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A review on recent advances on improving fuel economy and performance of a fuel cell hybrid electric vehicle

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A R T I C L E I N F O

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A B S T R A C T

Fuel cell hybrid electric vehicles (FCHEVs) are gaining recognition as a pivotal innovation in the quest for sustainable transportation, seamlessly blending the advantages of fuel cells with electric vehicle technology. As global initiatives to curtail greenhouse gas emissions and mitigate climate change gain momentum, FCHEVs offer a promising alternative to conventional internal combustion engine vehicles and battery electric vehicles (BEVs). This review aims to examine recent technological progress in enhancing FCHEV fuel efficiency and performance, focusing particularly on cost reduction, long-distance operational capabilities, and the incorporation of intelligent autonomous systems. A key innovation highlighted in this study is the exploration of cost-effective hydrogen storage techniques, including metal hydrides and chemical storage solutions, which have demonstrated potential to significantly increase storage capacity and reduce refueling times. Furthermore, advancements in energy management, particularly the integration of ultracapacitors and high-capacity batteries, offer new avenues for extending vehicle range and boosting overall efficiency. The emergence of autonomous FCHEVs represents another major leap forward, setting the stage for more efficient, self-driving vehicles in the near future. However, persistent challenges remain, including reducing hydrogen production costs, improving fuel cell durability, and developing a widespread hydrogen infrastructure. Addressing these issues will require ongoing innovation in fuel cell materials, hydrogen storage systems, and energy management strategies. This review underscores the transformative role FCHEVs can play in reducing emissions and enhancing energy efficiency in the transport sector. Collaboration between industry, researchers, and policymakers will be vital to unlocking the full potential of FCHEVs in creating a more sustainable future.

Abbreviations

FCEV	Fuel cell electric vehicle
EV	Electric vehicle
FCs	Fuel cells
HDVs	Heavy-duty vehicles

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GVWR	Gross vehicle weight rating
SERCA	Slope-weighted energy-based rapid control analysis
HEV	Heavy electric vehicle
DDPG	Deep deterministic policy gradient
PEM	Polymer electrolyte membrane
PAFCs	Phosphatic acid fuel cells
AFCs	Alkaline Fuel Cells
BEVs	Battery electric vehicles
BEVs	Battery electric vehicles
EMS	Electric motor control system
OER	Oxygen excess ratio
EMS	Energy management system
IWGAN	improved Wasserstein Generative Adversarial Network
STO	Siberian Tiger Optimization
FLC	Logic Controller
PFC	Power Follower Controller
DDQN	Double Deep Q-Network

1. Introduction

As the worldwide focus on environmental preservation and conservation of energy continues to rise, the investigation of cars that are powered by sources of non-traditional energy has emerged as a significant topic of study for both automobile manufacturers and academic institutions. A fuel cell electric vehicle (FCEV), often known as an FCEV, is thought to have a significant potential for producing zero emissions and achieving a high level of energy efficiency [[1–3]]. When compared to an electric-only vehicle (EV), it has a greater range and just requires a shorter amount of time to refill [4].

To add insult to injury, fuel cells (FCs) of hydrogen offer a greater density of energy than the lithium-ion batteries that are currently used in the majority of electric cars. Also, the FC system is unable to provide the required amount of power during dynamic situations such as starting up, climbing, or accelerating. This is due to the fact that the response rate of reaction gas is unable to keep up with the variations in load [5]. In addition, the functioning of the FC system involves the direct transformation of chemical into electrical energy. This enables the FCS to create power in only one direction, which means that it is difficult to keep the energy that is produced while the vehicle is braking or slowing down [6]. Failures in the fuel control system (FCS) may have a detrimental effect on the fuel efficiency, reliability, and durability of a fuel-cell vehicle [7,8]. To address these concerns, FCEVs are often combined with an additional system of energy storage (ES), such as a battery or ultra-capacitor (UC), to create a FC hybrid electric vehicle system [9,10].

Both battery electric cars and FC electric vehicles have the potential to make a substantial contribution to the reduction of emissions of environmental pollutants and greenhouse gases on a worldwide scale. Many commercial versions are obtainable on the market for passenger vehicles, and they show hopeful findings in terms of driving comfort, performance, and range. These models are accessible for both categories [11,12]. FC systems, on the other hand, seem to be more tempting than batteries for heavy-duty vehicles (HDVs), which have greater power and range needs [13,14] than passenger cars. This is because FC systems have a higher density of energy and can be refueled much faster.

When compared to traditional cars, fuel cell high-density vehicles (HDVs) maintain significant benefits in terms of energy consumption and emissions, as shown by the life-cycle study in. In order to determine which applications are most suitable to fuel cell technology, Kast et al. [15] categorize the market for heavy-duty vehicles (HDVs) based on vocation and weight class. According to the findings of the investigation, the majority of vehicles have enough room for tanks of hydrogen storage to be installed in the under the chassis, behind the cab, and side rails in order to have sufficient capacity to cover their daily operating range. In addition, the development of appropriate control systems for vehicle operation is required in order to maximize the lifespan and hydrogen economy of the system. Consideration of the intended vehicle range is critical when developing or purchasing a truck, and this measure might vary substantially according to the work function. For each sample truck, the quantity of hydrogen storage required to reach a target range is shown in Fig. 1, where the average gross vehicle weight rating (GVWR) is displayed.

Fuel cell electric vehicles, often known as FCEVs, are equipped with battery systems that are designed to accommodate the rapid and frequent load fluctuations that are characteristic of vehicle applications. Each cycle begins with a battery that is either completely charged (90%) or severely depleted (10%) in order to test the durability of the battery charge even further. According to Fig. 2, this research shows that all solutions can get the battery back to normal functioning without breaking any of its physical restrictions [16].

Using butanol as an example, Baral et al. [17] conducted the first comprehensive analysis of life-cycle and stochastic techno-economic evaluation of biomass systems of feedstock supply with entirely electric trucks, fuel cell hybrid electric, and diesel. The objective was to determine the effects of these systems on biofuel production. Regardless of the predicted conditions, such as truck payload (full or empty), pavement type (gravel or paved), road condition (normal or damaged), and road network (local or highway), researchers found that FC hybrid electric and trucks of fully electrical application less energy than diesel-powered trucks. Due to improved use of capital and operational resources, the costs of biomass preprocessing and downstream conversion decrease as the size of a biorefinery increases. This phenomenon is known as economy of scale. Fig. 3 shows that when the scale of the biorefinery increases, the expenses of transporting biomass, the emissions of greenhouse gases, and the amount of money and carbon footprint spent on producing butanol all go up.

In order to quickly find near-optimal plug-in HEV control trajectories that adhere to SOC bounds and restrict the activations of heat engine number and gear changes, Anselma [18] developed a version of the slope-weighted energy-based rapid control analysis (SERCA) method. First, we provide the heavy electric vehicle (HEV) numerical model. Then, we outline the specialized SERCA based control strategy and formulate the optimum plug-in HEV control issue with smooth driving constraints. Case study results show that SERCA can find near-optimal HEV control trajectories for a 1.5-h real-world driving mission in 2 min on a desktop computer, whereas universal optimal control methods like effective programming take over 10 h. The predicted increase in the operational plug-in cost of hybrid electric vehicles (HEVs) due to SERCA is constantly kept under a little percentage points when compared to the worldwide ideal reference offered by DP in terms of electrical and fuel energy usage.

An enhanced deep deterministic policy gradient (DDPG), founded on a fixed-time active disturbance rejection controller, was suggested by Tian et al. [19]. In addition to smoothly integrating thermal management with EMS, the suggested solution accomplishes accurate monitoring of the ideal operative temperature in fuel cell temperature

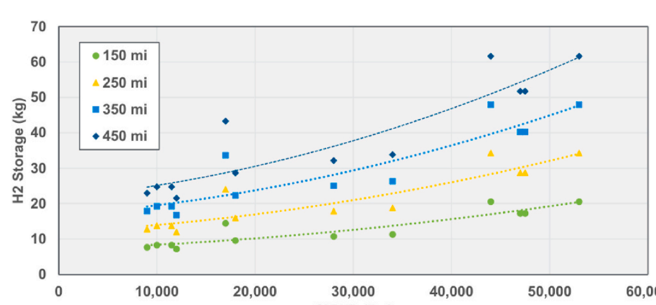

Fig. 1. Estimated amount of hydrogen storage needed to achieve a desired range for each representative truck, plotted as GVWR [15].

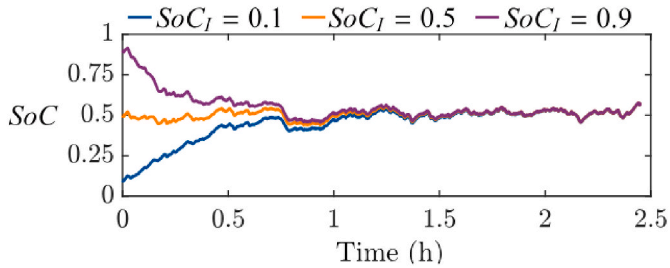

Fig. 2. Example of test to verify the robustness of strategies in terms of charge sustaining. The strategy under analysis is NLP [16].

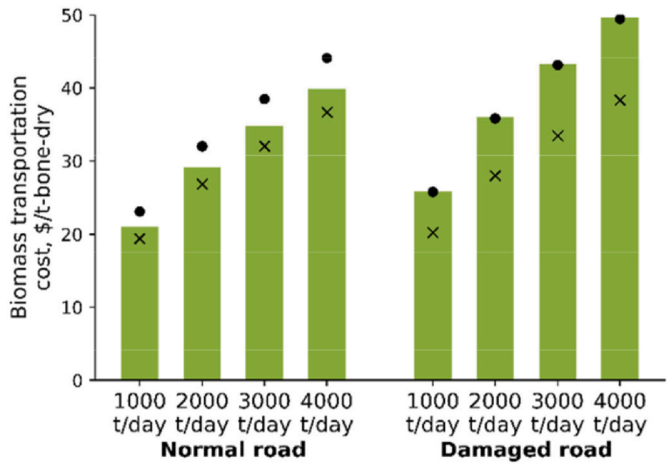

Fig. 3. Biomass feedstock transportation cost [17].

control. In particular, by fitting the connection between fuel cell power and temperature, the ideal operating temperature of the fuel cell may be found via FC thermal regulation studies. The results of the real-world vehicle tests and simulations performed on three distinct driving cycles demonstrate that this approach decreases hydrogen fuel consumption by 15.79% and enhances average FC efficiency by 1.87% when compared to the improved DDPG strategy based on traditional thermal regulation.

In response to the increasing global focus on environmental conservation and energy sustainability, alternative energy sources for vehicles have become an essential subject of research. Among the most promising technologies, fuel cell electric vehicles (FCEVs) have gained significant attention for their ability to generate zero emissions while offering high energy efficiency. Compared to electric-only vehicles (EVs), FCEVs provide the added advantages of extended driving ranges and quicker refueling times, making them particularly suitable for both passenger and heavy-duty vehicle applications [20].

Fuel cells (FCs), especially those powered by hydrogen, possess a higher energy density than lithium-ion batteries. However, challenges remain in delivering adequate power during dynamic conditions such as startup or acceleration due to the slower response of reaction gases. Additionally, the inability to store energy generated during braking or deceleration adds to the operational challenges these systems face [20]. To address these limitations, hybrid systems integrating fuel cells with battery storage systems (BSSs) have been developed, improving overall system efficiency [21]. Belkhier et al. [20] reported that fuel cells alone often struggle to meet the power requirements of hybrid electric vehicles (HEVs), which necessitates the integration of battery storage systems to support dynamic energy demands. Similarly, an Advanced Equivalent Consumption Minimization Strategy (AECMS) was proposed by Shawal et al. [21], aiming to optimize power distribution between the fuel cell and battery. This strategy resulted in a 29.59% improvement in fuel efficiency and an extension of the system's lifespan in fuel cell hybrid electric vehicles (FCHEVs).

The production and storage of hydrogen are critical components for ensuring the success of FCEVs. Halder et al. [22] reviewed the ongoing challenges associated with hydrogen production and emphasized the need for affordable storage solutions and widespread refueling infrastructure. Although technological advancements have been made, Huynh et al. [23] noted that the high operational costs and lower performance of existing FCHEVs continue to impede their wider adoption. The optimization of energy management systems (EMS) remains a key focus area. A genetic algorithm-based optimization technique for EMS, introduced by Mazouzi et al. [24], achieved a 28.5% improvement in fuel utilization in FCHEVs. Further analysis by Halder et al. [25] explored the potential for hydrogen-based systems to reduce environmental impact by enhancing energy storage and supply efficiency in FCHEVs. Messaoudi et al. [26] also investigated the integration of FCEVs into smart grid systems, emphasizing the importance of advanced powertrain designs and vehicle-to-grid (V2G) technologies for enhanced energy management. Further details could be found in Refs. [27,28].

