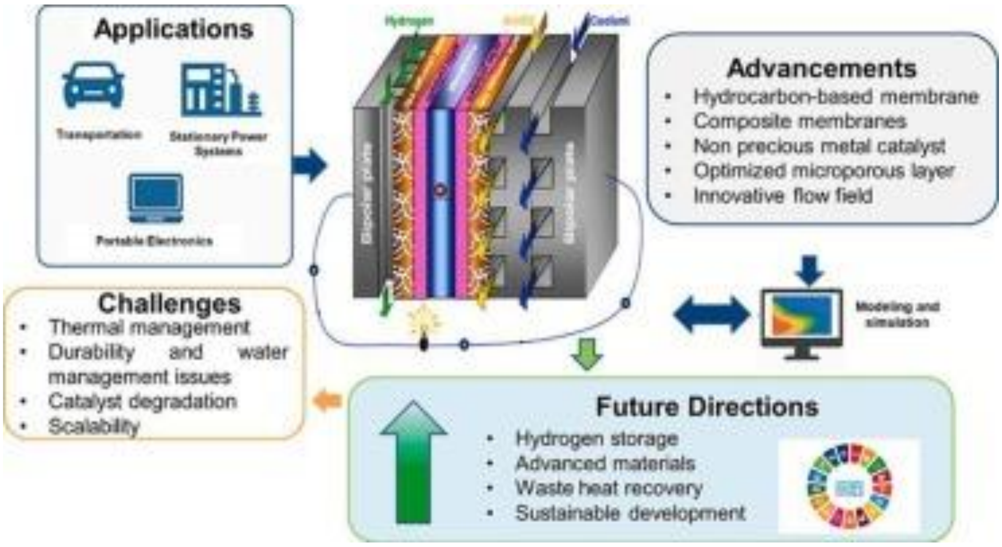

Figure 10. General discussion of the applications, issues, current technology development, and the future of proton exchange membrane fuel cell (PEMFC). The main application fields are transportation, stationary power systems and portable electronics. There is still a challenge in thermal management, catalyst degradation, scalability and water management. Development has been toward hydrocarbon and composite membranes, non-precious metal catalysts, optimized porous structures and innovative flow fields, with future developments looking at hydrogen storage, advanced materials, waste heat recovery and sustainable development. (Rimon et al., 2025)

Thermal and water management approaches become another area of PEMFC development. Considering that performance and durability significantly rely on well-prepared hydration of the membrane and low temperature distribution, their associations with more sophisticated methods, which includes insertion of micro-porosis components, innovative gas diffusion media, and hybrid cooling systems, have become evolving (Pourrahmani et al., 2022). Additionally, the usage of digital twin technologies and control algorithms led to improved degradation predictability and increased system-level integration of the automotive system (Jin et al., 2025). To contextualize the technological landscape of proton exchange membrane fuel cells (PEMFCs), **Figure 10** provides a schematic overview that highlights their main applications, the current challenges they face, the technological advancements achieved in recent years, and the future directions of research. The diagram emphasizes their role in transportation, stationary power generation, and portable electronics, while also noting material innovations, improved catalyst efficiency, and pathways toward sustainable development.

By contrast, SOFCs are high-temperature (typically 700-1000 ^{o}C) systems that have also recently undergone a cycle of innovation to address their historic shortcomings of slow start-up times, thermal stress, and material corrosion. One of the major advances was the advent of intermediate-temperature SOFCs (IT-SOFCs), which are used at temperatures of about 500-700 ^{o}C. Such systems eliminate thermal strains and allow faster start-up and an increase in the range of materials used in electrolytes and interconnections (Corigliano et al., 2022). The ubiquity of ceramic electrolytes in forms of gadolinium-doped ceria (GDC) and scandia-stabilized zirconia improved the ionic conductivity at low temperatures (Singhal & Kendall, 2020).

SOFCs further have the advantage of being able to simply use hydrocarbon fuels like methane, biogas, or even ammonia, in and of themselves, by internal reforming. Having this fuel flexibility position SOFCs well in terms of ensuring the sustainability of hydrogen infrastructure in regions where this is a weaker area, and this complements the overall strategies of a diversified low-carbon energy system (IEA, 2023). In addition, hybrid systems with gas turbines or other forms of heat recovery have also been reported to have achieved over 70% overall efficiencies and are thus very appealing in stationary settings where large amounts of baseload power is needed (Ye et al., 2025).

Besides achieving performance improvement, much interest has been developing the cost reduction of SOFC manufacture. Development of additive manufacturing and methods of scalable Fabrication can enable the ceramic component to be mass-produced at a low cost and increase reproducibility (Spreafico, 2024). In addition, the SOFC lifetimes have further been increased by incorporating durability coatings and protection layers, which have helped to reduce interfacial reactions and degradation at electrode-electrolyte interfaces (Corigliano et al., 2022).

Altogether, the parallel development of PEMFCs and SOFCs speaks of a strategic diversification of cell fuel technology development and deployment. PEMFCs are anticipated to play a major role in the transport sector because of their compactness and reactivity; SOFCs, in contrast, have an opportunity in distributed power generation, manufacturing, and long-duration stationary systems. They both are considered to be more and more complementary foundations of global energy transition, and their usage is determined by specific policies, infrastructure building and continuous materials science and systems innovation (IEA, 2023; Shi et al., 2025).

4.3. Advanced Hybrid Systems

Fuel cell combinations with other enabling energy storage and conversion technologies have become a valuable approach to increasing efficiency, reliability and flexibility in transportation and/or stationary power systems. The merits of other systems can be merged through hybridization thus reducing the shortcomings of specific technologies. For fuel cell hybrid electric vehicles (FCHEV), the hybridization of a proton exchange membrane fuel cell (PEMFC) with a high-power density storage device, i.e., lithium-ion battery or ultracapacitor, yields a dynamic energy balance between sustained energy provision and high responsiveness to peak power requirements (Huang et al., 2025).

Fuel cells are high-energy-density, relatively sluggish in response to transients and sensitive to rapidly changed loads. In contrast, batteries and ultracapacitors may react fast to changes in dynamic loads, but they have problems of low energy storage capacity and shortening after repeated use. Hybrid architectures are a combination of these systems, thus allowing the fuel cell to work near-optimal steady-state by enhancing fuel efficiency and durability of the components (Khalatbarisoltani et al., 2023). The battery or ultracapacitor is offered to offer a momentary high power during acceleration or rapid load change, as well as to store energy of regenerative braking thus decreasing hydrogen use and increasing system life.

Recent studies have been done on the power management strategy which seeks to maximize power transfer amid the various subsystems. As an example, the advanced control algorithms, which are usually combined with machine learning and predictive modeling, have proven to greatly enhance the recovery of energy efficiency, durability, and operational safety (Nebeluk & Ławryńczuk, 2022). E.g. the hybrid system can be predictive with respect to demand variations and real-time power distribution through the model predictive control (MPC) methods hence resulting in minimum losses across power electronics and reduce batteries life-span. To obtain an overview of the integration of hydrogen technologies in modern energy systems, the following **Figure 11** gives an overview of a conceptual free model for a microgrid energy management system (EMS). The diagram underlines the interconnection of renewable sources such as wind and solar energy, fuel cells, electrolyzers and energy storage systems with the utility grid, commercial and residential loads and electric vehicle (EV) charging infrastructure with the central role of EMS in balancing demand, optimizing flexibility and ensuring resilience.

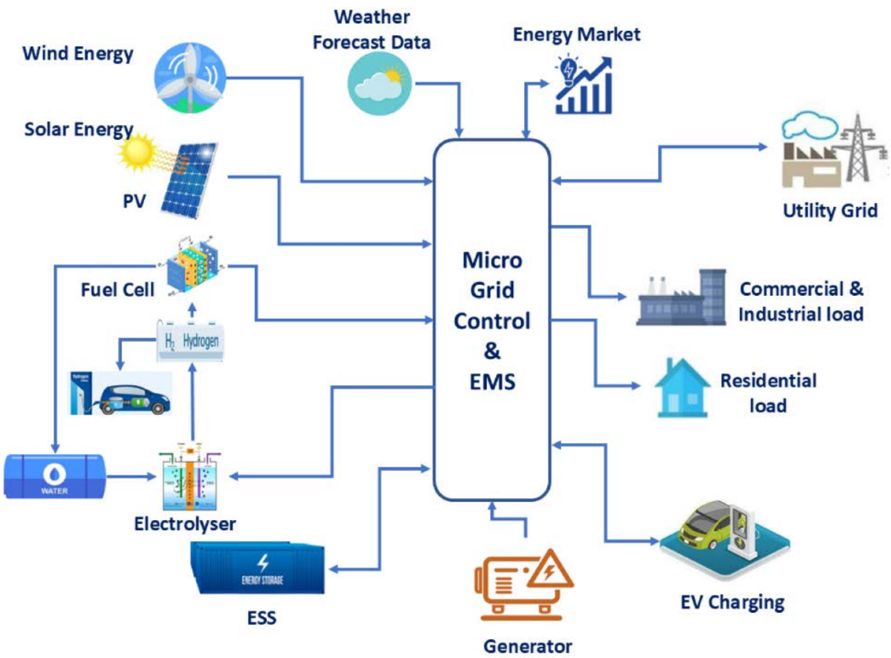

Figure 11. Conceptual Free model of a microgrid energy management system (EMS). The system combines renewable energy generation, including wind and solar integration, fuel cell, electrolyzer, energy storage system (ESS), generator and integration into the utility grid, commercial and industrial loads, residential loads and electric vehicle (EV) charging. The energy market signals and weather forecasting data are also included to optimize energy distribution, flexibility and efficiency in microgrid. (Khan et al., 2025)

Hybridization does not apply only in automotive industry. Combined fuel cell and battery (FC/Battery) and FC/supercapacitor systems are also growing in stationary applications to help maintain grid stability and absorb renewable resources. PEMFC-battery systems are of specific interest to distributed generation applications where they can offer stable base-load power with the battery substituting demand spikes and grid disturbances (Malik et al., 2025). Equally well, microturbines have been coupled to fuel cells, e.g., solid oxide fuel cells (SOFCs) in hybrid systems, capable of electrical efficiencies of over 70 percent (by utilizing high-temperature exhaust to power secondary turbines) (Ye et al., 2025).