In with the above background, there is an extensive opportunity for the further developments on FCHEVs **after through scrutiny on the existing research gaps, which motivates to carry out the present review article.** While promising solutions are offered by FCEVs and FCHEVs, there remain knowledge gaps in understanding the impact of surface roughness and wettability on nanoscale heat transfer. These factors are critical to optimizing such systems, yet they are often studied in isolation. This study seeks to address these gaps by using molecular dynamics simulations to investigate the combined effects of random surface roughness and wettability on the heat transfer performance of liquid argon in nanochannels. Therefore, the purpose of this review paper is to explore and compile recent advancements related to Fuel Cell Hybrid Electric Vehicles (FCHEVs), particularly focusing on fuel economy improvements and enhanced vehicle performance. The review seeks to.

a) **Examine Technological Developments** in fuel cell systems, hydrogen storage solutions, and energy management strategies, and how these innovations contribute to better fuel efficiency and overall performance of FCHEVs.
b) **Address Existing Obstacles** that impede the widespread use of FCHEVs, including the high costs of hydrogen production, fuel cell longevity, and the lack of comprehensive hydrogen refueling infrastructure.
c) **Conduct a Comparative Assessment** between FCHEVs and other automotive technologies such as Internal Combustion Engine (ICE) vehicles and Battery Electric Vehicles (BEVs), with an emphasis on efficiency, environmental benefits, and long-distance capability.
d) **Identify Future Research Opportunities** that focus on optimizing fuel cell designs, improving energy storage systems, and developing cost-efficient methods for hydrogen production.
e) **Analyze the Role of Policy and Collaboration**, discussing how government support and industry partnerships can promote the adoption of FCHEVs by creating a more favorable environment through regulations and infrastructure investments.
f) **Evaluate Environmental Benefits**, assessing how FCHEVs could significantly reduce carbon emissions and support sustainability efforts, especially in comparison to traditional gasoline-powered vehicles.

1.1. Fuel cell techniques

An exciting new sustainable energy technology, fuel cells transform the chemical energy in fuel into useable electricity. Their minimal emissions, silent operation, and great efficiency are just a few of the ways in which they excel above conventional internal combustion engines [29].

There are several fuel cell techniques, each with its own advantages and applications [30–33].

- Most fuel cells use a polymer electrolyte membrane (PEM), which allows them to work at low temperatures and starts up quickly. Applications in transportation, such as electric cars, are perfect for them.
- The efficiency of phosphatic acid fuel cells (PAFCs) for stationary power production is due to the fact that they function at higher temperatures.
- One kind of fuel cell that makes effective use of several types of fuels, such as natural gas, is the solid oxide FC. These cells employ a solid ceramic electrolyte and can function at very high temperatures.
- The highly efficient Alkaline Fuel Cells (AFCs) employ an electrolyte that is a liquid alkaline solution. Nevertheless, their poor contamination tolerance limits their usefulness.

A research was carried out to compare and contrast various FC technologies [34]. Before comparing the technologies according to fuel kinds, operating specs, and technological features, the authors provided an overview of how they generally function. Hydrogen production techniques, distribution, transport, storage, and uses were the intended foci of the discussion of hydrogen and fuels [35].

Hydrogen fuel cells (FCs) and their principles, as well as their standalone and co-generation uses, were covered in the article. A survey of FC technologies used in the built environment was detailed in a research released in Ref. [36]. It looked at the upkeep and advantages of FCs for tri-generation and co-generation applications, involving dependable electricity and heat production, reduced emissions, and more. The many forms of direct liquid FC technologies, as well as their principles, uses, and issues impacting their commercial development, were the primary focus of the published review [37]. There was talk of decarbonizing the energy system using hydrogen and FC systems [38].

Including its possible uses in industry, transportation, and energy storage systems, the authors provided a comprehensive overview of hydrogen's prospective use in electrical power generation and heat production. Also included was a summary of the literature on solid oxide FCs as a power generating technology [39]. Transportation, small-scale home systems, and the maritime sector were included in the studied applications. New viewpoints and the irreversibility of FC technologies were highlighted in the discussion of FC technology overview, which centered on the thermodynamic analysis and principle in FCs [40,41]. While one research looked at the current state of hydrogen FCs and their potential future uses, another looked at the potential future of developing FC systems and their uses [42]. As an alternative to conventional energy production resources, FC technologies were shown in this application [43].

1.2. Fuel cell applications

A clean and adaptable energy alternative, fuel cells have many potential applications. Because of their great efficiency and minimal emissions, they are an important technology for a greener future. Fuel cell applications are set to become more important in powering our planet as technology continues to improve [44]. Among the many significant uses of fuel cells are the following [45–47]:

In the realm of electric cars, FC electric vehicles are quickly becoming popular due to their superior range and rapid refilling capabilities when contrasted with battery electric vehicles (BEVs). They work well for passenger vehicles, buses, and long-distance trucks.

Fuel cells are useful for material handling vehicles like forklifts used in warehouses and distribution hubs. Indoor operations may be powered cleanly by them, and refilling during breaks is a breeze.

Maritime Vessels: Research on fuel cells as a cleaner alternative to diesel engines is underway, with the potential to power port boats and short-distance ferries.

Reliable backup power for essential infrastructure including data centers, hospitals, and communications facilities may be provided using fuel cells. Compared to diesel generators, they are more efficient and less polluting.

A kind of FC known as combined power and heat may increase microgrids' and buildings' total energy efficiency by producing heat and electricity at the same time.

Power Off the Grid: Fuel cells are an excellent choice for generating power in off-grid areas where connecting to the grid would be too costly or otherwise unfeasible. They have the potential to power large communities, off-grid cottages, and even communication towers.

1.3. Fuel cell based hybrid electric vehicle (EV)

Maintaining extended driving ranges and simple refilling while decreasing emissions is a significant problem for the transportation industry. Though revolutionary, the limited range of battery electric vehicles (BEVs) is a worry for some motorists. In this regard, FCHEVs—FC hybrid electric vehicles—emerge as a promising option. FCHEVs are a hybrid vehicle that combines the advantages of electric vehicles (such as low emissions and little noise) with those of conventional gas-powered vehicles (such as long range and quick refilling).

A model for a hybrid electric vehicle's powertrain components—the internal combustion engine (IC engine), energy storage system, FC, and electric motor(s)—was suggested by Chatterjee et al. [48] and is based on an efficient electric motor control system (EMS). In addition to tracking the vehicle's speed, environmental variables, engine load, driver inputs, and battery charge, the proposed EMS constantly checks these metrics in order to make judgments about power distribution and operating modes in real-time. With results showing increases in energy usage and lower environmental impact, the proposed technique is clearly more effective than standard EMS methods.

For FC hybrid electric vehicles, Chen et al. [49] suggested an EMS that optimizes the air supply and uses better dynamic programming (DP) to boost efficiency and dependability. Through the use of PSO, the cathode pressure of FC system and ideal oxygen excess ratio (OER) are determined for various current densities, with the greatest net power production of the system serving as the aim. A Bi-LSTM-based velocity prediction approach is created to forecast real-time changes in short-term velocities. To reallocate power between the battery and the FC system, the EMS cost function is adjusted according to the findings of energy allocation and the ideal gas supply circumstances of the FCs. Compared to the other two algorithms, the findings show that the suggested technique produces the lowest hydrogen usage.

For efficient energy management in hybrid electric cars equipped with fuel cells and ultra-capacitors, Kumar et al. [50] suggested a hybrid approach. A Spiking neural network and a Cheetah optimizer make up the suggested hybrid method. This approach is hence called the CO-SNN technique. The main objective of the optimization research is to reduce the hydrogen quantity that the FC system consumes, which is a measure of energy consumption. Prior work ignored conflicting data in favor of best-case scenarios within an objective framework, and researchers took into account uncertainties impacting the energy production, transformation, and consumption stages. Leaving these unknowns out of the system would result in poor performance, high operating costs, and potentially impractical solutions caused by constraints breaches. With the help of adjustable parameters, the suggested energy management system (EMS) hopes to deliver peak performance. To protect system performance from issues with optimality and feasibility, the method adds uncertainty into the set of constraints and cost function.

To improve energy optimization in FCEVs, Dhanka et al. [51] presented a new hybrid method called STO-IWGAN. The optimization of the hybrid system's performance and the energy management strategy are crucial to keeping the system running normally. An improved Wasserstein Generative Adversarial Network (IWGAN) is combined with the

Siberian Tiger Optimization (STO) in the STO-IWGAN approach. While the IWGAN approach is used to forecast the vehicle's power requirement, the STO method is used to optimize the operational parameters of the fuel cell system. With an efficiency rating of 95%, the suggested solution outperforms other current strategies when it comes to optimizing energy use for FCEVs. There is an efficiency rating of 85% for the existing HBO technique, 75% for the PSO method, and 65% for the WHO method.

In their presentation, Jouda et al. [52] tackled this problem of epistemic uncertainty in a midsize FC hybrid electric car using a deep stochastic reinforcement learning methodology. This method creates an EMS stochastic policy by using a deep REINFORCE framework, which involves an entropy regularization and deep neural network baseline. We compare the suggested method's efficiency with that of three existing EMSs: i) Fuzzy Logic Controller (FLC), Power Follower Controller (PFC), and Double Deep Q-Network (DDQN), a cutting-edge deep deterministic reinforcement learning method. The deep REINFORCE method outperforms DDQN, PFC, and FLC in terms of fuel efficiency by 7.68%, 13.53%, and 10%, respectively, when tested on the New York City cycle. Under a different validation cycle, the Amman cycle, the deep REINFORCE method outperforms DDQN, PFC, and FLC in terms of fuel efficiency by 5.31%, 9.78%, and 9.93%, respectively.

1.4. Key challenges of fuel-cell electric vehicles (FCEVs)

Despite the fact that FCEVs provide a viable solution for environmentally friendly transportation, there are a number of major obstacles that are preventing their broad use. A summary of the main obstacles is as follows.

a) Cold weather may reduce the efficiency and range of fuel cell electric vehicles (FCEVs).
b) Although the car does not emit any pollutants when using hydrogen, the manufacturing process generally uses fossil fuels, which results in emissions upstream. Finding environmentally friendly ways to produce hydrogen on a massive scale is of the utmost importance.
c) Fuel cells might need some work to make them last longer. Owners of FCEVs may be concerned about replacement expenses due to the fact that their lifetime is presently less than that of internal combustion engines.
d) A significant obstacle is the limited availability of hydrogen filling facilities. Potential customers of FCEVs are discouraged by the existing limited availability and the substantial expenditure required to build and maintain this infrastructure.
e) At this time, both BEVs and conventional gas-powered cars are much more affordable than FCEVs. The complicated components and high production costs of fuel cells are to blame for this.

These obstacles are not going away anytime soon, thanks to innovations in technology and improvements in infrastructure. The future of fuel cell electric vehicles (FCEVs) seems bright, what with falling prices, an increase in hydrogen filling stations, and the general maturation of fuel cell technology.

2. Advancement of electric vehicles technology

Electric vehicles (EVs) come in two main flavors: hybrids and all-electric as illustrated in Fig. 4. Hybrids like plug-in hybrids (PHEVs) use a combination of electric motor and gasoline engine, while all-electric vehicles (AEVs) run solely on electric power. Within AEVs, battery electric vehicles (BEVs) need to be plugged in for charging, while fuel cell electric vehicles (FCEVs) use hydrogen fuel cells and don't need to be plugged in but require hydrogen refueling stations [53,54]. The advent of electric vehicles (EVs) has ignited a significant increase in enthusiasm for cutting-edge battery technologies. Lithium-ion batteries have emerged as the prevailing source of power for electric vehicles (EVs), since their energy density has progressively grown, resulting in extended driving distances [55]. Furthermore, there has been a decrease

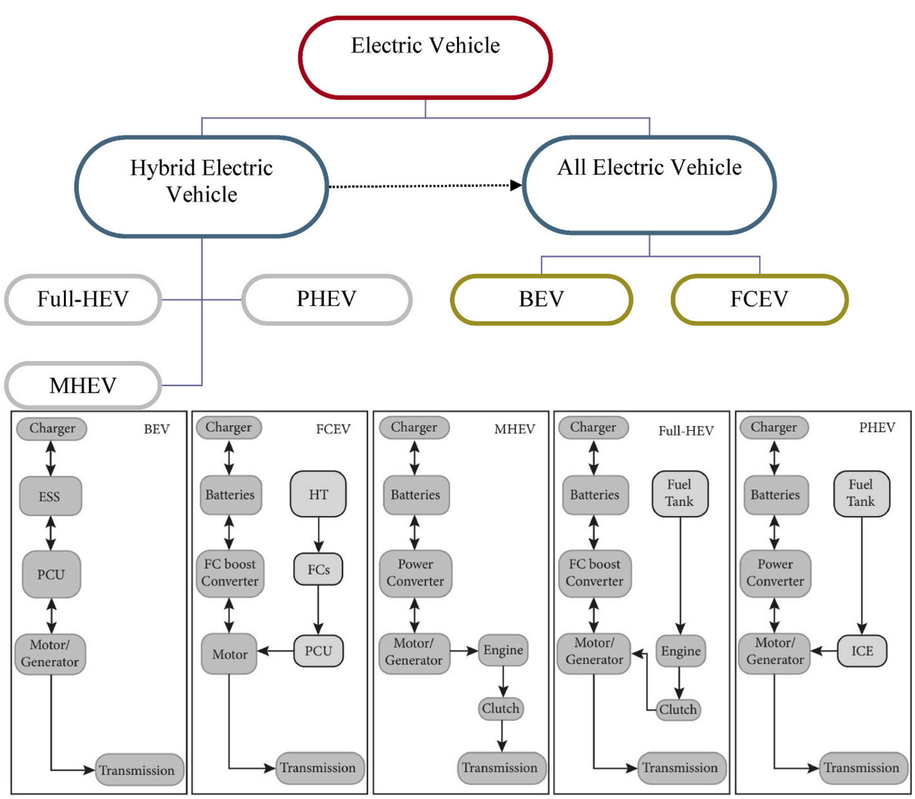

Fig. 4. General categorization of the Electric vehicle.

in the cost of production, resulting in increased affordability for customers [56].

Nevertheless, the potential of solid-state batteries offers even greater prospects for the future. Compared to liquid electrolyte batteries, solid-state batteries have the potential to provide higher energy density, longer battery life, and enhanced safety. In addition, they have the potential to result in more compact and less heavy batteries, so substantially augmenting the capabilities and effectiveness of electric vehicles [57,58].