The factor of hybridization is also important in minimizing the cost of the lifetime of the product. The hybrid systems can prolong the life of the fuel cell and the battery since the stress experienced by each component is relieved hence lowering the cost of maintenance and being economically attractive (Cheng et al., 2020). Moreover, since the hydrogen existing refueling infrastructures are scarce in most areas, the existent of a secondary energy storage device can further increase practicality of FCHEVs given the decrease in the reliance on the always-present supply of hydrogen.

In the future, it is anticipated that higher-performance hybrid systems will integrate not just conventional batteries and ultracapacitors, but also newer sources of storage that promise to be safer, higher in energy density and ability to scale: solid-state batteries and redox flow batteries, among others. Coupled with development in light materials and power electronics, these hybrid systems will make FCHEVs and, stationary fuel cells more comparable to battery electric vehicles (BEVs) and conventional hybrids in terms of efficiency, lifespan, and overall sustainability (IEA, 2023).

4.4. Categories and Characteristics of FCEVs and FCHEVs

These two groups (fuel cell electric vehicle (FCEV) and fuel cell hybrid electric vehicle (FCHEV)) are subsets of hybrids in the newly emerged hydrogen-powered transport. Whereas the two are powered by fuel cells as their main source of propulsion energy, they are distinguished by the architecture of their energy storage and conversion subsystems, and therefore operating characteristics, efficiency and application.

FCEVs may be characterized as the vehicles with the fuel cell system being the main energy conversion system, which directly produces electricity using hydrogen on board. These types of systems usually have the fuel cell as the constant baseline power to run the vehicle and a small, auxiliary battery or capacitor to smooth power dips as well as help during the transient loading event, like acceleration or regenerative braking (Wang et al., 2021). The key traits of FCEVs are their potential to deliver extended driving ranges of 500-700 kilometers on each refill, and the speed of the hydrogen refueling that could be relatively fast taking no more than ten minutes to match the fueling of conventional internal combustion cars (IEA, 2023). Moreover, due to the hydrogen high energy density storage thanks to hydrogen refueling infrastructure, the FCEVs have up to 20 times the range of many battery-electric vehicles (BEVs) (Hua et al., 2022).

FCHEVs are, instead, a hybridized development of the FCEV architecture, in which the fuel cell system would be supplemented with a larger secondary energy storage system, most often seen as a lithium-ion battery, and in some instances as an ultracapacitor. Such hybrid arrangement enables a separation of labor between fuel cell and storage system: the fuel cell is generally optimized to produce steady-state power with high efficiency, and the battery or ultracapacitor is optimized to consume power during acceleration or sharp driving requirements and provide power during regenerative braking (Khalatbarisoltani et al., 2023). FCHEVs increase durability and service life of the fuel cell stack one of the key issues of the wide adoption of FCEV technologies (Cheng et al., 2020) by reducing the dynamic load requirements imposed on the fuel cell.

Naturally, according to the classification, FCEVs and FCHEVs may be classified in both terms of scale and application type. FCEVs have thus far found their primary commercial point of entry in light-duty vehicles (passenger cars and compact vans), as shown with models such as the Toyota Mirai and Hyundai Nexo. With zero-exhaust emissions of any other gases than pure water vapor, due to the hydrogen propulsion form, these vehicles demonstrate the prospect of safe, environmentally friendly, and unobtrusive transport in cities and between cities (Gómez-Barroso et al., 2024). However, FCHEVs have received visibility in fields where high power transients and system survivability is a key factor like buses, trucks and other heavy duty/highly demanding transport applications. What this means is that in the former, the hybrid vehicle will strike a balance between a long driving range and the response to the load changes (Ye et al., 2025).

The next set or axis of classification was in the architecture of the hybridization itself. Parallel hybrid FCHEVs operate in parallel, wherein the fuel cell and the secondary battery supply power to the traction simultaneously, leaving more flexibility in managing power according to the driving status. On the contrary, in series hybrid FCEVs, the fuel cell mostly functions as an on-board generator that recharges the battery that subsequently powers the electric motor. This architecture also lowers the operational stress on the fuel cell and is more demanding on the battery configuration and advanced energy control systems (Huang et al., 2025). Another softer subcategory is complex hybrids, where parallel and series elements are combined in order to get maximum operational flexibility.

FCEVs Performance characteristics FCEVs are generally focused on high autonomy, low emissions, and rapid refueling, and are generally able to compete with internal combustion engine vehicles on user convenience. Although they are a bit more complex, the FCHEVs maximize total efficiency by smartly allocating power flows and overcoming the shortcomings of the fuel cell system, especially when operating at very low temperatures or subjected to high transient loads (Malik et al., 2025). Notably, FCHEVs are also placed as a good bridging technology, one that builds synergies between hydrogen-fuelled fuel cells and high-performing battery technologies, thus meeting/moving challenges in both directions.

The development of the two types demonstrates a converging trend: FCEVs aim at long-range, energy-density transportation applications whereas FCHEVs are the convergence of several storage and conversion technologies to obtain resiliency, efficiencies and longer life of the components. The difference between the two types is not only technological but also strategic in relation to the differences in the routes that the automotive business attempts to take in the direction of carbon-neutral mobility to meet the global energy transition objectives (IEA, 2023; Nebeluk & Ławryńczuk, 2022).

4.5. Energy Efficiency and Performance in Fuel Cell Systems

Energy efficiency is a characteristic feature of fuel cell systems in that it defines both the technical feasibility as well as the competing potential of the fuel cell technology among other prop Transcell technologies. Efficiency has many dimensions in the case of fuel cell vehicle E and hybrid vehicles (FCEV and FCHEV), including the electrochemical performance of the cell stack, the balance-of-plant efficiency, the system-level energy conversion, and the coupling of the vehicle power system. While efficiency is a factor in performance, it is also regarded as performance because of the durability, dynamic response and operational stability within various driving patterns.

Generally speaking, the efficiency of a proton exchange membrane fuel cell (PEMFC), the most popular form in automobile applications, is being expressed as the ratio of the electrical energy output to the chemical energy of hydrogen input at fundamental level. In ideal operation, thermodynamic efficiency of the PEMFCs can reach efficiency levels of up to 83 percent, although an operating efficiency of at least a moderate 40-60 percent is more common depending upon the operating conditions of load, temperature, and pressure (Barbir, 2020). Still lower in use in transportation because of the high operating temperature, but capable of even higher efficiencies, are solid oxide fuel cells (SOFCs), seeing SOFC stationary and auxiliary appliances operating with efficiencies of 60-70% (Oprescu & Rapaport, 2022).

Among the main benefits of fuel cells over internal combustion engines is the fact that chemical energy is transformed continuously to electricity without the restriction of the Carnot-cycle efficiency. Unlike combustion engines, which are thermodynamically operating at an upper limit of circa 30-35 percent efficiencies, fuel cells avoid that upper limit by means of direct electrochemical conversion, which theoretically results in higher efficiencies and less emissions of greenhouse gases per unit of energy output (IEA, 2023). This difference is the base of the strategic advantage of FCEVs and FCHEVs as the facilitators of decarbonized mobility.

Operating conditions are also transient and have a strong influence on performance. When the power demand is suddenly changed fuel cells also have a slower dynamic response than batteries, which has a direct impact on acceleration and the braking efficiency during regeneration. This problem is of special concern in automobile situations where dynamic changes in loading are common. The software solution to the problem with FCHEVs, i.e., hybridization of FCHEVs, is to delegate the peak load requirements to batteries or ultracapacitors, in which manner the fuel cell may run in a relative steady-state condition where its efficiency and durability are optimized (Khalatbarisoltani et al., 2023). At this synergy FCHEVs are more efficient at a systems level, compared to standalone FCEVs and so in real driving cycles which represent variable loads (Ye et al., 2025). To further show the structural composition and functional microarchitecture of a catalyst layer in a proton exchange membrane fuel cell (PEMFC), **Figure 12** shows a cross-sectional view of the physical arrangement of carbon support particles, agglomerated secondary particles, platinum clusters, and ionomer chains for electrochemical reaction and overall cell efficiency (Xie et al., 2021).

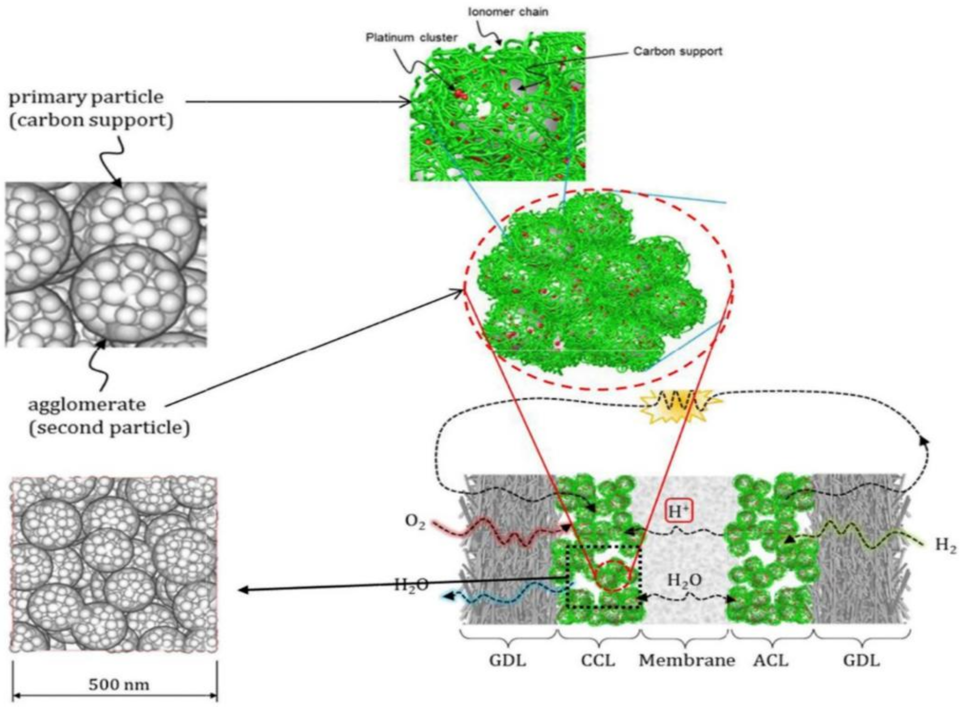

Figure 12. Diagrammatic cross-sectional view of the structure of a catalyst layer in a proton exchange membrane fuel cell (PEMFC). The diagram indicates main carbon support particles, agglomerated secondary particles, Pt clusters and ionomer chains. The microstructural responses between the gas diffusion layer (GDL), catalyst layer (CCL, ACL) and membrane have been highlighted and detailed the routes of oxygen (O_2), hydrogen (H_2), protons (H +), and water (H_2O), and the generation of heat. (Xie et al., 2021)

The performance indicators critical to durability and lifetime are still on the table. It is estimated that fuel cell stacks installed in commercial FCEVs available today can provide similar lifetime values of 5,000-8,000 hours, hence, adequate to pass their life cycle when used in passenger cars, but not in the case of heavy-duty trucking or bus applications (e.g., the 25,000-30,000-hour mark) (Gómez-Barroso et al., 2024). The catalyst poisoning, membrane dehydration, and mechanical stresses are the primary factors of performance degradation that become more efficient with time and cause minimum efficiency reduction in start-stop cycles (Cheng et al., 2020). The limitations are being surmounted by developments in non-precious metal catalysts, long-lived membranes, enhanced thermal and water management systems, and extend operating life and reduce performance deficit compared to conventional powertrain gradually.

System-level efficiency also relies on auxiliary systems such as air compressors, air humidifiers, cooling, and power electronics which are generally referred to as the balance-of-plant (BoP). The subsystems have the potential to consume 30 percent of the gross power of the fuel cell, thus making the net efficiency affectively impacted (Zamel & Li, 2013). More recent advances have been directed toward high efficiency air management systems and lightweight heat exchangers and advanced control algorithms that optimize BoP operation at varying loads. This was complemented by the fact that efficiency is optimized in real-time in FCHEVs using predictive energy management strategies that frequently take advantage of artificial intelligence (Huang et al., 2025).

Compared to rival technologies, FCEV and FCHEV have their own distinctive strengths and weaknesses in performance. Fuel cell systems offer greater driving and refueling than battery electric vehicles (BEVs), albeit with reduced round-trip efficiency, because of the energy losses incurred from producing, compressing, storing, and delivering hydrogen into the overall cycle (Staffell et al., 2019). In comparison, BEVs are more efficient in both aggregate, and are limited by battery size, charging time, and mass. Relative to internal combustion hybrid vehicles, the fuel cells are significantly more energy-efficient, do not produce emissions in the tailpipe, and suffer fewer impediments to wide propagation due to immature infrastructure and higher cost; however, fuel cell vehicles still face some drawbacks recognizable in the field.

Generally, the efficiency and performance of fuel cell system are an outcome of interaction of a complex compatibility between electrochemical processes, materials engineering, system integration and management strategies of characteristics of energy. Even though there are still difficulties to improve on, especially relating to the lifespan of the consumable, the BoP consumption of energy, and supply chain loss of hydrogen, perspectives of technological evolution indicate that fuel cell systems are moving to a pattern of better efficiency, longer lifespan, and a more competitive nature in the global transport business.

4.6. The Role of Hybridization – Combining Fuel Cell and Battery

One of the most important strategies in terms of optimization of energy consumption, maximizing efficiency, and prolonging power train life expectancy is hybridization of gas cell cars. Although fuel cells (FCs) offer a clean and sustained production of electricity using the electrochemical reaction of hydrogen, they have limited quick start/stop and overall operational lifetime under random overloads and elevated costs because they demand high amounts of PGMs. The use of batteries, instead, offers high power density, quick response, and efficient short-term energy storage at the cost of relatively lower energy density and capacity degradation after repeated used. When the two technologies are joined in a hybrid-based architecture, the two shortcomings of each are overcome and the complementary strengths exploited (Pukrushpan et al., 2004; Ye et al., 2025).

Dynamic Fuel Cell-Battery Power Split is the main role of the hybridization. In practice, the fuel cell is commonly sized to meet an average power of a vehicle, so that the fuel cell operates at high efficiency when operating at steady-state loads, whereas the battery contributes to transient spikes in power that is typically needed when accelerating the vehicle, or when climbing hills (Karbowski et al., 2010). This also prevents the fuel cell against sudden changes of current, which explicitly catalyzes the degradation processes that include catalyst dissolution and membrane thinning (Gómez-Barroso et al., 2024). The battery is not exposed to deep discharge so often, because the fuel cell provides baseline energy to drive longer.

Hybridization is also verified to allow regenerative braking energy, which would otherwise be used as heat, to be stored at the battery, which helps increase vehicle efficiency in general and expands driving range (Huang et al., 2025). The battery serves as an energy buffer, and this is similar to tapping into a source of wasted energy, which may be used on the subsequent acceleration cycle. A key feature of this property is that it becomes especially important in urban driving patterns, where the stop/go driving patterns would otherwise overstress the fuel cell when used exclusively.

System-level, hybridization also makes it possible to downsize the fuel cell stack. A smaller stack makes it lighter and less expensive to build and the battery powers up its high-power events. Previous research has found that hybridized fuel cell-battery system has the potential of reaching efficiencies up to 50-60 percent in the real conditions, which is higher than stand-alone forms of a fuel cell (Khalatbarisoltani et al., 2023). Besides, the installation of the reduced load cycling will increase a far-ahead stack lifetime considerably, which is one of the most imminent obstacles to commercialization.

The different hybrid architectures have been postulated to include series, parallel and series-parallel and have different power flow strategies. In the series arrangement, the battery is charged by the fuel cell and the powering of the electric motor is done using this battery. In parallel systems power is supplied directly to the motor by the fuel cell and battery with the control systems making balance decisions on the contribution of the two. More complex energy management systems (EMS) are now being devised to dynamically trade-off efficiency, performance, and component life (Huang et al., 2025).

The other most important advantage of hybridization is that it will be able to incorporate supercapacitors with batteries. Supercapacitors also have a very high power density and fast charging/discharging rate that provides high powers over a short-time, as compared to batteries that offer medium-term storage and fuel cells that have a longer life term (Khalatbarisoltani et al., 2023). Tri-hybrid systems are also being more developed in areas of heavy duty usage, namely buses and trucks, where high energy capacity as well as resilience to transient usage is paramount.

The hybridization is also helpful in thermal management to improve optimization Because of the varying optimal temperature ranges of the batteries and the fuel cells (the former may perform best at 20-40 ^{o}C, the latter at 60-80^{o}C), manufactures can strategically distribute loads to ensure that the devices operate within their optimal performance temperatures, losing little to no efficiency due to undercooling or overheating (Gómez-Barroso et al., 2024).

To sum up, hybridization is not just a technological compromise but it is a synergetic process that makes fuel cell car to have a performance, greater durability, and sustainability. Combining the constant power source of fuel cells and batteries, which have a quick response time to buffering, allows the hybrid system to benefit by having both the best of both worlds in an efficient, secure, clean system that can be relied upon in areas of transportation. With energy management techniques and materials still moving forward, integration between fuel cells and batteries will likely continue to play a key role as the technology behind sustainable mobility moves to the next phase.