However, there are still obstacles that need to be addressed. The scarcity of raw elements such as cobalt and lithium, which are essential for lithium-ion batteries, poses an environmental concern due to the methods used to harvest them. Disposing of these batteries at the end of their useful life is an additional challenge, as the existing techniques can be costly and intricate, which may result in their disposal in landfills. It is crucial to tackle these problems to ensure the advancement of battery technology and the expansion of the electric vehicle market [59].

There is continual progress in battery technology. Scientists are now investigating novel materials and manufacturing techniques in order to enhance the performance and efficiency of batteries. Significant progress has been made using silicon as an anode substance and graphene for its electrical conductivity and robustness. Another captivating field of study is battery management systems [60]. These systems employ algorithms and machine learning to oversee battery condition and enhance charging and discharging cycles. Through efficient battery management, one may prolong the lifespan of batteries and minimize the chances of failure [56,61].

The proliferation of charging infrastructure has significantly transformed the electric vehicle (EV) market [62]. The issue of range anxiety, which was a big problem for early users because of the limited distance the vehicle could travel, has been much diminished. Public charging stations are more common and can be found in convenient locations such as commercial districts, parking lots, and highways. This level of accessibility enables electric vehicle (EV) drivers to effortlessly locate charging stations, thereby reducing the concern of running out of power while driving [59,63].

In addition, improvements in fast-changing technology have significantly decreased the amount of time required for charging. In the past, the process of charging an electric vehicle (EV) used to be time-consuming, which posed a barrier to its general acceptance. Currently, thanks to the implementation of fast-changing technology facilitated by protocols such as CCS and CHAdeMO, electric vehicles (EVs) may be charged in a matter of minutes. The convenience we enjoy today is a result of the advancement in high-power charging technology, which allows for quick charging with power output of up to 350 kW [64].

In addition to addressing concerns about limited driving distance and faster charging, the growth of public charging infrastructure also addresses other issues in the electric vehicle (EV) industry. It aims to solve the problem of limited charging options for individuals who do not have their own charging stations, specifically people living in apartments or multi-unit buildings. This enhances the accessibility of electric vehicles, rendering them a feasible choice for a broader demographic [60,65]. Moreover, by facilitating the utilization of sustainable energy sources such as solar or wind power for the functioning of charging stations, this infrastructure contributes to the mitigation of the overall carbon emissions associated with electric vehicles. The expansion of public charging infrastructure has been further stimulated by government incentives and laws that aim to reduce greenhouse gas emissions and encourage the adoption of electric vehicles. Several nations have enacted plans to facilitate the establishment of charging stations, which encompass financial efforts and tax incentives for electric vehicle (EV) proprietors. These measures have expedited the expansion of the electric vehicle (EV) industry and made a significant contribution to promoting a more ecologically sustainable transportation sector [66,67].

The emergence of autonomous driving technology represents a significant breakthrough that has the capacity to fundamentally transform the way people commute, particularly when combined with electric vehicles (EVs). Autonomous vehicles function independently without the need for human intervention, enabling passengers to unwind and fully experience the voyage without the burden of driving responsibilities. This technology has the capacity to enhance the convenience and efficiency of electric vehicles (EVs), as they may be charged and operated autonomously, without the need for a driver [68].

With the continuous advancement of autonomous driving technologies, electric vehicles (EVs) are anticipated to have a progressively prominent part in the future of transportation. Their high energy efficiency and reduced greenhouse gas emissions make them a highly attractive substitute for conventional gas-powered vehicles. Due to increasing apprehension regarding climate change, numerous governments are aggressively promoting the use of electric vehicles (EVs) as a means to mitigate carbon emissions. Autonomous driving technology has the potential to boost the attractiveness of electric vehicles (EVs) by increasing their accessibility and convenience for users. To summarize, the integration of electric vehicles (EVs) and autonomous driving technology has the capacity to transform our transportation methods and greatly diminish the environmental consequences of travel [69].

2.1. Battery electrical vehicles

Battery Electric Vehicles (BEVs) are a notable progression in the automotive sector, providing a more environmentally friendly and sustainable means of transportation in contrast to conventional internal combustion engine vehicles. Battery Electric Vehicles (BEVs) rely exclusively on electricity stored in rechargeable batteries, thereby removing the requirement for fossil fuels and minimizing the release of detrimental emissions. The adoption of this technology has increased in recent years as a result of growing environmental concerns, government incentives, and breakthroughs in battery technology [70]. A crucial element of a Battery Electric Vehicle (BEV) is its battery pack, responsible for storing the necessary electrical energy to operate the vehicle's electric motor [60]. BEVs often utilize lithium-ion batteries because of their notable attributes such as high energy density, extended longevity, and comparatively rapid charging capabilities. Battery technology has played a vital role in enhancing the distance and capabilities of battery electric vehicles (BEVs), thereby alleviating a major worry among prospective purchasers - the fear of limited range [71,72].

Range anxiety is the apprehension about depleting the battery power of a vehicle before reaching a recharge point. Manufacturers have been striving to enhance the range of battery electric vehicles (BEVs) in order to address this concern and enhance the practicality of electric vehicles for daily use [73]. Progress in battery technology, including increased energy densities and quicker charging rates, has greatly expanded the driving distance of battery electric vehicles (BEVs), rendering them a feasible choice for a broader spectrum of consumers. The charging infrastructure is a crucial component of the battery electric vehicle (BEV) ecosystem. In order to facilitate the extensive use of electric vehicles, it is crucial to have a strong and comprehensive infrastructure of charging stations [64,73]. Public charging stations, office charging, and home charging solutions collectively contribute to ensuring that owners of battery electric vehicles (BEVs) have convenient and easily accessible charging options. The advancement of rapid-charging technology, such as DC fast chargers, has additionally contributed to the reduction of charging durations and enhancement of the general convenience associated with having a battery electric vehicle (BEV) [74].

BEVs excel in terms of performance due to their ability to deliver quick torque, resulting in a driving experience that is both smooth and very responsive. The lack of a conventional combustion engine leads to a quieter operation and reduced maintenance needs. Battery electric vehicles (BEVs) possess a lower number of movable components in comparison to cars with internal combustion engines, hence decreasing the probability of mechanical malfunctions and streamlining maintenance protocols.

The cost is a crucial determinant impacting the adoption of Battery Electric Vehicles (BEVs). Although the initial expense of buying a Battery Electric car (BEV) may exceed that of a conventional car, the overall cost of owning the vehicle throughout its lifecycle can be lower because of the savings on gasoline and maintenance [75]. Government incentives, tax credits, and declining battery costs are contributing to the increased affordability and accessibility of Battery Electric Vehicles (BEVs) for customers. The pursuit of electrification in the automotive sector is primarily motivated by the significant environmental advantages it offers. Battery electric vehicles (BEVs) generate no exhaust emissions, thereby mitigating air pollution and minimizing greenhouse gas emissions. Society may effectively decrease its carbon footprint and alleviate the effects of climate change by adopting electric vehicles that are fueled by renewable energy sources [76]. Accordingly, the electrical vehicle connected technically to many parameters as illustrated in Fig. 5, including cost, emissions, material, design or topology, policy, etc.

Battery Electric Vehicles (BEVs) offer several advantages and disadvantages compared to traditional internal combustion engine vehicles (Fig. 6). Understanding these pros and cons is essential for consumers considering the switch to electric vehicles [76]. The advantages of BEVs in terms of environmental impact, energy efficiency, and lower operating costs make them an attractive option for many consumers. However, challenges such as limited range, charging infrastructure, and upfront costs need to be considered when deciding to switch to an electric vehicle. Continued advancements in technology and infrastructure are addressing some of these drawbacks, making BEVs an increasingly viable and sustainable choice for modern transportation [77].

2.2. Hybrid electrical vehicle

Hybrid Electric Vehicles (HEVs) are a promising approach for tackling the difficulties of reducing fuel consumption, minimizing emissions, and improving overall vehicle economy. HEVs, or hybrid electric vehicles, utilize a combination of an internal combustion engine (ICE), an electric motor, and a battery pack to create a distinctive propulsion system that takes advantage of the benefits of both traditional vehicles and electric vehicles [78]. By integrating several power sources, hybrid electric vehicles (HEVs) are able to run with greater efficiency, minimize their environmental footprint, and enhance the overall driving experience. An important benefit of HEVs is their capacity to alternate between the internal combustion engines (ICE) and electric motor, depending on the driving conditions and power requirements. HEVs can enhance fuel efficiency by efficiently employing the electric motor for low-speed city driving and the ICE for high-speed highway travel. The smooth switch between power sources is controlled by advanced energy management technologies that guarantee the vehicle functions in the most optimal mode at all times [79].

HEVs can be categorized into three primary architectural types: series hybrid, parallel hybrid, and series-parallel (power-split) hybrid. In a series hybrid design, the Internal Combustion Engine (ICE) is only utilized to produce electricity that is then used to power the electric motor, which then propels the wheels. This configuration eliminates the physical linkage between the internal combustion engine (ICE) and the wheels, enabling more versatility in the transmission of power. Notable examples of series hybrid automobiles are the Fisher Karma and Renault Kangoo [80]. Parallel hybrid vehicles are equipped with both an Internal Combustion Engine (ICE) and an electric motor, which have the ability to operate separately or in conjunction to propel the vehicle. This design optimizes performance and efficiency by capitalizing on the advantages of both power sources. The Honda Insight and General Motors Parallel Hybrid Trucks employ a parallel hybrid configuration to achieve efficient power distribution [81].

The power-split hybrid configuration integrates features from both series and parallel hybrids, enabling the engine and battery to independently or jointly provide power to the vehicle. This configuration increases the electric driving distance of the car and improves overall fuel efficiency. Power-split hybrids can be classified into two main configurations: single-mode and dual-mode [82,83]. Dual-mode installations are known for their enhanced performance and fuel efficiency. General Motors' two-mode hybrid full-size trucks and SUVs are prime examples of dual-mode hybrids. Effective energy management is essential for maximizing the efficiency of hybrid electric vehicles (HEVs). Energy management systems can optimize fuel efficiency, minimize pollutants, and improve driving dynamics by effectively regulating the flow of energy between the internal combustion engines (ICE), electric motor, and battery. Multiple techniques, including regenerative braking, engine start-stop systems, and predictive energy management, are used to optimize the vehicle's efficiency [84].

The categorization of control techniques for Hybrid Electric Vehicles (HEVs) is a crucial element in maximizing their performance and efficiency (Fig. 7). Control techniques can be classified according to their methodology for regulating power allocation between the internal combustion engine (ICE) and the electric motor [85]. The objective is to minimize fuel consumption and maximize power utilization. Control strategies encompass a range of methodologies, such as rule-based procedures, deterministic rule-based systems, optimization-based techniques, and real-time optimization methods. These solutions seek to achieve a harmonious equilibrium between the competing goals of enhancing fuel efficiency, reducing emissions, and optimizing vehicle performance by effectively distributing power from the various energy sources inside the hybrid electric vehicle (HEV) system. Through the process of categorizing and comprehending the various control strategies at hand, researchers and practitioners can formulate more efficient and customized solutions to optimize the overall performance of hybrid electric vehicles [86].

When selecting a control method for a system, one must carefully consider the many trade-offs involved, as seen in Table 1. Certain techniques, such as Fuzzy Logic, provide exceptional performance in terms of simplicity and speed, however they may necessitate prior understanding of the system. Conversely, Dynamic Programming provides a more extensive and universal answer, but it requires greater computational resources and potentially intricate methods. The duration of computation is another critical element. Model Predictive Control (MPC) strategies are particularly advantageous for real-time applications due to their ability to prioritize rapid solutions [87]. The table also indicates that certain control strategies, such as Energy Consumption

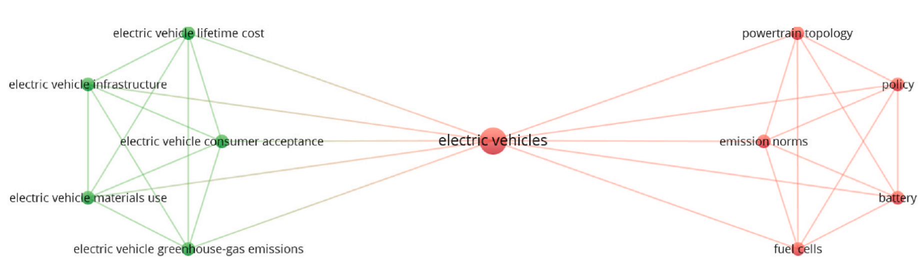

Fig. 5. Connection of the electric vehicle with various parameters.

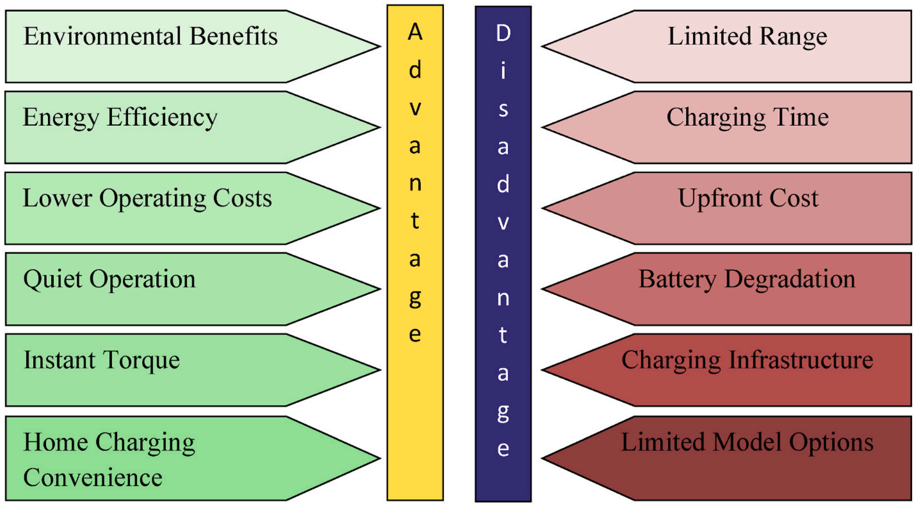

Fig. 6. Advantage and disadvantage of the battery electric vehicle.

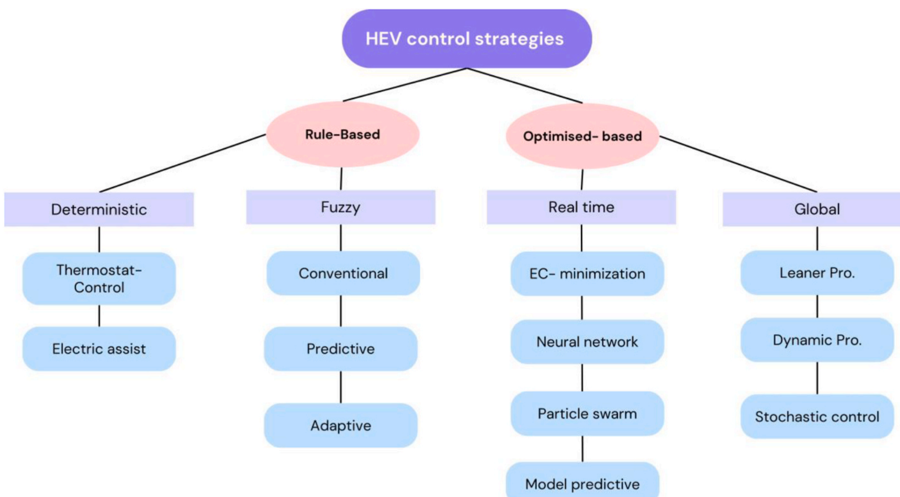

Fig. 7. Classification of control strategy.

Table 1
Comparison chart for various control strategies.

Control Strategy	Structural Complexity	Computation Time	Solution Type	A Priori Knowledge	Energy Consumption Focus
Fuzzy Logic	No	Short	Global	Required	Yes
Genetic Algorithm	Yes	More	Global	Optional	No
Particle Swarm Optimization	No	More	Global	Optional	No
Energy Consumption Minimization Strategy	Yes	Short	Local	Optional	Yes
Pontryagin's Minimum Principle	No	Short	Local	Required	No
Dynamic Programming	Yes	More	Global	Required	Yes
Model Predictive Control	No	Short	Global	Optional	No
Stochastic Dynamic Programming	Yes	More	Global	Optional	No
Neural Network	Yes	Short	Global	Required	Yes

Minimization Strategies, specifically aim to decrease energy usage, while others prioritize obtaining a desirable system behavior regardless of energy requirements, such as Pontryagin's Minimum Principle. This information is crucial for choosing a strategy that is in line with the general objectives of the system [88].

2.3. Fuel cell hybridization and power supplies

The realm of electric vehicles is perpetually advancing, with artificial intelligence (AI) increasingly contributing to the enhancement of these technologies. An example of innovation is the FCHEV, which stands for Fuel Cell Hybrid Electric Vehicle. This innovative concept integrates the capabilities of a fuel cell with an additional energy storage system (ESS) [89]. The Energy Storage System (ESS) can function as either a battery or an ultracapacitor, providing a hybrid solution that offers numerous benefits.

The primary advantage of FCHEVs resides in their capacity for enhanced fuel efficiency. The fuel cell serves as the main power source, while the ESS supplements electricity during acceleration or times of high demand [90]. The implementation of this sophisticated power management system has the capability to enhance the efficiency of fuel cell operation, resulting in superior fuel economy as compared to conventional fuel cell electric vehicles (FCEVs). Fuel cell hybrid electric vehicles (FCHEVs) also provide improved performance. The Energy Storage System (ESS) has the capability to provide surges of energy to enhance acceleration, resulting in a more seamless and reactive driving encounter. Moreover, FCHEVs retain the fundamental benefit of fuel cell cars, which is the complete absence of emissions from the tailpipe. FCHEVs provide a compelling blend of efficiency, performance, and clean operation, rendering them a very promising technology for the future [91].

Nevertheless, incorporating this technology comes with its own set of difficulties. Efficient and dependable power converters are necessary for managing the power flow between the fuel cell, ESS, and electric motor [92]. Size, weight, and converter efficiency are critical factors for achieving optimal performance. Another obstacle to overcome is electromagnetic interference (EMI). The intricate interaction of electrical components in FCHEVs can produce electromagnetic interference (EMI), which has the potential to impact the functioning of the system [93]. Table 2 summarizes the specifications of various Fuel Cell Electric Vehicles (FCEVs) and Fuel Cell Hybrid Electric Vehicles (FCHEVs). It highlights the range and fuel efficiency (MPGe) of different models. Some key takeaways include the impressive range of the Honda Clarity Fuel Cell (434 miles) and the excellent fuel economy of the Toyota Mirai (66 MPGe). The table also reveals missing data for some models, suggesting the need for further research for a more comprehensive comparison.

2.4. Energy storage systems for fuel cell-based hybrid electric vehicles (FCEVs)

Fuel Cell Hybrid Electric Vehicles, abbreviated as FCHEVs, depend on a meticulously synchronized interplay among various energy sources and storage technologies. The fundamental component of this system is the Main Energy Source (MES), which supplies a consistent and high-capacity stream of power. Fuel cells are very suitable for this function, as they provide a significant amount of energy stored in a compact volume. Batteries can also serve as an energy storage system (MES), although their capacity to provide rapid power delivery may be restricted [94].

The Rechargeable Energy Storage System (RESS) functions as a supplementary component, activating at instances of power surges required for acceleration or situations with significant energy requirements. This job is ideally suited for ultracapacitors and flywheels. These energy storage systems have a high-power density, enabling them to provide substantial power for brief periods. Moreover, their rapid discharge rates make them well-suited for managing abrupt surges in power requirements [95]. Engineers depend on their comprehension of power and energy density to select the most efficient combination. This map facilitates the selection process, guaranteeing a consistent power supply to the vehicle using fuel cells and batteries, while also incorporating ultracapacitors and flywheels to deliver additional power when necessary. The subsequent sections will delve into these energy sources and storage technologies with greater elaboration [96].

Table 2
Summary of different model of FCEVs and FCHEVs using Hydrogen as energy source.

Vehicle Model	Type	Fuel Economy (MPGe)	Range (Miles)
Honda FCX Clarity (2014)	FCEV	–	231
Honda Clarity Fuel Cell (2017)	FCEV	–	434
Toyota Mirai (2016)	FCEV	66 (city/hwy)	312
Hyundai Tucson Fuel Cell (2016)	FCEV	49 (city)/51 (hwy)	265
Hyundai ix35 (2013)	FCHEV	–	369
Toyota FCHV-adv (FCHEV)	FCHEV	–	400-500 (est.)
Audi Sportback A7h-tron Quattro (2014)	FCHEV	62 (overall)	310.7
Honda FCV Concept (2014)	FCEV	–	435
Mercedes-Benz F800 (2010)	FCEV	–	373
Nissan Terra FCEV SUV (2012)	FCEV	–	–
Roewe 950 Fuel Cell (2014)	FCEV	–	249
Volkswagen Golf Hymotion (2014)	FCEV	–	310
Kia Borrego FCEV (FCHEV)	FCHEV	–	426

2.4.1. Fuel cell

Fuel cells offer a promising alternative to conventional heat engines for electricity generation. Unlike engines that rely on mechanical energy conversion with lower efficiency, fuel cells directly convert chemical energy from fuel (like hydrogen) and air into electricity through an electrochemical reaction, producing only water as a byproduct. This technology combines advantages of both engines and batteries: continuous operation with fuel supply and load-dependent behavior similar to batteries [97].

The concept behind fuel cells dates back to the early 19th century with inventions by Schönbein (1838) and Grove (1839) [98,99]. The first functional fuel cell was demonstrated by Bacon in 1950, followed by advancements by International Fuel Cells for NASA's space program [100]. Since the mid-1960s, research efforts have focused on broader applications like stationary power and transportation, with government funding from the US, Japan, and Canada. Despite significant progress, ongoing research and development are crucial to reduce costs and improve efficiency for wider adoption of fuel cell technology.

2.4.2. Batteries

Rechargeable batteries are essential for electric vehicle applications because they have the capacity to store and discharge electrical energy. Secondary batteries, in contrast to non-rechargeable primary batteries, have the ability to undergo multiple cycles of charging and discharging. Battery capacity is quantified in ampere-hours (Ah), which denotes the cumulative amount of electric current that a battery can supply over a specific duration [101]. The watt-hour (Wh) is used as a unit to quantify the amount of energy stored, indicating the overall power output that can be utilized. The State-of-Charge (SOC), shown as a percentage, indicates the amount of useable charge that remains in the battery. It is crucial to keep the battery's state of charge (SOC) within a specified range in order to optimize its longevity. Moreover, the capacity of a battery is directly related to its discharge current. Measured by the "C-rate," a greater C-rate indicates a more rapid discharge but also a faster depletion of the battery. The discharge capacity of the battery is determined by the chemical reactions that take place within it and the temperature at which it operates [102].

2.4.3. Ultracapacitor

Ultracapacitors, or supercapacitors, serve as an intermediary between traditional capacitors and batteries. With a much greater capacitance (measured in Farads) compared to their milli-farad equivalents, these devices are highly effective in storing electrical energy. Nevertheless, the increased capacity of these capacitors is offset by a decrease in energy density (Wh/m^3) when compared to conventional capacitors. Their secret lies in an electrolyte solution that enables the storage of ions on electrodes with a huge surface area, resulting in a significantly higher charge density compared to ordinary capacitors [103]. The electrochemical storage method exhibits a trade-off, as it results in slower charge and discharge times due to the mobility of ions. However, this trade-off eventually leads to their remarkable capacity. However, ultracapacitors have a high efficiency of over 90% and can operate across a wide range of temperatures, which makes them highly desirable for various applications. Their distinctive attributes are seen in tasks such as replacing batteries in specific instances, starting engines, and supplying backup power. Recent progress in nanomaterials and manufacturing has led to substantial cost reductions and higher capacitance. This progress has opened up new possibilities for the application of nanomaterials in several fields, including regenerative braking systems. With the ongoing advancement of technology, ultracapacitors are positioned to have a progressively significant impact on the future of storing energy [104].

2.4.4. Flywheel

Flywheel energy storage (FES) use a rotating rotor to store and discharge energy. Applying torque to the rotor increases its rotating speed, leading to the storage of energy. Applications of torque to the rotor in a Flywheel Energy Storage (FES) system result in an increase in its rotational speed according to the concept of conservation of angular momentum. The principle of angular momentum conservation asserts that the angular momentum of a system remains unchanged until subjected to an external torque. When torque is exerted on the rotor in a Flywheel Energy System (FES), the rotor acquires angular momentum and thereby rotates at an increased speed. The energy stored in the system is directly proportional to the square of the rotor speed and its moment of inertia per unit area. Hence, by augmenting the rotational velocity of the rotor by means of torque, the system may accumulate a greater amount of energy. Next, the stored energy can be released by applying torque to an external device.

In contrast, the flywheel discharges energy by delivering torque to a linked apparatus. FES provides two methods of generating output: mechanical and electrical [105]. The mechanical solution offers a notable efficiency benefit, achieving a round-trip efficiency of up to 97% thanks to the use of sophisticated bearings. Presently, FES systems have accomplished energy and power densities ranging from 10 to 150 Wh/kg and 2–10 kW/kg, respectively. These systems typically have a lifespan of approximately 15 years. Research prototypes exhibit the possibility for increased capacity and speed. Various research institutions are currently engaged in the development of FES systems for electric vehicles (EVs) owing to their numerous benefits, including extended durability, reduced maintenance requirements, quick responsiveness, fast charging capabilities, and limited sensitivity to temperature variations. Nevertheless, the primary obstacles for the general adoption of electric vehicles are effectively handling the gyroscopic forces and maintaining safety [106].

2.5. Environmental impacts analyses of vehicles

Electric vehicles (EVs) are highly beneficial for the environment, especially in comparison to conventional gasoline-powered cars. This advantage arises from two fundamental distinctions: their construction and the source of their energy. Firstly, electric vehicles emit negligible amounts of exhaust emissions. Battery and fuel cell electric vehicles (FCVs) emit little emissions when in use, resulting in a substantial reduction in air pollution when compared to gasoline-powered cars [107].

Furthermore, the environmental consequences of electric vehicles (EVs) are significantly influenced by the source of their electricity. Research indicates a significant decrease in well-to-wheel (WTW) CO_2 emissions for electric cars (EVs) [108]. In 2018, EVs emitted 38 million tons of CO_2, while gasoline vehicles emitted a staggering 78 million tons (IEA, 2019). Projections indicate that electric vehicles (EVs) may continue the current trend and potentially emit 230 million tons less of carbon dioxide equivalent (CO2) in 2030 compared to gasoline automobiles, which produce 450 million tons of CO_2 (IEA, 2019). However, there are other elements that can affect the environmental impact of electric vehicles (EVs) [109].