4.7. Comparative Performance Assessment of Fuel Cell Hybrid Electric Vehicles (FCHEVs) and Alternative Powertrain Technologies

4.7.1. FCHEVs versus BEVs: Efficiency, Infrastructure, and Life-Cycle Trade-Offs

Comparison of fuel cell hybrid electric vehicles (FCHEVs) with battery electric vehicles (BEVs) forms a salient part of the current debate on the most viable avenue toward decarbonizing road transport. The technologies are both solutions that offer zero tailpipe emissions, but the technical specifications, infrastructural need and life-cycle implications of the two technologies differ significantly which inform their competitiveness compared to one another under varying circumstances.

BEVs use only electrochemical storage in high-capacity batteries of a lithium-ion or other rechargeable battery and the battery load is charged by electric grid. This configuration makes the powertrain simpler, increases the total efficiency and has fewer moving part than the traditional internal combustion engines and indeed FCHEVs have. Typical BEVs convert grid energy to wheels with approximately 75-85 percent energy efficiency, far above FCHEVs at 40-60 percent depending on the system configuration and the operating parameters (Offer et al., 2010; Burchart-Korol et al., 2020). This greater efficiency of BEVs can be explained by the fact that they directly utilize electricity instead of using the energy that would be lost in producing, compressing or liquefying hydrogen, distributing it and bringing it to the fuel cell.

Although these characteristics provide efficiency benefits, BEVs have major shortcomings in regard to driving range, charring duration, and battery depreciation. Current lithium battery energy density is significantly less than that of high-pressured hydrogen resulting in heavier battery packs on long range BEVs. Not only does this weight penalty impair the vehicle efficiency at higher driving range but also impact the vehicle dynamics and impose bulk limitations on payload which is essential in heavy-duty use (Diaz-Gonzalez et al., 2012; Lutsey & Nicholas, 2019). Conversely, FCHEVs have the advantage of the greater gravimetric energy density of hydrogen that allows significantly longer ranges (more than 500 km), and without a significantly greater mass impact, compared to conventional internal combustion vehicles, whose refueling process has a similar time; usually between three and five minutes (IEA, 2022).

The other significant difference is where the infrastructure requirements are concerned. BEVs require a large number of charging stations and are frequently limited by charging rate, especially when connected to a typical house outlet: recharging can take many hours. The rapid-charging phenomenon means that despite fast-charging station proliferation, charging at high voltages does put considerable pressure on battery health and increases the capacity fade during repeated charging cycles (Pellow et al., 2020). Instead, FCHEVs need hydrogen refueling stations that are too few and far between, and are capital-intensive, at least currently (Melaina & Penev, 2013; Hydrogen Council, 2021).

Life-cycle analysis suggests that BEVs will have a comparatively low greenhouse gas emission profile in areas with high/dominant renewable/low-carbon electricity supplies due to the fact that most emissions are attributed to the use of the vehicle. Nevertheless, the environmental and social challenges associated with mining and refining of much needed raw materials like lithium, cobalt, and nickel appear, especially in locations with poor labor and environmental regulation (Dunn et al., 2012; Olivetti et al., 2017). However, on the other hand, within the FCHEVs also, particularly minimal raw materials and hydrogen tank and balance of plant materials are needed, whereas fuel cell stacks continue to be very reliant on the platinum group metals, which are rare and costly (Chen et al., 2023). Moreover, the climate advantage of FCHEVs is highly contingent on how hydrogen is produced: when hydrogen is generated through steam methane reforming with no carbon capture, it leads to high emissions, but when generated through renewable electrolysis to produce a so-called green hydrogen, low or even negligible carbon can be expected (IEA, 2022).

Upon its application, BEVs have, already, taken up the bulk of the market share in the light-duty passenger car market following the decrease in the cost of battery technology, the proliferation of charging facilities, and favorable policy support. By contrast, FCHEVs enjoy limited usage as they are being introduced mostly into niches where high autonomy, fast fueling, and lightweight in comparison to operating energy are the guiding factors (e.g., buses, heavy-duty trucks, and long-haul fleets) (Moultak et al., 2017; Shi et al., 2025).

In general, the analysis of comparison distinguishes a non-competitive but complementary relation between FCHEVs and BEVs. Although BEVs have better utility in the short- to medium-range with stable supply of charging points, the FCHEV has exclusive benefits in heavy-duty and long-distance transport as well as in fleet-based transport. Technological advances in energy storage, deployment of infrastructure and decarbonization of electricity and hydrogen supply chains will define the long-term trend of both technologies.

Table 3. Comparison of FCHEVs and BEVs

Criterion	FCHEVs (Fuel Cell Hybrid Electric Vehicles)	BEVs (Battery Electric Vehicles)
Energy Source	Hydrogen (H_2) stored in high-pressure tanks; electricity generated on-board via fuel cell stack	Electricity stored in lithium-ion or alternative batteries
Refueling/Charging Time	3–5 minutes for hydrogen refueling (similar to gasoline vehicles)	30 minutes to several hours depending on charger level and capacity
Driving Range	Typically, 500–700 km per refuel (long-haul capable)	Typically, 300–500 km per charge (limited for long-haul without fast charging)
Infrastructure	Limited hydrogen refueling stations; costly to expand	Expanding charging network; relatively mature and widespread
Efficiency	40–60% system efficiency; efficiency losses in hydrogen production and transport	70–90% efficiency from grid-to-wheel (higher overall efficiency)
Emissions	Zero tailpipe emissions; sustainability depends on hydrogen production method (green vs grey hydrogen)	Zero tailpipe emissions; life cycle emissions depend on electricity generation mix
Cost	High upfront vehicle cost; expensive hydrogen fuel (USD 8–12/kg in many regions)	Lower upfront cost relative to FCHEVs; lower operating cost with cheap electricity
Best-Suited Applications	Long-range, heavy-duty transport, buses, trucks, fleet operations	Urban mobility, short to medium range passenger vehicles

4.7.2. FCHEVs vs Internal Combustion Hybrid Vehicles

The debate between Fuel Cell Hybrid Electric Vehicles (FCHEVs) and Internal Combustion Hybrid Vehicles (ICHVs) commonly, but not limited to, the Nature of the gasoline-electric hybrids), is part of a larger debate regarding the course to decarbonization of the transport sector. Although ICHVs have enjoyed a high level of acceptance because of their comparatively cheap prices, old technology, and pre-existing gasoline infrastructure, FCHEVs appear to be much more of a breakthrough toward zero-emission driving with hydrogen portrayed as the most sustainable energy carrier (IEA, 2022).

Tailpipe emissions is one of the differentiating factors. Although HCHVs consume less fuel than plain internal combustion engine (ICE) cars, they still produce carbon dioxide, not to mention other pollutants. Regenerative braking, downsizing of the engine, and improved energy management practices are behind much of their performance success (Mock & Tietge, 2019). Compared to them, FCHEVs, which can utilize green hydrogen produced by renewable power, are zero-emission vehicles in themselves by virtue of the end product of powering up (Hydrogen Council, 2021).

ICHVs are generally equal or better at well-to-wheel efficiencies than conventional ICEs, i.e., 25-30% (Bandivadekar et al., 2008). Compared to BEVs, HFCVs, and HEVs, the overall well-to-wheel efficiencies on the order of 35-45% are achievable with HFCVs depending on the hydrogen production process, H storage and conversion losses (Diaz-Gonzalez et al., 2012; Shi et al., 2025). Although batteries in the hybrid system offer further efficiency advantages through regeneration of braking energy and a smoothing of the load demands, the reliance on combustion sources intrinsically chips away at the possibility of influencing the benefits of the powertrain through emissions.

On performance grounds FCHEVs have an advantage in driving distance and refueling times compared to battery only vehicles and in longer distance traveling since FCHEVs often equal or exceed ICHVs in long distance driving performance (Offer et al., 2010). Nevertheless, as long as the hydrogen infrastructure in a given economy has not been fully developed, the maturity and cost advantage of ICHVs give them an upper edge over competitors (Melaina & Penev, 2013). The up-front cost of FCHEVs however costs more, mainly because of the use of expensive materials such as platinum-based catalysts, and high-performance hydrogen storage systems, whereas ICHVs have economies of scale and advances to a mature platform (Chen et al., 2023).

One of the issues raised is sustainability in the long run. Although ICHVs can act as a transitional technology, they have a similar dependence on fossil fuels as the technology that contributes problems to the efforts to achieve net-zero emissions by mid-century (Lutsey & Nicholas, 2019). Hydrogen-powered FCHEVs, on the other hand, offer a scalable solution to decarbonization, especially in the case that production, storage, and distribution systems of hydrogen remain technologically and economically possible.

ICHVs have been a short- to medium-term strategy in terms of the reduction of emissions in existing infrastructures, whereas FCHEVs constitute a long-term strategic choice leading to climate neutrality.

The rate of infrastructure development, reduction in prices in hydrogen technologies, and regulation incentives would be the important considerations of how FCHEVs will supplant the hybrids in the world transport industry markets.