- Driving style: Energy usage is influenced by factors such as speed, inclines, and frequent stops in traffic. Scientists can determine this consumption by analyzing a car's resistance and driving behaviors.
- What is the source of energy for the car: The output power of fuel cell vehicles (FCVs) is influenced by the lower heating value of the fuel, such as hydrogen or ethanol.
- The fuel cell's efficiency: The efficiency of the system is contingent upon variables such as the operating temperature and the choice of materials. Generally, a 65% efficiency is regarded as the norm.
- The efficiency of supercapacitors: The energy consumption of supercapacitors is determined by their charging and discharging properties, as well as the efficiency of the DC/DC converter.
- The source of electricity: The greenhouse gas (GHG) emissions of electric vehicles (EVs) can be affected by the composition of the power production mix utilized for charging. Electric vehicles (EVs) experience reduced emissions in regions with cleaner energy systems.

There are methods to alleviate these factors [109].

- Smart energy management systems can enhance the environmental efficiency of electric vehicles by optimizing the size of components, cruising range, and fuel consumption.
- Tools for conducting life cycle assessments: Models such as GREET take into account variables such as energy efficiency, trip distances, and energy sources in order to offer a more thorough assessment of the environmental effects of an electric vehicle.

Electric vehicles provide a possible remedy for mitigating air pollution and greenhouse gas emissions in the transportation sector. Efficient energy management systems and life cycle assessment tools can boost the environmental benefits of electric vehicles (EVs) by considering numerous elements that influence their environmental impact.

Choosing an electric vehicle (EV) might be intricate since each model possesses distinct attributes. Table 3 presents a detailed analysis of the fundamental distinctions among Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs), and Fuel Cell Electric Vehicles (FCEVs) [110]. Battery Electric Vehicles (BEVs) that have the highest battery capacity, ranging from 20 to 80 kWh, give priority to electric propulsion and proudly have no emissions from their tailpipes. Plug-in hybrid electric vehicles (PHEVs) with a battery capacity ranging from 4.5 to 10 kWh provide the flexibility of using both electric and gasoline power sources. On the other hand, hybrid electric vehicles (HEVs) with a smaller battery capacity of 1.3–1.6 kWh are mostly reliant on gasoline power and use the battery for

Table 3
The comparison of the main characteristics of Electric Vehicles (BEVs, PHEVs, HEVs, FCEVs) [110].

	BEVs	PHEVs	HEVs	FCEVs
Battery Capacity Range (kWh)	20–80	4.5–10	1.3–1.6	Vary based on the Configuration
Tailpipe Emissions	Zero PM, NO_X, SO_X emissions from tailpipe Zero CO_2 emission	Transfer CO_2 emission into the atmosphere	Transfer CO_2 emission into the atmosphere	Zero CO_2 emission. Releases Water and heat
Source of Energy	Electricity from charging station	Electricity from charging station and Fuel	Fuel	Hydrogen Fuel
GHG Emissions small car (400 km) large car (200 km)	21.2–28.1 tons of CO_2-eq emissions	21–28.7 tons of CO_2-eq emissions	21.5–35.1 tons of CO_2-eq emissions	22.7–34.8 tons of CO_2-eq emissions

supplementary assistance. Fuel cell electric vehicles (FCEVs) include adjustable battery capacities and release solely water and heat as byproducts while in use. However, their functioning depends on hydrogen synthesis, which may potentially generate greenhouse gases (GHG) depending on the specific technology employed [111].

The table also considers the lifetime greenhouse gas (GHG) emissions for various car sizes. Although battery electric vehicles (BEVs) have the advantage of producing the least number of pollutants from their tailpipes, their overall environmental impact is heavily influenced by the cleanliness of the energy infrastructure they rely on. Plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) offer a means of transitioning to reduced emissions while still relying on gasoline as a fuel source. Fuel cell electric vehicles (FCEVs) emit no pollutants from their tailpipe, but they do rely on the manufacture of hydrogen that is generated in an environmentally friendly manner. When selecting the most suitable electric vehicle (EV) for yourself, it is important to take into account your driving habits, the availability of charging infrastructure, and your environmental preferences.

3. Challenges and limitations of fuel cell hybrid electric vehicles (FCHEVs)

Fuel Cell Hybrid Electric Vehicles (FCHEVs) are a promising step forward in the search for sustainable transportation alternatives. By combining hydrogen fuel cells and electric powertrains, FCHEVs have the potential to drastically mitigate greenhouse gas emissions, reduce dependency on fossil fuels, and provide greater driving ranges than battery-powered vehicles. Nevertheless, despite their potential, FCHEVs confront significant challenges that prevent widespread acceptance and commercialization.

This comprehensive review explores the major challenges in FCHEVs technology, concentrating on six crucial areas which are hydrogen viability, hydrogen storage, and economic impact of fuel cell, battery lifetime, power electronic interface, and energy management system optimization. Each area has distinct technical, economic, and infrastructural issues that must be solved before FCHEVs may reach their full potential in the global transportation landscape.

3.1. Hydrogen viability

The viability of hydrogen as a fuel source for FCHEVs presents a complex challenge due to its production methods. The energy efficiency considerations are also one of the critical factors in its viability. This section discusses the limitations of hydrogen production methods and energy efficiency factors.

3.1.1. Hydrogen production method

This section discusses five hydrogen production methods and their limitations towards FCHEVs. For instance, steam methane reforming, electrolysis, Photoelectrochemical (PEC) water splitting, and dark fermentation.

3.1.1.1. Steam methane reforming. Steam Methane Reforming (SMR) continues to be the main technique for generating hydrogen, making up roughly 95% of worldwide production [112]. The process of SMR involves natural gas (mainly methane) undergoing a reaction with steam at high temperatures ranging between 700 °C and 1000 °C and 3–25 bar pressure with the help of a catalyst, commonly nickel [113]. There are two primary steps involved in the process. The first step is known as endothermic which deals with the reaction of $CH_4 + H_2O \rightleftharpoons CO + 3H_2$. The second step is related to the exothermic water-gas shift reaction, $CO + H_2O \rightleftharpoons CO_2 + H_2$.

Although SMR has many positive claims, it also has limitations. The main environmental concern with SMR is its high CO_2 emissions. Through the study of life cycle assessment of various hydrogen production methods, Parkinson et al. [114] found that SMR without carbon capture emits 9–12 kg CO_2 per kg of H_2 produced. The International Renewable Energy Agency (IRENA) [115] reported that SMR is responsible for approximately 6% of global natural gas consumption and 2% of global CO_2 emissions [116]. The dependence of SMR on natural gas makes it vulnerable to price fluctuations and supply issues. The long-term sustainability challenges of SMR have been discussed by Acar et al. [117] due to its reliance on finite fossil fuel resources and potential price volatility. The challenges in geopolitical and energy security associated with hydrogen production methods are highlighted by Lebrouhi et al. [118]. These existing studies are concerned with the heavy reliance of SMR on fossil fuels such as natural gas as it may impact the environment.

3.1.1.2. Electrolysis. Electrolysis is one of the promising methods for producing hydrogen due to its ability to split water into hydrogen and oxygen by using electricity. This process is a plus point when the electricity comes from renewable sources, thus making hydrogen production more sustainable and environmentally friendly. The general reaction for water electrolysis is $2H_2O \rightarrow 2H_2 + O_2$. In this section, three main types of electrolyzers and their limitations are discussed thoroughly. For instance, Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM) Electrolysis, and Solid Oxide Electrolysis Cells (SOEC) [119].

As for Alkaline Electrolysis (AE), it operates in a liquid alkaline electrolyte solution, typically potassium hydroxide (KOH) or sodium hydroxide (NaOH). The electrolyte facilitates the movement of hydroxide ions (OH-) from the cathode to the anode. The reaction at the cathode is represented as $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ whereas at the anode, the reaction is $2OH^- \rightarrow 1/2\, O_2 + H_2O + 2e^-$. The first limitation of the AE process is the purity requirement for water and electrolyte. AE processes require high-purity water and regular electrolyte maintenance to avoid contamination and degradation of electrodes. This is due to the impurities that reduce efficiency and increase the degradation of process components. To prove the limitations, a study was conducted by Becker et al. [120] and found that even minute iron contamination as low as 0.1 ppm can reduce electrode efficiency by up to 15% over 1000 h of operation. Another challenge is temperature constraints. The common operating temperature between 60 °C and 80 °C limits overall system efficiency. This constraint was found in an existing study done by Yodwong et al. [119] which increased the operating temperature to 90 °C able to improve system efficiency by up to 5%, but also accelerated electrode degradation by 20% over a 2000-h test duration. As an outcome, novel nickel-based catalysts ensure maintaining stability at higher temperatures, thus allowing for operation up to 100 °C without significant degradation. Recently, El-Shafie et al. [121] figured out that the AE system has corrosion and durability issues. This is caused by to highly alkaline environment, specifically at elevated temperatures. The traditional nickel-based electrodes show a 10%–15% decrease in catalytic activity over 10,000 h of operations. To overcome the material degradation issue in the AE system, El-Shafie et al. [121] worked on plasma-sprayed ceramic coatings which is effective in reducing 50% of degradation rate, hence extending electrode lifetimes by several years.

Proton Exchange Membrane (PEM) electrolysis, uses a solid polymer electrolyte membrane that facilitates the movement of protons from the anode to the cathode and separates the product gases [119]. This process takes place under acidic conditions. The reaction at the anode represented as $H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$ while at the cathode is $2H^+ + 2e^- \rightarrow H^2$. The main challenge is expensive catalyst materials. This is due to heavy use of platinum-group metals (PGMs) as catalysts in PEM during the oxygen evolution reaction (OER) occurring at the anode. A comprehensive investigations by Liu et al. [122] and Stiber et al. [123] delved into optimizing catalyst loading and revealed that decreasing PGM loading from 2 mg/cm^2 to 0.5 mg/cm^2 only resulted in a 5% decrease in performance but led to a 30% reduction in costs. However, it was observed that further reductions in loading significantly impacted performance. Another challenge is in terms of water management and purity requirements. PEM fuel cell systems necessitate ultra-pure water to prevent membrane and catalyst contamination and degradation. In a study by Yang et al. [124], the researchers examined the influence of water impurities on PEM performance and determined that even minimal amounts of <1 ppm of metallic ions could result in a 10% efficiency decrease over 5000 h of operation. They constructed an enhanced water purification system that decreased contaminants to less than 0.1 ppm but acknowledged that this heightened system intricacy and cost. Besides, membrane degradation is challenging in PEM electrolysis due to high current densities. In a long-term investigation, Frensch et al. [125] researched the mechanisms of membrane degradation. The results indicated that running at 3 A/cm^2 for 10,000 h led to a 15% reduction in membrane thickness and a 20% rise in hydrogen crossover. This study emphasized the need for advanced membrane materials to improve durability.

The last electrolysis process is Solid Oxide Electrolysis Cells (SOEC) which operates at high temperatures usually 700 °C–1000 °C, using a solid oxide or ceramic electrolyte to conduct oxygen ions from the cathode to anode. The reaction at cathode is $H_2O + 2e^- \rightarrow H^2 + O_2^-$ whereas at the anode is $O_2^- \rightarrow 1/2O_2 + 2e^-$. One of the limitations is the complex and costly process of producing SOEC components, especially the ceramic electrolytes and electrodes. According to studies done by Sarner et al. [126] and Buchheit et al. [127], the current production costs for SOEC stacks were around $2000 per kilowatt, with materials accounting for 40% of the costs and processing for 35%. The analysis indicated that with advancements in materials and manufacturing techniques, it might be possible to reduce these costs to $500 per kilowatt by 2030. However, the researchers also emphasized that this would still surpass the targets set for widespread commercialization. On the other hand, Xu et al. [128] examined how the high operating temperatures of SOECs present challenges for rapid start-up and shut-down. The researchers discovered that thermal cycling, from room temperature to 800 °C and back, led to a 0.1–0.2% permanent performance decline due to microstructural alterations and interfacial degradation. The study highlighted the necessity for enhanced materials and cell designs to improve thermal cycle resistance. Besides start-up and shut-down cycle issues, SOEC has sealing and interconnect challenges. In a recent study, Schilm et al. [129] explored innovative glass-ceramic sealants for SOECs, addressing the significant engineering challenges of maintaining gas-tight seals and effective electrical connections at high temperatures. The composite sealant tested exhibited enhanced stability at 750 °C for over 5000 h, demonstrating a 60% reduction in leak rates compared to conventional sealants. Nevertheless, the researchers emphasized the necessity for further enhancements in long-term stability and ease of application to facilitate large-scale deployment.

3.1.1.3. Photoelectrochemical (PEC) water splitting. Photoelectrochemical (PEC) water splitting is a process that involves the absorption of light by a semiconductor photoelectrode, generating electron-hole pairs. The water-splitting reaction is directly driven at the electrode-electrolyte interface by these charge carriers.

One of the primary limitations in PEC water splitting is the material stability in aqueous electrolytes. In a thorough investigation, Chen et al. [130] examined the degradation of materials in PEC systems. The research revealed that although traditional III-V semiconductors are highly effective, the semiconductors suffered significant corrosion, resulting in a performance decline of up to 30% after 1000 h of operation. Apart from that, low Solar-to-Hydrogen (STH) efficiency is challenging. Karuturi et al. [131] examined advanced PEC materials and noted that the top STH efficiency in stable systems reached approximately 10%, which is significantly lower than the theoretical maximum of 30%. The researchers highlighted the necessity for novel materials and architectures to address this gap.

There is also an issue related to charge carrier recombination. The effective separation and movement of charge carriers produced by light is essential for the performance of PEC. In a study by Shi et al. [132], the dynamics of charge carriers in bismuth vanadate photoanodes were investigated, consequently discovered that as much as 70% of efficiency losses were due to recombination within the material. In order to overcome this issue, the researchers suggested methods involving nanostructures to reduce this loss to 50%. However, the researchers emphasized that additional enhancements are still necessary. The limited light absorption range is also concerning the researchers due to many PEC materials unable to utilize the full solar spectrum effectively. Liu et al. [133] investigated tandem photoelectrode structures to broaden the absorption range. Throughout the research, it can be seen that silicon/perovskite tandem devices achieved a 20% increase in photocurrent compared to single-junction devices, yet the stability issues persisted under long-term operation.

Last but not least, the PEC water-splitting system experiences bubble formation and management issues. This happens when the formation of gas bubbles at the electrode surface hinders the reaction and decreases efficiency. The influence of bubble formation on PEC performance was examined by Zhang et al. [134], hence revealing that at elevated current densities, bubble presence could diminish the active surface area by as much as 40%. By implementing a nanoarchitecture electrode design, the bubble release was enhanced, thus reducing the impact to 25%. However, PEC needs further optimization to achieve high-efficiency operation.

3.1.1.4. Dark fermentation. Dark fermentation is the process of producing hydrogen through certain bacteria as a byproduct of their metabolism in the absence of oxygen. Common substrates include glucose, cellulose, and various waste materials.

The major issue in dark fermentation is the relatively low production of hydrogen. A comprehensive review by Kumar et al. [135] explored metabolic engineering strategies to enhance hydrogen yields. Through the overexpression of hydrogenase enzymes in Clostridium beijerinckii, the researchers successfully raised the hydrogen yield by 30%, achieving a total of 2.8 mol H_2/mol glucose. Nonetheless, further advancements are needed to ensure the process becomes economically competitive. Dark fermentation also has substrate utilization efficiency issues. The efficient conversion of all organic compounds in complex substrates to hydrogen is not possible. In a study by Manikandan et al. [136], the use of lignocellulosic biomass for dark fermentation revealed that while readily fermentable sugars were quickly converted, lignin and some complex carbohydrates were largely unutilized, thus limiting the overall hydrogen production to 40–60% of the theoretical maximum based on substrate composition.

Environmental conditions such as pH and temperature sensitivity have a profound impact on dark fermentation processes. Researchers Dzulkarnain et al. [137] studied the effects of pH and temperature on hydrogen production, and it was found that deviations of ±0.5 pH units or ±3 °C from optimal conditions could lead to up to a 40% decrease in hydrogen yield. The maintenance of stable conditions in large-scale reactors continues to pose a significant challenge. There is also an issue in the genetic instability of hydrogen-producing strains. It can be difficult to sustain the steady performance of hydrogen-producing microorganisms over long periods. In a study conducted by Goveas et al. [138], the focus was on examining the genetic constancy of modified Escherichia coli strains that were enhanced for hydrogen generation. The researchers noted a progressive decrease in hydrogen output, with a 15% drop after 50 generations, emphasizing the necessity for improved approaches to uphold genetic stability in production strains.

Despite the studies done by existing researchers in implementing FCHEV technology, the challenges and limitations persist. Thus, there is a need to further explore advanced hydrogen production methods to mitigate the existing issues.

3.1.2. Energy efficiency considerations

Exploring the essential factors affecting the viability of Fuel Cell Hybrid Electric Vehicles (FCHEVs), the overall energy efficiency of hydrogen as a fuel is of utmost importance. This section delves into the well-to-wheel efficiency, energy losses throughout production, transportation, and storage, as well as the efficiency of fuel cells in converting hydrogen to electricity.

3.1.2.1. Well-to-wheel Efficiency Comparison. The efficiency of the entire energy chain from fuel production to vehicle operation is taken into consideration when assessing well-to-wheel efficiency. This analysis reveals the efficiency variances among FCHEVs, Battery Electric Vehicles (BEVs), and Internal Combustion Engine (ICE) vehicles. Table 4 provides the comparison of different types of vehicles in terms of production, distribution, powertrain, and overall efficiencies.

Based on Table 4 and Fig. 8, FCHEVs show high efficiency rates which are 37.8% and 40.5% compared to ICE. Thus, it can be concluded that FCHEVs technology is more efficient and has the potential to grow in the transportation field. Further advancements are needed to address the gaps and solutions to overcome the challenges.

3.1.2.2. Energy losses. The energy losses happen during production, transportation, and storage. Different methods of producing hydrogen have varying levels of efficiency. Green hydrogen production through electrolysis has an efficiency of approximately 70%, while Steam Methane Reforming (SMR), which uses natural gas, achieves around 75% efficiency. Both methods result in energy losses, with SMR currently being more efficient than electrolysis.

Following production, hydrogen necessitates transportation and storage, resulting in additional energy losses. Typically, the efficiency of hydrogen distribution, encompassing compression, transportation, and dispensing, stands at around 90% [115]. This efficiency is subject to variation based on factors such as distance and transportation method, for example, pipelines or tanker trucks.

Energy losses may also occur during the storage of hydrogen, although these losses are generally less significant in comparison to production and transportation losses. Hydrogen storage can take the form of compressed gas, liquid, or solid-state hydrogen storage materials, each with its efficiency considerations and trade-offs [141].

3.1.2.3. Efficiency of fuel cells. Fuel cells play a vital role in FCHEVs by converting hydrogen into electricity with an efficiency of around 60% [115]. This efficiency exceeds that of internal combustion engines (ICEs), which generally operate at approximately 25%.

The fuel cell conversion process involves the electrochemical combination of hydrogen and oxygen to generate electricity, water, and heat. This process is inherently more efficient than combustion as it directly converts chemical energy into electrical energy without the intermediate step of generating heat to drive mechanical work, as in ICEs. The typical components of a fuel cell system include the following.

- Anode: Where hydrogen gas is supplied and split into protons and electrons.
- Cathode: Where oxygen from the air combines with the protons and electrons to form water.
- Electrolyte: This allows protons to pass from the anode to the cathode while blocking electrons, forcing them to flow through an external circuit to generate electricity.

The efficiency of fuel cells is influenced by the following factors.

- Type of Fuel Cell: Automotive applications commonly use proton exchange membrane fuel cells (PEMFCs) due to their high-power density and rapid start-up times, although they are generally around 60% efficient.
- Operating Environment: The performance of fuel cells can be influenced by temperature, pressure, and humidity levels.
- Integration of Systems: Additional energy losses can be introduced, and system efficiency can be reduced by auxiliary components like compressors, pumps, and inverters.

The efficiency of fuel cells highlights their potential advantages and current limitations in the broader landscape of vehicle technologies, underscoring the need for ongoing advancements to make FCHEVs technologies more competitive with Battery Electric Vehicles (BEVs) in terms of overall energy efficiency. It is important to note that FCHEVs offer advantages in terms of refueling time and potentially longer range, which are considered more efficient in particular applications.

3.2. Hydrogen storage

The success of FCHEVs relies heavily on efficient and safe hydrogen storage, which directly affects vehicle range, safety, and cost. High-pressure storage, cryogenic storage, and chemical storage are the main storage methods, each with its distinct challenges and possibilities for enhancement.

3.2.1. High-pressure storage

Onboard hydrogen storage in FCHEVs currently relies heavily on high-pressure storage tanks operating at 700 bar. This section discusses materials, cost implications, and safety.

In terms of materials, advanced composite materials, mainly carbon fiber, are utilized in these tanks to withstand high pressures while keeping weight to a minimum. Carbon fiber's exceptional tensile strength and low density make it an ideal choice for this purpose, but the intricate manufacturing process contributes to the overall cost. Safety remains a top priority due to the potential for catastrophic failure resulting from any leak or rupture. Stringent testing and safety standards are enforced to ensure the tanks' integrity under diverse conditions [142]. Research has indicated that the composite materials of tanks are capable of enduring impacts and tolerating various temperatures, thereby improving their dependability in practical situations [142]. However, the persistent issue of hydrogen embrittlement, in which hydrogen atoms infiltrate and compromise the integrity of materials, remains a major obstacle. Efforts are underway to explore advanced coatings and material treatments to reduce this risk [142].

Regarding the cost implications, the high expense of these specialized tanks is a major obstacle to the widespread adoption of FCHEVs. This cost is mainly attributed to the energy-intensive process involved in producing carbon fiber and the high material expenses. Moreover, the manufacturing process necessitates precise engineering and quality control to ensure that safety and performance standards are met. According to the U.S. Department of Energy, the cost of high-pressure storage systems must be decreased by at least 50% in order to make FCHEVs competitive with traditional vehicles [143]. Efforts to diminish costs involve the exploration of new manufacturing methods, such as automated fiber placement, and the utilization of alternative, more

Table 4
Well-to-wheel efficiency comparison.

Author	Type of Vehicle	Production Efficiency	Distribution Efficiency	Powertrain Efficiency	Overall Efficiency
IRENA [115], Glenk et al. [139]	FCHEV (Green H_2	70% (Electrolysis)	90%	60% (Fuel Cell)	37.8%
IRENA [115], Glenk et al. [139]	FCHEV (SMR H_2	75% (SMR)	90%	60% (Fuel Cell)	40.5%
Wu et al. [140]	ICE	85% (Refining)	98% (Distribution)	25% (Engine)	20.8%

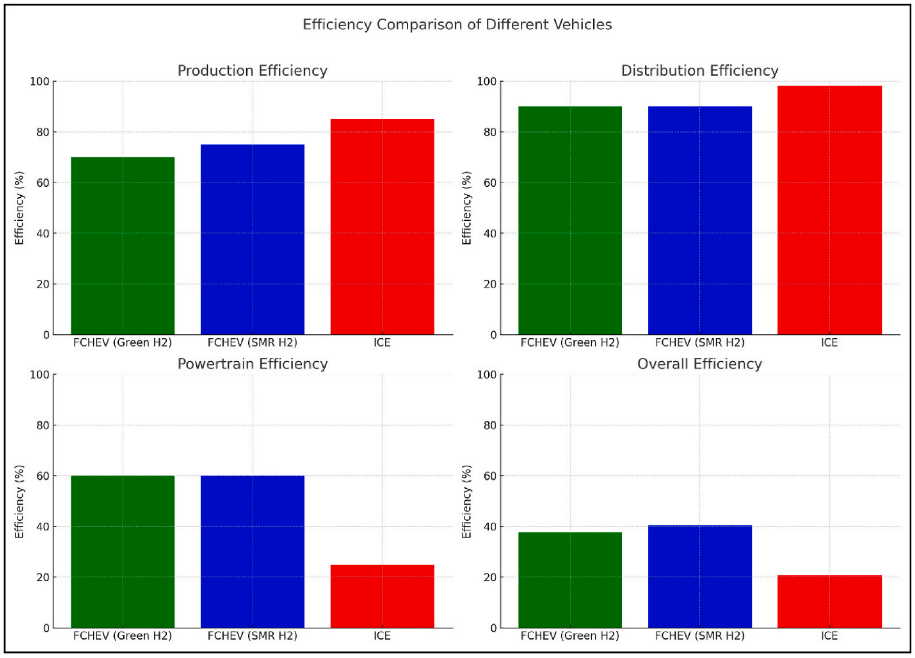

Fig. 8. Efficiency comparison of different vehicles.

affordable composite materials. Additionally, research is underway to develop hybrid tank designs that blend metal and composite materials to strike a balance between cost and performance [144].

Finally, it is extremely important to ensure the safety of high-pressure hydrogen storage. To prevent overpressure situations, current safety protocols involve the use of pressure relief devices that release hydrogen in a controlled manner. Furthermore, advanced sensor systems are utilized to detect leaks and monitor the integrity of the tank in real-time [145]. Various regulatory organizations, such as the International Organization for Standardization (ISO) and the Society of Automotive Engineers (SAE), have implemented strict standards governing the design, testing, and operation of hydrogen storage systems. These standards address factors like burst pressure, permeation rates, and impact resistance. Adhering to these standards is critical for ensuring the safe functioning of FCHEVs [146]. On top of that, public perception of hydrogen safety plays a significant role in the adoption of FCHEVs. For instance, educational campaigns and transparent communication about the rigorous safety measures in place are vital for building consumer confidence [147].

These limitations should be given attention in order to improve materials, reduce cost, and enhance safety measures to facilitate high-pressure hydrogen storage.

3.2.2. *Cryogenic storage*

Cryogenic storage involves storing hydrogen in liquid form at extremely low temperatures (−253 °C) which offers high energy density but exposes significant technical challenges.

As the temperature of liquid hydrogen rises, it starts to evaporate, which can lead to the loss of hydrogen and an increase in pressure. It is important to properly manage this evaporation to ensure the efficiency and safety of the system. Boil-off losses occur because even with the best insulation, some heat can still penetrate. Consequently, a small amount of the stored liquid hydrogen constantly evaporates, causing the pressure inside the storage vessel to rise [148]. In line with that, boil-off presents a key challenge due to the continual hydrogen loss, leading to decreased overall storage system efficiency. This loss can be particularly significant during extended storage periods or when the hydrogen is not used regularly. Research indicates that boil-off rates can vary from 0.3% to 3% per day, depending on the tank size and the quality of insulation [149]. Moreover, managing pressure build-up from boil-off is crucial to prevent safety concerns and adds intricacy to the design of the storage system.

Apart from that, insulation requirement is also a concerning limitation. Sustaining the extremely low temperatures needed for storing liquid hydrogen requires advanced insulation systems. Existing insulation technologies struggle to concurrently balance effectiveness, weight, and cost considerations. The difficulty lies in creating insulation that can uphold its effectiveness over extended periods while remaining lightweight and cost-efficient. Multi-layer insulation (MLI) systems, which consist of alternating layers of reflective foils and spacers, are frequently utilized in cryogenic applications. Although MLI systems substantially diminish radiative heat transfer, they are prone to compression and can lose their effectiveness if not installed or maintained correctly [150]. Additionally, the insulation must endure mechanical stresses and vibrations common in automotive applications, which can diminish its performance over time. A recent study has brought attention to the shortcomings of existing insulation technologies in fulfilling the requirements of mobile hydrogen storage. For instance, the use of vacuum-insulated double-walled tanks, which, despite being efficient, result in increased weight and expense for the storage system, thereby restricting their feasibility for extensive use in automotive applications [151].