As mentioned by the Table 4, the key differences between FCHEVs and ICHVs are the long-term (however, when the hydrogen infrastructure becomes mature) sustainability offered by the former against the short-term (but soon to become more economically efficient) efficiency of the latter.

Table 4. Comparison of FCHEVs and ICHVs

Criterion	FCHEVs (Fuel Cell Hybrid Electric Vehicles)	ICHVs (Internal Combustion Hybrid Vehicles)
Tailpipe Emissions	Zero (only water vapor when using green H_2)	CO_2 and pollutants from combustion
Energy Efficiency (well-to-wheel)	35–45% (depending on H_2 production & hybridization)	25–30% (limited by thermodynamics of combustion)
Fuel Source	Hydrogen (potentially renewable)	Gasoline/Diesel (fossil fuels)
Refueling /Recharging Time	3–5 minutes (hydrogen refueling)	3–5 minutes (gasoline refueling)
Driving Range	Comparable or superior to ICHVs (500–700 km typical)	500–800 km typical
Technology Maturity	Emerging, higher costs, limited infrastructure	Mature, cost-effective, global infrastructure
Sustainability Outlook	Aligned with net-zero targets if powered by green H_2	Transitional technology; reliant on fossil fuels
Market Position	Long-term strategic option	Short- to medium-term bridging solution

4.8. Sustainability, Range, and Cost

Sustainability is necessarily attached to compliance with Fuel Cell Hybrid Electric Vehicles (FCHEVs) as long as there is dependence on the hydrogen molecule as an energy carrier and the life cycle implications of the components. Hydrogen is a carbon-neutral solution, especially when produced by electrolysis of water using renewable fuels, in line with decarbonization targets in the long-term (Bhandari et al., 2013). Nevertheless, FCHEV sustainability profile greatly depends on the method of hydrogen production. Natural gas-based grey hydrogen has a large carbon footprint but green hydrogen, which is generated via renewable electricity, has a minimal impact (IEA, 2023). To this end, the environmental benefit of FCHEVs requires additional growth in renewable hydrogen infrastructure and supply chains. Also, the life cycle assessments point to the fact that manufacturing the fuel cell materials themselves, such as platinum-group metals and composites into catalysts as well as vehicle structures, can lead to environmental pressures without established recycling mechanisms (Mekhilef et al., 2012).

FCHEVs have a competitive edge in regard to driving range over Battery Electric Vehicles (BEVs). The FCHEVs commonly have a range of 500 to 700 kilometers per hydrogen fill which is similar or higher than the range of conventional ICEVs (Syré et al., 2024). The feature makes them especially suitable in the long-haul transportation, heavy-duty work, and those markets where speedy refueling is critical. The on-boarding process makes them convenient with a refueling time of less than five minutes closely relating to that of conventional vehicles to reduce the range anxiety that is often associated with BEVs (Chen et al., 2023). In heavy-duty applications, the FCHEV is becoming an increasingly attractive alternative to the BEVs, due to the relative disadvantages of large battery packs in terms of weight and charging time being a significant limitation in practices (Pera et al., 2025).

Nevertheless, cost dimension is still one of the major obstacles to mass FCHEV adoption. The use of Fuel cell systems with hydrogen is more costly than both battery packs and internal combustion engines because of their material cost, including the platinum in catalysts and carbon fiber in hydrogen storage tanks (Jokisch & Mennel, 2008). Moreover, the current hydrogen fuel cost is still expensive, and its production and delivery infrastructures are not at the stage that can result in competitive levels with electricity or gasoline (IEA, 2023). Although estimates indicate that the cost of hydrogen must be less than USD 2/kg to make FCHEVs financially competitive in a mass market, this target will be reached through the development of renewable energy integration, the increase in electrolyzer efficiency, and the development of supply chains (IRENA, 2022). Currently, FCHEVs are generally more expensive to own than either BEVs or hybrid ICEVs, a difference that is more pronounced in organizational markets over passenger vehicle markets, although niche applications such as buses and heavy trucks may have a more balanced price-performance advantage given FCHEVs operational range and refueling duration (Yilmaz & Krein, 2013).

In essence FCHEVs are in an in-between phase with sustainability, range and cost being the USPs. Where range and long-term recharging is less a concern and infrastructure is more mature, BEVs are expected to take the lead, especially in short-range and urban transportation. On the other hand, long-range applications across several industries are likely to be served by FCHEVs, which have superior energy density, faster top-ups, and lower cost. To be fully sustainable, it will be necessary to decarbonize the supply chains of hydrogen, recycle and substitute materials, and cost competitiveness will depend both on technological breakthroughs and the policies. Under these conditions, FCHEVs can transition out of the niche provider category and become a mass contribution to the world movement towards sustainable transportation as well.

CHAPTER 5

Prospects and Challenges in the Development of FCHEVs

5.1. Anticipated Technological Innovations

The future development of fuel cell hybrid electric vehicles (FCHEVs) is highly linked to technological innovations to improve performance, reduce costs and increase overall system reliability. In recent years, research efforts have focused more on breakthroughs in materials, system and intelligent control strategies, which together hold the promise of transforming FCHEVs into a mainstream solution for sustainable mobility. The innovation expected can be examined along a number of dimensions, which are interrelated and include fuel cell stack design, hybrid powertrain configurations, the advanced energy storage, digitalization and integration with renewable energy infrastructures.

One of the biggest directions is in the area of next generation fuel cell stacks, in particular proton exchange membrane fuel cells (PEMFCs), which are dominant in automotive applications because they operate at a relatively low temperature and have fast response time. Current research efforts are aimed at improving the power density and durability, while at the same time reducing the use of platinum-group metals (PGMs). The expected innovations are novel catalyst formulations, such as nanostructures of platinum alloys or non-precious metal catalysts (NPMCs), which can bring a significant decrease in cost with no compromise in performance (Zhao et al., 2022). Advanced membrane materials of higher proton conductivity and enhanced thermal stability are also expected to appear, enabling the cells to operate more efficiently at higher temperatures, which in turn will increase the tolerance to fuel impurities and water management issues (Kim et al., 2021).

Another major innovation trajectory is solid oxide fuel cells (SOFCs), especially when converted into hybrid technologies with gas turbines or batteries. SOFC-based FCHEVs, despite not being commercially available, offer the potential of high efficiencies (above 65%) and fuel flexibility, including the possibility of running on ammonia or bio-derived fuels (Pan, Chen, & Wang, 2023).

Advances in additive manufacturing of SOFCs are expected to lower the cost of production and facilitate the scale-up process, while novel ceramic composites are designed to enhance mechanical robustness and cycling stability (Mueller et al., 2021).

At the level of the hybrid system design, future FCHEVs are expected to shift towards triple-hybrid designs which incorporate fuel cells, batteries, and supercapacitors. Such designs would offer the option of fine-tuning power delivery, with the fuel cells providing a baseline energy supply, the batteries handling medium load fluctuations, and the supercapacitors providing an instantaneous power boost for accelerating or brakes regeneration. This tripartite architecture is expected to achieve maximum hydrogen efficiency, prolong life of components, and offer unprecedented flexibility in coping with different driving cycles (Pan et al., 2023).

Closely related to hybridization is the development of energy management systems (EMS). Future EMS innovations will be based on advanced artificial intelligence (AI) and machine learning (ML) algorithms that are able to perform predictive optimization. By utilizing real-time information from GPS, LIDAR, traffic prediction systems, EMS will be able to anticipate the road conditions, optimize the energy flows, and dynamically distribute the power between the fuel cell, battery and the auxiliary loads (Wu et al., 2021). Reinforcement learning-based strategies have already been shown to make huge improvements in fuel economy and durability, and further developments in digital twin technologies is expected to offer virtual environments for continuous optimization and fault detection (Mohammadi et al., 2023).

Parallel to electrochemical improvements, lightweight and multifunctional materials are expected to be a game changer. Advanced composites, such as carbon fiber reinforced polymers (CFRPs) and aluminum-lithium alloys will reduce the weight of structural components, improving range and efficiency (Hassan et al., 2023). Simultaneously, multifunctional materials that can have structural strength while also having energy storage capabilities (sometimes called "structural batteries") are being explored for future FCHEVs (Manthiram, 2020).

Another important innovation path is the thermal and water management systems, which are paramount for ensuring safety as well as efficiency. Future FCHEVs will also be expected to incorporate phase-change materials (PCMs) and thermoelectric generators (TEGs) for better heat management and recovery of waste heat into useful electricity (Xie, Liu, Wang, & Xu, 2023). Advanced coolings designs using nanofluid based heat transfer and smart sensor based control loops are expected to maintain respective temperature ranges across the powertrain and storage components (Gulzar et al., 2022).

From an infrastructural perspective integration with green hydrogen production as well as with smart grids is also an important innovation. Electrolyzers fed with surplus renewable energy are expected to provide hydrogen for FCHEVs, which will allow a circular energy economy, matching vehicle operation to the overall decarbonization objectives (Nikiforidis et al., 2021). The expected development of compact, onboard hydrogen storage systems with improved gravimetric and volumetric densities, e.g. metal-organic frameworks (MOFs) or cryo-compressed hydrogen tanks, could greatly increase driving distances while reducing the frequency of refueling (Staffell et al., 2019).