Regarding energy efficiency, the liquefaction process for hydrogen is energy-intensive, potentially reducing the overall efficiency of the hydrogen fuel cycle. Recent assessments indicate that liquefaction typically consumes about 30–40% of the energy content of the hydrogen being processed, making it a significant efficiency loss in the hydrogen supply chain [152]. This high energy requirement for liquefaction presents a major limitation for the widespread adoption of liquid hydrogen storage. It not only increases the overall cost of hydrogen as a fuel but also potentially negates some of the environmental benefits of using hydrogen, especially if the energy for liquefaction comes from non-renewable sources. High energy liquefaction demands also create obstacles to expanding hydrogen infrastructure. Significant capital investment and energy resources are needed for large-scale liquefaction facilities, which can hinder the expansion of hydrogen distribution networks. Research indicates that liquefaction plants can consume between 10 and 13 kWh/kg of hydrogen, varying based on plant size and technology employed [153].

Even though cryogenic storage offers high energy density, it still encounters significant obstacles in managing boil-off losses, meeting strict insulation standards, and addressing energy inefficiencies in the liquefaction process. These challenges remain major obstacles in the widespread acceptance of liquid hydrogen storage.

3.2.3. Chemical storage

Chemical hydrogen storage involves the attachment of hydrogen to other substances, like metal hydrides or chemical hydrides. These materials release hydrogen when they are heated or subjected to other chemical processes. This section discusses challenges on materials, kinetics releasing, reversibility and cycling, system integration, and safety considerations.

Efficiently storing and releasing hydrogen at practical temperatures and pressures remains a significant challenge due to the shortcomings of current materials, which are often either too heavy or expensive for widespread use in FCHEVs [154]. The gravimetric and volumetric hydrogen storage capacities of numerous chemical storage materials do not meet the targets set for automotive applications. For example, practical conditions result in most metal hydrides achieving less than 2 wt% hydrogen storage capacity, which is significantly short of the U.S. Department of Energy's ultimate target of 7.5 wt% for onboard hydrogen storage systems [155]. In addition, hydrogen desorption for many promising materials necessitates temperatures exceeding 300 °C, which is not practical for vehicle use due to concerns about energy efficiency and safety. Materials designed to operate at lower temperatures often encounter issues with slow kinetics or insufficient storage capacity [156]. The high cost of materials presents another substantial obstacle. Numerous high-performance chemical storage materials rely on costly rare earth elements or intricately synthesized compounds, rendering them economically impractical for mass-market vehicles [157].

The next limitation is related to release kinetics. The materials must release hydrogen at a fast enough rate to meet the dynamic needs of FCHEVs. Many chemical storage materials have slow hydrogen release rates, especially at lower temperatures, which can result in inadequate hydrogen supply during high power demand in vehicles [154]. Improving release rates is a challenge as it often clashes with other desirable properties. Materials with stronger metal-hydrogen bonds generally have higher storage capacities but slower release rates. This trade-off between capacity and kinetics is a major obstacle in material design [158]. Additionally, managing the heat required for the endothermic dehydrogenation process makes system design more complex. Inadequate heat supply can decrease hydrogen flow rates and reduce overall system efficiency [159].

In terms of reversibility and cycling issues, chemical storage materials must maintain their performance over many hydrogenation-dehydrogenation cycles for practical application in FCHEVs. Many materials experience a decrease in capacity and changes in structure after repeated cycles [160]. Maintaining cycling stability is especially difficult for complex hydrides and reactive hydride composites. These materials often undergo phase separation or create stable intermediate compounds during cycling, resulting in reduced hydrogen storage capacity and slower kinetics over time [161]. The deterioration of material performance leads to the need for frequent replacement of the storage medium or the need to oversize the storage system to compensate for capacity loss, both of which increase the overall cost and complexity of the vehicle fuel system [162].

The integration of chemical storage systems into vehicles comes with added challenges. Ensuring precise temperature control, managing pressure, and facilitating efficient heat transfer within the storage system increases the complexity and weight of the vehicle design [163]. Moreover, the volumetric efficiency of the entire storage system, which includes essential components such as heat exchangers and control systems, is often significantly lower than that of the storage material alone. This difference makes it challenging to achieve the compact storage solutions necessary for vehicle applications [163].

Lastly, the safety issue should be addressed when dealing with chemical storage. This is due to complex hydride-based chemical storage materials that can be reactive with air and moisture, making them pyrophoric. This reactivity requires sturdy containment systems and safety protocols, introducing additional complexity and potential failure points to the vehicle fuel system [154].

In summary, even though chemical storage has the potential for high hydrogen storage capacities, it encounters various obstacles related to material characteristics, system planning, and real-world application. Overcoming these hurdles is essential for the practicality of chemical hydrogen storage in FCHEVs.

3.3. Economic impact of fuel cells in FCHEVs

FCHEVs face considerable economic obstacles as the world shifts towards sustainable transportation. Despite the potential environmental advantages they offer, FCHEVs are held back by a range of economic factors. This section presents a thorough examination of the economic challenges confronting FCHEVs, particularly focusing on fuel cell technology.

3.3.1. High production costs

The high production costs of fuel cell systems for vehicles continue to pose a significant economic obstacle due to various contributing factors.

One such factor is the expenses associated with catalysts. In particular, platinum, which is utilized as a catalyst in proton exchange membrane fuel cells (PEMFCs), continues to exert a substantial impact on costs. Despite continuous efforts to decrease the amount of platinum used, it still represents a significant portion of the overall stack cost. Banham et al. [164] highlighted that in current PEMFC designs, platinum can make up to 40% of the stack cost. The volatility of platinum prices in the global market introduces additional economic uncertainty into fuel cell production.

As for the specialized components, special materials and intricate manufacturing processes are necessary for producing important fuel cell parts like bipolar plates, gas diffusion layers, and membranes. These parts demand exact precision and stringent quality control, which greatly impacts the overall expenses. For instance, according to Tang et al. [165], the membrane electrode assembly (MEA) alone could represent 50–70% of the total fuel cell stack cost, depending on production volume and design criteria.

In relevant to scale of production, FCHEVs have higher per-unit costs compared to conventional vehicles because of their relatively low production volumes, which leads to a lack of economies of scale. This issue is especially evident in the initial stages of market entry. According to a comprehensive cost analysis conducted by Shin et al. [166], increasing the production volume from 1000 to 100,000 units per year could potentially result in a 45% reduction in fuel cell system costs, underscoring the crucial role of scale in achieving economic feasibility. Fig. 9 shows the reduction in fuel cell system cost when increasing the production volume.

3.3.2. Limited infrastructure and high fuel costs

The lack of widespread hydrogen refueling infrastructure poses a significant economic challenge in terms of infrastructure development costs, hydrogen production and distribution, and regional variations.

The establishment of a hydrogen refueling station requires a substantial amount of capital. According to Greene et al. [168], the infrastructure development cost of a single hydrogen refueling station can vary from \$1.5 million to \$3.5 million, based on its capacity and location. This significant initial investment, combined with low usage rates due to the limited number of FCHEVs on the road, presents a major economic hurdle to infrastructure development.

Another challenge faced by FCHEVs is the hydrogen production and distribution process. In numerous areas, the price of hydrogen fuel

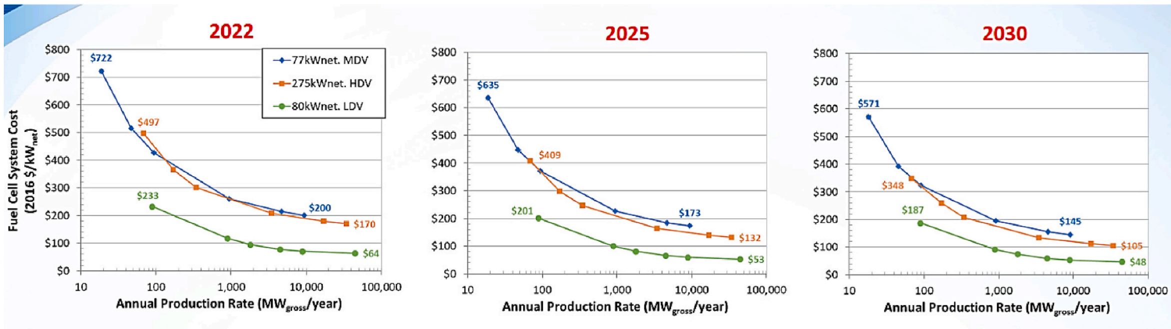

Fig. 9. Comparison of fuel cell system cost through the year 2022–2030 [167].

remains elevated compared to traditional fuels, largely due to energy-intensive manufacturing methods and the absence of an extensive distribution infrastructure. According to Pedersen et al. [169] thorough study, the cost of hydrogen fuel could be 2 to 4 times more expensive than gasoline per mile, depending on the production process and local energy costs. This significant difference in price significantly affects the operational expenses of FCHEVs and their appeal to consumers.

Regional variations can significantly impact the economic feasibility of hydrogen infrastructure. Local energy prices, current infrastructure, and government regulations all play important roles. In existing research, Le et al. [170] discovered that the cost of hydrogen fuel could be as much as 40% lower in countries with plentiful renewable energy resources compared to regions that heavily rely on fossil fuels for hydrogen production.

3.3.3. Maintenance and durability challenges

The long-term economic viability of fuel cells is impacted by unique durability challenges, despite having fewer moving parts compared to internal combustion engines.

Over time, performance loss in fuel cell systems occurs due to various degradation mechanisms. A study by Chen et al. [112] highlighted important degradation factors such as catalyst sintering, carbon corrosion, and membrane thinning. These issues not only decrease the efficiency of the fuel cell but also have the potential to shorten the lifespan of the vehicle, thereby affecting its total cost of ownership.

Auxiliary systems like air compressors, humidifiers, and cooling systems play a vital role in ensuring the overall durability of FCHEVs in balancing the plant components. Failures in these components can result in substantial maintenance expenses. According to a study by Zeng et al. [171], balance of plant components can contribute to as much as 30% of the total maintenance costs in FCHEVs throughout their lifespan.

Besides, maintaining and repairing the specialized fuel cell technology necessitates a skilled workforce. The limited availability of expertise in fuel cell systems can lead to increased maintenance expenses and prolonged downtimes. Thompson et al. [172] emphasized the importance of substantial investment in training programs and specialized service centers to support the expansion of the FCHEV market.

3.3.4. Market uncertainty and investment risks

The FCHEV market encounters notable uncertainties that influence economic decision-making. For instance, dependence on policies, competition from other technologies, and investment landscape.

As for the policy dependence, the economic feasibility of FCHEVs is greatly affected by government policies and incentives. According to Fanoro et al. [173], the analysis of policy frameworks on FCHEV adoption in various countries revealed that inconsistent or short-term policies lead to considerable market uncertainties and investment risks.

The competing technologies, particularly the rapid progress of battery electric vehicles (BEVs) present a significant challenge to FCHEVs. A comparative study by Pollet et al. [174] highlighted that the improving performance and declining costs of battery technology create intense competition in the zero-emission vehicle market.

Furthermore, the market risks for manufacturers and investors are significant due to the uncertain future of hydrogen infrastructure and potential shifts in energy policies. This uncertainty could result in increased financing costs for FCHEV projects and a hesitancy among stakeholders to invest in the technology. According to Waseem et al. [175] comprehensive analysis of investment trends in hydrogen technologies, a 30% decline in private sector investment in FCHEV-related projects was attributed to perceived market risks between 2020 and 2023.

3.3.5. Research and development costs

Ongoing investment is necessary for continuous research and development in fuel cell technology to overcome technical challenges. However, there are significant challenges related to continuous innovation needs and material research.

The fuel cell sector needs to dedicate a higher proportion of its earnings to Research and Development (R&D) in comparison to more established automotive technologies. This persistent necessity for innovation to enhance performance and decrease expenses has an impact on profitability and may hinder cost-reduction endeavors. According to Fan et al. [176] and Li et al. [177], R&D expenditure in the fuel cell industry averages 8%–12% of revenue, whereas it stands at 3%–5% in the traditional automotive sector.

Regarding materials research, considerable research endeavors are directed toward creating substitute catalysts and membrane materials to lower expenses and enhance efficiency. Despite their potential, these research projects demand significant long-term investments with uncertain outcomes. According to a study conducted by Kim et al. [178] and Sharma et al. [179] on advanced materials for PEMFCs, the shift from laboratory-level discoveries to commercial offerings typically requires 10–15 years, necessitating consistent funding during this timeframe.

To this point, the economic implications of fuel cells in FCHEVs present complex obstacles to their widespread adoption. The high costs of production, limited infrastructure, worries about durability, expensive fuel, market instabilities, and stiff competition from alternative technologies all contribute to the economic constraints of FCHEVs. Industry, government, and research institutions need to work together to overcome these barriers. As technology advances and economies of scale become a reality, it is possible that some of these economic challenges can be reduced. Nevertheless, achieving economic viability for FCHEVs is still a complicated process that relies on technological progress, support from policies, and market conditions.

3.4. Battery lifetime in FCHEVs

FCHEVs primarily rely on fuel cells for power, but they also use batteries to help manage power and enhance efficiency. Nevertheless, the batteries in FCHEVs encounter various obstacles and restrictions in terms of their lifespan, which can affect the vehicles' overall performance and economic feasibility.

3.4.1. Degradation mechanisms

The batteries in FCHEVs, typically lithium-ion batteries, are subject to various degradation mechanisms that can reduce their lifetime. For instance, capacity fades, power fade, and temperature-related degradation.