Finally, cost reduction, achieved by mass production and modularity, is an equally important innovation pathway. Modular FCHEV platforms that are shared across passenger cars, buses, and trucks will help achieve the economies of scale more quickly, lower development costs and help to get the various components into the market faster. Combined with expected cost reductions for hydrogen production to less than $2/kg by 2030 from a current price of $5-$6/kg (IEA, 2023), these improvements could help make FCHEVs cost-competitive with battery electric vehicles (BEVs) and internal combustion engine hybrids.

In summary, expected technological innovations in FCHEVs promise to change the landscape of sustainable transportation for the next decade. From materials science innovations and hybrid architectures to intelligent energy management and integration with renewable infrastructures, the combined goal of these innovations is to provide cleaner, more efficient, and cost-effective vehicles. Their success will be a decisive factor in determining whether FCHEVs can move from niche applications to a dominant place in the global transport sector.

5.2 Hydrogen Refueling Infrastructure and Economic Viability

The widespread introduction of fuel cell hybrid electric vehicles (FCHEVs) requires the development of hydrogen refueling infrastructure in parallel with the development of the technology in the vehicle itself. Without a good refueling network that is accessible and economically feasible, FCHEVs cannot reach the level of widespread usage regardless of their technical advantages. The infrastructure challenge is therefore generally acknowledged as one of the most important bottlenecks in the shift toward hydrogen-based mobility (Hydrogen Council, 2021; IEA, 2023).

To date, the number of operational hydrogen refueling stations is still low and its distribution is not yet uniform. Countries like Japan, South Korea, Germany and the United States have invested heavily in hydrogen corridors but the total for the world is small compared with the ubiquitous availability of charging stations for battery electric vehicles (BEVs). The patchy density of refueling stations makes potential users more range anxious and compromises the convenience issue that is so important to consumer acceptance. Thus, future development strategies focus not only on the increase of the number of stations, but also on optimizing their location depending on traffic flows, logistics centers and urban centers for efficient utilization at minimal costs (Melaina & Penev, 2013).

A key factor in the economic viability of hydrogen refueling infrastructure is the cost of producing and distributing hydrogen. Today, levelized cost of hydrogen (LCOH) is higher than fossil fuels and electricity and ranges from $5 - $6 per kg when produced from natural gas reforming with carbon capture or renewable electrolysis. Projections by the IEA (2023) and the Hydrogen Council (2021) indicate that with technological learning, scale-up of electrolyzer production and falling renewable electricity prices, the cost may be less than $2/kg by 2030. Reaching this threshold is generally felt to be important to achieve on total cost of ownership parity with BEVs and internal combustion engine vehicles (Staffell et al., 2019).

The transport and storage of hydrogen is of course also of decisive importance for the economy of infrastructure. Present options for hydrogen supply include hydrogen in compressed form at 350-700 bar, hydrogen in cryogenic form as a liquid, and more recently options for hydrogen storage and supply using liquid organic hydrogen carriers (LOHCs) or metal hydrides. While compression and liquefaction are established as commercial processes, they are energy intensive and expensive. Future innovations in lightweight composite storage tanks, solid-state storage media and distributed electrolysis at fueling stations are expected to lower the costs and improve safety (Nikiforidis et al., 2021). Furthermore, the co-location of electrolyzers with renewable power plants would reduce transportation requirements and could connect green hydrogen production directly to end-users for transportation (Pellow et al., 2020).

From the point of view of refueling time and user convenience, hydrogen refueling stations already have clear advantages over BEV charging, with typical refueling times of 3-5 minutes for passenger cars and 10-15 minutes for heavy-duty trucks (Farra, Almansoori, & Elkamel, 2021). Future station designs are expected to increase throughput and decrease costs by means of modular station architectures, standardized components and automation of refueling processes. This will be crucial for fleet operators, logistics companies and public transportation providers, for whom downtime is directly equivalent to economic loss.

The economic models for infrastructure deployment are increasingly showing the need for public-private partnerships. The high initial capital investments for hydrogen stations (of the order $1-2 million per station, depending on their capacity) posed financial risks for private investors when the vehicle penetration is low, as is currently the case (Melaina & Penev, 2013). Therefore, many governments have introduced subsidies, tax credits or direct co-investments in station networks in order to generate initial demand pull. In the medium to long term, business models involving the combination of hydrogen sales with additional services, such as balancing the grid, local storage or connection to renewable energy centres, could improve profitability (Yilmaz and Krein, 2020).

The economic viability of FCHEVs as compared with BEVs and internal combustion engine vehicles is dependent on both the cost of the fuel and its infrastructure availability. Studies suggest that the total cost of ownership of FCHEVs is potentially competitive in certain segments such as heavy duty transport, buses, and long-haul freight due to the benefits associated with fast refueling and high range compared to the infrastructure cost (Wang, Yu, & Yang, 2022). In contrast, passenger cars could still struggle against BEVs due to the rapid growth of the charging infrastructure and decreasing cost of batteries (Lutsey & Nicholas, 2019).

The expected development of hydrogen refueling infrastructure is an essential component of the viability of FCHEVs. Future prospects lie in the development of low-cost production of hydrogen by large-scale use of renewable sources for electrolysis, storage and transport technology and the establishment of a network of stations at strategic locations. Achieving economic sustainability will take coordinated policy support in combination with technological innovation and collaboration across the automotive, energy and public sectors. Without these advancements, FCHEVs may continue to be limited to niche applications; however, with these advancements, they have the potential to play an essential role in decarbonizing transportation globally.

5.3. Regulatory Framework and Supporting Policies

The development of fuel cell hybrid electric vehicles (FCHEVs) cannot be divorced from the regulatory and policy environment in which FCHEVs are developing. While technological innovation and infrastructure development are the technical backbone of the hydrogen mobility transition, political commitment and regulatory alignment are the enabling framework that determines market feasibility, investment attractiveness and societal adoption (Hydrogen Council, 2021; IEA, 2023).

One of the most influential factors in FCHEV deployment is the worldwide initiative to decarbonise, which is anchored in international agreements such as the Paris Agreement and national net-zero emissions commitments by mid-century. To achieve these goals, vehicle emission standards have been tightened with many countries issuing zero-emission requirements that clearly favor fuel cell and battery electric vehicles over traditional internal combustion engines. For instance, the CO2 fleet emission reduction targets for 2030 and beyond have been introduced in the European Union, and the Zero Emission Vehicle (ZEV) mandate has been introduced in California-driven by the policy, automakers are required to increase the share of ZEVs in their portfolios (Mock & Tietge, 2019). These regulations give a regulatory pull for automakers to invest in FCHEV technologies as a part of the compliance strategies.

In addition to regulatory requirements, there are direct policy measures (subsidies, tax credits, grants for hydrogen vehicles and infrastructure etc.) that have more direct links to the market. Japan and South Korea have been pioneers in offering generous subsidies for FCHEVs which helps greatly reduce the purchase prices to consumers, and also for the growth of hydrogen fueling stations. The German National Hydrogen Strategy passed in 2020 directs billions of euros toward mentoring hydrogen structures and automobile introduction, indicating a solid state-down strategy to market innovation (Ehebrecht, Heinrichs, & Weyer, 2021). These policies will be broadened and matured, paying more attention to long-term financial viability, and steady phasing out of direct subsidies, once economies of scale are reached.

A very important point is the standardization of hydrogen technologies and safety rules. If FCHEVs are to become a global technology, harmonized technical standards need to be developed with regard to hydrogen storage pressure levels, fueling connectors, refueling protocols and vehicle safety requirements. Current efforts by organizations like International Organization for Standardization (ISO) and Society of Automotive Engineers (SAE) are geared towards ensuring interoperability and safety across markets (Melaina & Penev, 2013). New technologies for high pressure (e.g. 700 bar tanks) and cryogenic will create demands for new safety standards and regulators will have to find a balance between consumer protection and technological flexibility.

Policy support also goes to funding for research and development (R&D), which is critical for the development of next-generation FCHEV technologies. The U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office, for instance, provides funding for work in the area of low-PGM catalysts, high-efficiency electrolyzers and hydrogen infrastructure projects. Hydrogen technologies are already included in funding programs of the European Union (EU) under Horizon Europe, including in the framework of collaborative research programs with industrial consortia (Nikiforidis et al., 2021). This is expected to foster R&D investment and expedite commercialization of the innovations with cost reduction across the hydrogen value chain.

Equally important is the development of integrated energy and transport policies that place hydrogen mobility in the context of wider strategies for the integration of renewable energy and smart grids. As production of hydrogen increasingly moves towards renewable-powered electrolysis, policies that support sector coupling, that is, linking electricity, heating and transport will be at the heart of securing the flexibility and resilience of energy systems (Staffell et al., 2019). National hydrogen roadmaps, such as those introduced in Germany, France, China and Australia, reflect the growing acknowledgement of the value of hydrogen as more than a transport fuel; a systemic energy vector.

From a socio-economic point of view, policy frameworks also have to take account of the market creation and the barriers to consumer adoption. Early adopters of FCHEVs are faced with higher purchase prices and limited refueling infrastructure, which can discourage widespread uptake. To overcome these barriers, governments can use actions such as preferential access to urban low emission zones, free or discounted parking and reduced toll fees for hydrogen vehicles. These complementary policies make FCHEVs more attractive to consumers and increase the perceived value of FCHEVs compared to conventional vehicles (Lutsey & Nicholas, 2019).

Finally, the regulatory environment will have to move with the times in order to keep up with technological and market changes. As the hydrogen economy gets more mature, regulatory attention will shift towards making the sustainable hydrogen value-chain. This includes setting carbon intensity standards for hydrogen production (green, blue or grey), incentivizing lifecycle emissions reductions and enforcing regulations for recycling of critical materials as used in fuel cells and energy storage systems (Dunn et al, 2015). Future policies are expected to focus more on traceability, certification and cross-border dropout of hydrogen, which will be the essential prerequisites for the integration of global markets.

The regulatory and policy environment for FCHEVs is a definite factor in determining how they will develop in the future. The combination of emission standards, subsidies, R&D funding and harmonized safety regulations creates both a push and a pull for the technological adoption. It is expected that in the future, there will be greater demand for sustainability requirements, more integrated sectoral policies, and new incentive mechanisms that will speed up the adoption by consumers. Together, these regulatory mechanisms and policy tools will determine whether FCHEVs will grow from a transitional niche technology to become a cornerstone of global decarbonized mobility.

5.4. Critical Assessment of Recent Trends

In the past years, research and development in fuel cell hybrid electric vehicles (FCHEVs) have been increasing rapidly, which is a manifestation of a combination of advances in material science, electrochemical engineering and digital control systems. However, a critical analysis of these trends indicates both successes and continuing obstacles that continue to define this technology's future.

One of the most impressive has been the increase in durability and performance of the fuel cell. Performance of low platinum group metals catalysts, new membranes, and bipolar plate coatings has been improved to decrease the degradation rate and improve the system lifetime under dynamic driving conditions (Chen et al., 2023; Wang, Zhang, Xie, & Wang, 2022). However, some challenges still need to be met for these materials innovations to be scaled up to mass production at costs acceptable to the automotive industry. However, it is still found that platinum loading has been reduced significantly, complete replacement with non-precious catalysts is still not satisfactory and commercially feasible, and durability under real-world conditions still remains a problem (Zhao, Li, & Chen, 2022).

Artificial intelligence (AI) is another major trend seen in energy management strategies. Model predictive control, reinforcement learning, and digital twin models are more and more used for the purpose of optimizing the energy distribution in real-time among the fuel cell/battery/supercapacitor subsystems (Liu, Xu, Wang, & Zhang, 2021; Wu, Liu, & Jin, 2021). While these methods have shown impressive fuel economy gains in simulations and pilot studies, their real-world implementation in commercial vehicles still needs validation, especially in terms of computational load, cybersecurity threats, and reliability under a variety of operating conditions (Pan, Zhang, & Li, 2023).

At the infrastructure level, hydrogen refueling network is expanding, although unevenly regionally. Early hydrogen corridors have been constructed in Japan, South Korea and parts of Europe; clusters have been developed in California and some metropolises in North America (Hydrogen Council, 2021; Ehebrecht, Heinrichs, & Weyer, 2021). However, coverage is still not sufficient on a global level, and without policy coordination on an international scale, fragmented markets continue to be a threat. The small size of hydrogen production and the dependence of many areas on natural gas reforming also beg the question of the true benefits of FCHEVs on the environment today relative to battery electric vehicles (BEVs) (Nikiforidis, Hernandez-Aldave, Payne, & Brett, 2021; Bhandari, et al., 2013).

An economic dilemma confronting FCHEVs is that they are very expensive to produce and it is not certain that FHEVs will be competitive in the long term. While battery cost reduction trends indicate a drastic cost reduction in fuel cell stacks and hydrogen storage systems, BEV technology has benefitted from even greater cost reductions due to economies of scale in battery production (Lutsey & Nicholas, 2019). Comparative lifecycle assessment shows that FCHEVs might be advantageous in long-haul, high-utilization, and heavy-duty application but cannot compete in passenger market applications where BEV has already won over (Niknejad, Petri, & Krauss, 2022; Wang, Yu, & Yang, 2022). Thus, the key trend is segmentation of the markets, with

FCHEVs potentially carving out niches in the area of freight, public transport and niche forms of mobility, as opposed to widespread passenger adoption.

From an environmental point of view, FCHEVs provide obvious benefits only if the hydrogen is generated from renewable sources. Grey hydrogen or blue hydrogen is still being used in many places and this goes against the narrative of zero-emission mobility. As described in Staffell et al. (2019) and IEA (2023), the sustainability of FCHEVs must be intimately connected with the decarbonization of hydrogen production. As a result, although technological advances in electrolyzer technologies and decreasing prices of renewable energy suggest greener supply chains are in store, the point at which this happens cannot be foreseen and until it happens at scale, the environmental dominance of FCHEVs will continue to be under debate.

Finally, there is a clear trend to increase the policy focus on hydrogen as an energy vector rather than a standalone as a mobility solution, which needs to be critically evaluated in the future. While this systems approach strengthens the position of FCHEVs in integrated energy networks, it also creates vulnerabilities. A framework that does not prioritize transportation in national hydrogen strategies is likely to result in competing claims for renewable hydrogen across sectors - such as heavy industry, aviation and grid storage - which will divert investment and delay the deployment of FCHEVs (Pellow, Emmott, Barnhart, & Benson, 2020).

In conclusion, the current FCHEV trends critical evaluation highlights a technology on the crossroads. On one hand, technological developments in material, AI-based energy management systems and pilot infrastructure projects clearly indicate progress towards technical feasibility. On the other hand, high cost, durability, infrastructure installation and sustainable sourcing of hydrogen are still unresolved issues which provide enormous hurdles to mass adoption. For the foreseeable future, the future of FCHEVs will most probably be one of niche applications to those sectors for which their capabilities - long range, fast charging and energy flexibility - offer a distinct advantage. Their long-term role will ultimately be shaped by the success in global upscaling of renewable hydrogen production, regulatory alignment and the ability to ensure that technological innovations can be translated into cost-effective, durable and consumer accepted solutions.

CHAPTER 6

Conclusions

6.1. Key Findings and Achievements

The research into fuel cell hybrid electric vehicles (FCHEVs) has been covered with a wide variety of findings that reflect the technological maturity as well as current challenges of this area. One of the most important is the great improvement in fuel cell performance and durability in the last decade. Advances in proton exchange membrane fuel cells (PEMFCs) in particular with reduced Pt group metal loadings and novel membrane and catalyst structures have allowed fuel cells to run more efficiently and with higher resistance to degradation in dynamic driving conditions (Chen, Hou, Liu, & Zhao, 2023; Wang, Zhang, Xie, & Wang, 2022]. This advancement has made fuel cell systems cost-effective and reliable, making them a viable propulsion option in the shift to sustainable mobility.

Another trend observed is the integration of hybrid architectures, in which fuel cells are used in combination with batteries and supercapacitors to balance energy demands and improve system flexibility. The hybridization approach not only reduces the consumption of hydrogen since it can operate the fuel cell in the high-efficiency range, it also prolongs the life of the energy storage devices by more effectively distributing transient loads (Pan, Liu, Sun, & Zhang, 2023; Sun, Li, & Zhou, 2021). This synergy has become one of the pillars of the design of FCHEV and there is a clear benefit over stand-alone fuel cell or battery systems in terms of range, responsiveness, and resilience.

The findings also identify the imperative for fast development of energy management strategies (EMSs) that maximize the use of multiple power sources in FCHEVs. From rule based system to advanced model predictive control (MPC) and reinforcement learning approaches, EMS innovations have been proven to be a great way to improve fuel economy and minimize system degradation in both simulations and real-world demonstrations (Liu, Xu, Wang, & Zhang, 2021; Wu, Liu, & Jin, 2021). Predictive EMSs, taking advantage of GPS, traffic information and artificial intelligence, is one of the most promising facets of the advances of the last years, with some studies proving that their efficiency can increase by 15% (Tella et al, 2024).

In addition, the study highlights the growing role of hydrogen refueling infrastructure and renewable hydrogen production in determining the viability of FCHEVs. Pilot projects in Japan, South Korea, Germany and California show that well-developed hydrogen corridors can be an effective aid in early adoption (Ehebrecht, Heinrichs, & Weyer, 2021). At the same time, new electrolyzer technologies, in particular, proton exchange membrane electrolyzers and solid oxide electrolyzers, promise to reduce costs and to produce green hydrogen on a large scale with renewable energy (Nikiforidis et al., 2021; Turner, 2004). These accomplishments are critical to ensuring that FCHEVs live up to their environmental promise, operating on hydrogen with as small of a carbon footprint as possible.

Another major achievement is in the comparative benefits of FCHEVs against competing technologies for some applications. While battery electric vehicles (BEVs) are increasingly dominant in passenger mobility, FCHEVs have superior performance in terms of range over long distances, fast refueling and heavy payload. Life cycle assessments and techno-economic studies indicate that FCHEVs may be especially competitive in heavy-duty freight transport, public buses and fleet operations, where down times for charging are costly and energy demands are high (Niknejad et al., 2022; Wang et al., 2022). This segmentation highlights the complementary role of the FCHEVs in the larger ecosystem of low-emission transport technologies.

Finally, the results show that the policy support and regulatory frameworks have played a significant role in shaping the development of FCHEV. National hydrogen strategies, vehicle purchase subsidies and investments in refueling infrastructure have together led to accelerated adoption in certain markets (Hydrogen Council, 2021; IEA, 2023). Importantly, policy focus on life cycle sustainability, including the production of hydrogen, its distribution and end-of-life recycling of vital materials, has contributed to the understanding of the overall socio-economic context FCHEVs are expected to expand within (Dunn et al., 2015).

In conclusion, the main achievements in the development of FCHEV can be summarized as improvements in the core technologies, successful integration of hybrid energy systems, energy management improvements, improvements in hydrogen infrastructure and renewable production, identification of competitive niches and supportive regulatory frameworks. Together, these findings present FCHEVs as a technologically advanced and strategically positioned solution in the transition towards a sustainable transport sector, while also setting the stage for solving the challenges that still remain in the regression of costs, infrastructure scalability and environmental sustainability.

6.2. Potential Directions for Future Research

Despite the great progress made during the development of fuel cell hybrid electric vehicles (FCHEVs), there are some open questions that need to be addressed by dedicated studies in order to make this technology more widely available. A multi-dimensional agenda will be used for future research, which includes materials science, systems integration, hydrogen infrastructure, and socio-economic analysis.

One of the important directions is the synthesis of new generation catalysts and membranes for fuel cells. Although efforts have been made to decrease the platinum loading and research on non-precious metal catalysts, research is still required to design materials with low cost, high activity and long-term stability under changing operation conditions (Zhao et al., 2022; Wang et al., 2022). Single-atom catalysts, alloyed nanostructures, and advanced ionomer membranes with improved hydration and thermal endurance are the promising areas (Kim et al., 2021). In addition, further research should also be conducted into recycling strategies for precious and critical metals in order to ensure sustainable supply chains (Dunn et al., 2015).

Another interesting research direction is in thermal and water management strategies. Efficient thermal management of the fuel cell stack as well as of the auxiliary components (battery, power electronics) is a challenge. Advanced heat exchanger technologies, thermal interface materials and phase change materials (PCMs) can be researched to stabilize the operating conditions and mitigate degradation (Xie, Liu, Wang, & Xu, 2023; Gulzar, Ma, Hussain, & Rehman, 2022). In addition, the water management in PEM fuel cells, that is balancing the membrane hydration while avoiding flooding, is still an area that needs further modeling efforts and novel flow-field architectures.

The use of artificial intelligence (AI) and digital twin as tools for fuel cell system optimization is another promising field for research. While model predictive control and reinforcement learning have shown promise, there are still limited real-world applications, due to computational and data challenges. Future research is recommended on embedding light weight AI algorithms into VUCs, cyber-secure architectures, validating digital twin models under heterogeneous driving conditions, etc. (Wu et al., 2021; Pan et al., 2023). The combination of predictive EMS with vehicle-to-everything (V2X) communication and autonomous driving systems is also a promising future.

At the infrastructure level, research is needed for the scalability of hydrogen production, distribution and refueling networks. However, even though the electrolyser technologies are advancing, the cost reduction of renewable electricity, the better lifetime of electrolyser, and the efficient coupling with intermittent energy sources are necessary for large-scale green hydrogen production (Nikiforidis et al., 2021; Turner, 2004). Investigations on novel storage solutions such as liquid organic hydrogen carriers (LOHCs) and solid-state hydrides have the potential to further improve the practicality of hydrogen logistics. In addition, comparative techno-economic assessments should continue to determine the most viable pathways for different regions and sectors (Bhandari et al., 2022).

A further research direction is the life cycle and sustainability evaluation of the FCHEVs in comparison with BEVs and conventional hybrid. While LCA has indicated the potential of FCHEVs in heavy-duty transport and long-range applications, systematic studies with consideration of developing hydrogen production pathways, end-of-life recycling, and second-life applications of fuel cell components are still rare (Niknejad et al., 2022; Burchart-Korol et al., 2020). Such work would give a more precise picture of the environmental and economic trade-offs between different low-emission technologies.

Finally, socio-economic and policy aspects should be taken into account in future research. Questions of consumer acceptance, refueling convenience and long-term cost competitiveness are not just technical but are issues of behavioral and policy research. Comparative studies on policy frameworks in different regions, such as the early implementation of hydrogen infrastructure in Japan versus the Green Deal measures in Europe, could provide insights for best practices to enable FCHEV adoption (Hydrogen Council, 2021; IEA, 2023).

In conclusion, the possible avenues of future studies in FCHEVs range from materials innovation, system optimization, infrastructure scalability, sustainability assessment, and policy frameworks. These problems are highly interdisciplinary and thus require teamwork between engineers, chemists, computer scientists, economists, and policymakers. Only by such integrated approaches will FCHEVs be able to develop from niche applications to a strong and widespread technology contributing significantly to global decarbonization targets.

6.3. Final Reflections on the Evolution of FCHEV Technology

The evolution of fuel cell hybrid electric vehicles (FCHEVs) is an interesting story at the nexus of technological innovation, environmental sustainability and transformation in the transport sector. FCHEs experienced a shift during the past two decades from experimental prototypes to commercially available models with expanding infrastructure and supportive policy environments. However, their long-term place in the mobility landscape is still dependent on the interaction between technical development, economic competitiveness and social acceptance.

One of the most profound thoughts that comes out of this study is that FCHEVs are not just incremental improvements over the conventional vehicle but in fact, represent a paradigm shift in the way energy is produced, stored and utilized in transport systems. Unlike internal combustion engines which are powered by finite fossil fuels, FCHEVs are powered by hydrogen which is a versatile energy carrier that can be produced from renewable resources, which means it has the potential to produce near zero lifecycle emissions (Staffell et al., 2019; IEA, 2023). Their hybrid architecture enables them to combine the benefits of the fuel cell and battery to provide a combination of extended range, fast refueling, and operational flexibility that is not possible with either of these battery-based or fuel cell-based technologies.

However, the evolution of FCHEVs has also made clear how difficult the challenge of cost competitiveness still is. For FCHEVs, major cost reductions in fuel cell stacks, hydrogen storage systems and power electronics still render them to be economically inferior to battery electric vehicles (BEVs), particularly in passenger car markets where charging infrastructure is developing rapidly (Nikiforidis et al., 2021; Lutsey & Nicholas, 2019). This reality means that in the near term, the future position of FCHEVs may be even more firmly rooted in heavy-duty, long-haul, and fleet-based applications where their benefits in range, refueling time, and payload size are greater than the cost difference (Wang et al., 2022).

Another important observation relates to the relevance of infrastructure co-evolution. The success of FCHEVs is interlinked with the parallel development of hydrogen filling stations and the development of large-scale production facilities for renewable hydrogen. Lessons from early adopter regions such as Japan, California and Germany underline the fact that without the synchronous investments in infrastructure, even technically better vehicles have a hard time gaining market penetration (Ehebrecht, Heinrichs, & Weyer, 2021; Melaina & Penev, 2013). This interdependence implies that the path forward for FCHEVs needs to be viewed as part of a broader systemic change rather than as a standalone technological replacement.

The social aspect of FCHEVs further adds to the reflection. Consumer acceptance is influenced by far more than technical specifications such as range and performance: it is colored by perceptions of safety, convenience and environmental impact. However, trust in hydrogen as a safe fuel varies between regions, as it can be affected by the historical connection to some high-profile accidents or some of the population remains unaware of this technology (Hydrogen Council, 2021). Improved awareness through communication, safety demonstrations and public policy buy-in will be necessary if long-term adoption is to be achieved.

From a sustainability point of view, FCHEVs are a promise and paradox. On the one hand, they provide a way to radically decarbonize and de-pollute the air, notably in sectors where electrification by battery alone is technically or economically challenging (Burchart-Korol et al., 2020). On the other hand, they are extremely sensitive to upstream factors such as methods of hydrogen production, carbon intensity of the energy mix, and material recyclability (membranes, catalysts, storage tanks, etc.) (Dincer & Acar, 2015; Dunn et al., 2015). Both points are important for adopting a life-cycle systems approach which addresses FCHEVs not in isolation but as integral parts of energy, industrial and mobility systems.

Finally, the reflection confirms that the future of FCHEVs is a (collaborative) multi-scalar issue. Their success will rely on both advances in materials science and energy management as well as the convergence of industrial strategies, government policies, and international cooperation. Cross-sector synergies (i.e. cross-cutting links between the transport, energy and digital industries) are said to be a key enabler to scale FCHEVs and to embed them in the wider green transition (Hydrogen Council, 2021; IEA, 2023).

In conclusion, the development of FCHEVs mirrors both the success of scientific and engineering innovation and the systemic difficulty of decarbonizing transport. The technology is still in development and while there are still uncertainties, the technology is no longer experimental or speculative. However, FCHEVs are an intimate, yet still developing, part of the future mobility picture when their hybrid structure gives unparalleled benefits in certain applications. Their course will ultimately testify to the degree to which research, policy and industry can come together and break down barriers to realize their full potential in the quest for sustainable transport.

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