The battery capacity reduces over time, leading to a decrease in the amount of energy it can hold. This decline is especially problematic in FCHEVs, where the battery is crucial for managing power. According to a study by Hou et al. [180], capacity fade in FCHEV batteries can occur at a faster rate than in pure battery electric vehicles (BEVs) due to the unique charge-discharge patterns in hybrid systems.

As for power fading, the battery's ability to deliver peak power also diminishes over time, which can impact the vehicle's performance, especially during high-power demand situations such as acceleration. Research of Liu et al. [181] has shown that power fades in FCHEV batteries may be up to 20% higher than in comparable BEVs after 5 years of operation, attributed to the more frequent and intense power fluctuations.

In addition, the generation of heat during fuel cell operation can affect the thermal regulation of the battery system. Battery degradation can be hastened by prolonged exposure to excessive heat. Song et al. [182] found that FCHEV batteries in high-temperature conditions may undergo capacity loss up to 30% faster than those in milder climates.

3.4.2. Cycling stress

The unique operational characteristics of FCHEVs such as frequent charge-discharge cycles and depth of discharge variations subject their batteries to specific cycling stresses.

For instance, in FCHEVs, the battery goes through frequent charging and discharging cycles as it distributes power between the fuel cell and the vehicle's requirements. These frequent cycles may speed up the degradation process. Zeng et al. [171] noted that FCHEV batteries could potentially undergo three times as many micro-cycles per day compared to BEVs, ultimately decreasing their overall lifespan.

The depth of discharge (DoD) in FCHEV batteries also may vary significantly based on driving conditions and power management approaches. Wide DoD variations can hasten battery deterioration. In a thorough investigation by Ma et al. [183,184], it was revealed that FCHEV batteries might endure 15%–25% more pronounced DoD variations compared to BEVs, contributing to faster capacity fade.

3.4.3. System integration challenges

The integration of batteries with fuel cell systems in FCHEVs presents unique issues that may affect battery lifetime. For example, the battery lifetime may undergo power electric stress and charge management complexity issues.

In relevant to power electronic stress, the intricate power management systems coordinating the fuel cell, battery, and electric motor may cause additional electrical stress on the battery. According to Khalatbarisoltani et al. [185], the power electronics in FCHEVs could induce high-frequency current ripples, potentially hastening battery degradation by 5%–10% compared to simpler BEV systems.

Furthermore, the charge management strategy in FCHEVs presents greater complexity than in BEVs due to having dual power sources. Suboptimal charge management may result in unnecessary cycling or unfavorable state-of-charge ranges. Studies by Gharibeh et al. [186] suggested that inefficient charge management strategies could decrease battery lifetime by up to 20% in FCHEVs.

3.4.4. Environmental and operational factors

The environmental and operational factors can exacerbate battery lifetime issues in FCHEVs. In this section, the cold weather performance and driving patterns are discussed.

In cold weather, FCHEVs encounter specific challenges. The ability of the fuel cell to start in cold conditions and the decreased performance of the battery in low temperatures can place additional strain on the battery system. According to a study by Waseem et al. [176], FCHEV batteries in cold climates may degrade up to 40% faster than those in more temperate climates.

In terms of driving patterns, the varied driving patterns of FCHEVs, including extended periods of low-power usage followed by high-power requirements, can impact the battery system. Bartolucci et al. [187] noted that urban FCHEV usage, marked by frequent stops and starts, could reduce battery lifespan by 10%–15% when compared to patterns dominated by highway driving.

3.4.5. Economic implications

The battery lifetime issues in FCHEVs such as replacement costs and performance degradation have significant economic implications.

According to a study by Khalatbarisoltani et al. [188], FCHEVs may require more frequent battery replacements compared to BEVs, resulting in higher ownership costs. The study estimated that over 10 years, FCHEV owners might need to replace their batteries 1.5 to 2 times more often than BEV owners, significantly impacting long-term operating expenses.

Not only the battery replacement costs but as the battery deteriorates, the overall performance and efficiency of FCHEVs may decrease, potentially leading to higher hydrogen consumption and reduced range. This reduction in efficiency due to battery degradation, as highlighted in a longitudinal study by Khan et al. [189,190], could result in a 5%–8% decrease in overall efficiency over five years for FCHEVs, compared to a 3%–5% decrease for BEVs. This degradation may also impact the resale value and operational economics of the vehicle.

Conclusively, the longevity of batteries poses notable challenges despite their vital role in the functioning of FCHEVs. The distinct operational traits of these vehicles expose batteries to strains that can hasten deterioration compared to other electric vehicle varieties. These concerns impact not only the effectiveness and productivity of FCHEVs but also carry significant financial consequences. Effectively dealing with these challenges related to battery lifespan remains a crucial area for enhancing the overall sustainability and competitiveness of FCHEVs in the automobile industry.

3.5. Power electronic interface in FCHEVs

FCHEVs depend on the power electronic interface to regulate energy flow between the fuel cell stack, battery, and electric motor. Yet, this intricate system encounters various obstacles and restrictions that affect the overall effectiveness, productivity, and dependability of FCHEVs. The challenges that could be related to power electronic interface are complexity and integration, efficiency losses, size, and weight constraints.

3.5.1. Complexity and integration challenges

The power electronic interface in FCHEVs is more complex compared to conventional electric vehicles due to the need to manage multiple power sources.

The incorporation of fuel cells, batteries, and electric motors necessitates complex power management tactics, which can result in higher costs, potential failure points, and difficulties in optimizing the system. According to Pramuanjaroenkij et al. [191], the power electronic framework in FCHEVs typically involves 30%–40% more components compared to battery electric vehicles (BEVs), leading to increased initial costs and maintenance intricacy.

Efficiently developing control strategies for managing power flow between the fuel cell and battery also remains a significant challenge. Inadequate control can diminish system efficiency and hasten component deterioration. A comprehensive assessment conducted by

Pramuanjaroenkij et al. [192] revealed that even advanced control strategies in FCHEVs could cause up to 10% energy loss due to inefficient power distribution between the fuel cell and battery.

3.5.2. Efficiency losses

Power electronic interfaces in FCHEVs face efficiency challenges such as conversion losses, wide operating range, and partial load efficiency.

Losses occur during multiple power conversion stages in FCHEV power electronic systems, such as DC/DC for fuel cell and battery and DC/AC for motor drive, leading to cumulative efficiency reductions. According to Yodwong et al. [119], FCHEV power electronic systems may experience an overall conversion efficiency that is 3%–5% lower than comparable BEVs due to these additional conversion stages.

Efficient operation across a wide range of voltages and currents is necessary for power electronic components to accommodate the varying outputs of fuel cells and batteries. This requirement often results in design compromises that can diminish peak efficiency. A study by Yodwong et al. [119] indicated that the average operating efficiency of DC/DC converters in FCHEVs could be up to 2% lower than in more narrowly optimized BEV systems.

In the case of efficiency at partial load, FCHEVs frequently run at partial load, causing the power electronic components to operate with less than optimal efficiency. Enhancing the efficiency at partial load while maintaining full-load performance poses a significant challenge. According to research conducted by Kang et al. [193,194], power electronics in FCHEVs may exhibit efficiency that is up to 15% lower during typical urban driving cycles compared to highway driving, mainly due to operating at partial load.

3.5.3. Size and weight constraints

The power electronic interface in FCHEVs faces significant challenges related to size and weight. There is limited space for power electronics due to the need to accommodate fuel cell and battery systems, leading to the requirement for highly compact designs. This limitation may result in compromises in performance or thermal management. According to a study conducted by Pramuanjaroenkij et al. [191], the power density requirements for FCHEV power electronics were typically 20%–30% higher than for BEVs, pushing the boundaries of existing technology.

Regarding weight consideration, the inclusion of additional power electronic components adds to the overall vehicle weight, which could potentially impact range and efficiency. Balancing this impact while upholding performance remains an ongoing challenge. Yodwong et al. [8] estimated that the power electronic system in FCHEVs could make up 5%–8% of the total vehicle weight, in comparison to 3%–5% in similar BEVs.

In summary, it is essential to tackle these issues in order to enhance the overall performance and economic feasibility of FCHEVs. The intricacies involved in controlling numerous power sources in a confined automotive setting persist in presenting significant engineering challenges in the design and enhancement of FCHEV power electronic systems.

3.6. Energy management system in FCHEVs

The energy management system plays a vital role in FCHEVs by effectively managing power allocation between the fuel cell stack and the battery. Despite its significance, the system encounters various obstacles and constraints that influence the overall effectiveness, productivity, and dependability of FCHEVs.

3.6.1. Complexity of power distribution

Optimizing power distribution between the fuel cell and battery while driving in real-time is a highly intricate task. The energy management system needs to continuously adapt to changing power requirements, fuel cell properties, and battery charge status. According to Tanç et al. [195] inefficient power distribution strategies may cause efficiency losses of up to 10% in FCHEVs compared to optimal scenarios.

The energy management system must be able to quickly adjust to sudden changes in power demand, which can be difficult due to the slower response time of fuel cells in comparison to batteries. This limitation can lead to temporary power shortages or excessive reliance on the battery. Aminudin et al. [196] noted that during rapid acceleration, FCHEVs could experience delays of up to 2 s in power delivery, potentially impacting vehicle performance and driver satisfaction.

Optimizing for multiple objectives is a key challenge for energy management system, as it often involves balancing conflicting goals such as fuel economy, battery life, and performance. Aminudin et al. [197] conducted a thorough review, emphasizing the difficulty advanced energy management system strategies face in achieving more than 85% of the theoretical optimal balance among these competing objectives.

3.6.2. Fuel cell degradation management

Optimizing the operating point of the fuel cell is a complex task aimed at minimizing degradation while meeting power demands. Accelerated degradation can result from frequent starts and stops or operations at extreme power levels. According to Gharibeh et al. [198], inefficient energy management system strategies could increase fuel cell stack degradation by up to 20% over the vehicle's lifetime.

Efficiently managing cold starts while reducing stress on the fuel cell system poses a significant challenge for the management system. Improper management of cold starts can lead to accelerated degradation. Aminudin et al. [196] discovered that FCHEVs in cold climates could experience up to 30% faster fuel cell degradation due to suboptimal cold start management by the energy management system.

3.6.3. Computational limitations

The real-time characteristic of energy management system operation in FCHEVs presents vital computational challenges. For instance, real-time optimization and predictive capabilities.

Achieving real-time optimization on automotive-grade hardware presents a challenge due to the complexity of the calculations involved, which can restrict the implementation of sophisticated energy management system strategies. According to Khalatbarisoltani et al. [185], the computational limitations in real-time operations could lead to energy management system performance dropping by up to 8% compared to theoretically optimal strategies.

The integration of predictive elements into energy management systems, such as predicting future power needs and route characteristics, is computationally intensive and often constrained by available hardware and sensor data. As reported by Khalatbarisoltani et al. [185], the inefficiency of current energy management system implementations in predictive capabilities could result in real-world driving scenarios experiencing efficiency losses of up to 7%.

3.6.4. Integration with vehicle systems

When interacting with safety systems, it is essential to ensure that energy management system decisions do not contradict vehicle safety systems, such as stability control or emergency braking, as this can complicate system design. According to Gharibeh et al. [199], addressing conflicts between energy management systems and safety systems may cause delays of up to 100 ms in critical power distribution decisions. The energy management system needs to be compatible with a range of drivetrain components, which can differ among various FCHEV models, potentially limiting the applicability of energy management system strategies. Gharibeh et al. [198] discovered that energy management system strategies tailored for specific drivetrain configurations might experience a reduction in efficiency of up to 10% when applied to different FCHEV models.

Overall, the energy management system in FCHEVs encounters several obstacles and constraints. These encompass the intricacy of power distribution, adaptability to diverse conditions, computational constraints, and integration challenges with other vehicle systems. It is essential to tackle these hurdles in order to enhance the overall efficiency, performance, and dependability of FCHEVs. The multidimensional nature of these issues highlights the continuous requirement for research and development in FCHEV energy management strategies to overcome these limitations and optimize vehicle performance.

3.6.5. Summary of energy management system challenges

Table 5 summarizes the challenges faced in FCHEVs technology, specifically in energy management systems.

4. Future perspectives of fuel cell-based hybrid electric vehicles (FCHEVs)

4.1. Cost impact

The high cost of Fuel Cell Hybrid Electric Vehicles (FCHEVs) remains a major obstacle to their widespread adoption, primarily due to the expense of key components such as fuel cell stacks and hydrogen storage systems. Tackling these costs is crucial for advancing FCHEV technology and making it more accessible to a larger market.

One key strategy for reducing costs is to focus on the fuel cell stacks and hydrogen storage systems themselves. Advances in materials science and manufacturing processes are essential in this regard. For instance, the development of high-performance catalysts can enhance the cost-effectiveness of fuel cells. Research by Azeem et al. [200] highlights the significance of optimizing control strategies in hybrid electric vehicles, which indirectly affects the cost of integrating advanced energy storage systems like batteries and ultracapacitors. Improving the efficiency and longevity of these components can help lower overall system costs. Moreover, employing advanced manufacturing techniques can lead to considerable cost reductions. Innovations in production technology and large-scale manufacturing can help reduce the costs of both fuel cell stacks and hydrogen storage systems. Baba et al. [201] offer a detailed review of current power electronic converter topologies used in fuel cell electric vehicles, identifying technical challenges and opportunities for cost reduction. Their research indicates that enhancing the efficiency and reliability of power converters can significantly decrease overall vehicle costs.

In addition to material and manufacturing advancements, recycling and reusing fuel cell components are effective strategies for cost mitigation. Møller-Holst et al. [202] examine various recycling and reuse methods for fuel cell components, demonstrating how these practices can lower the demand for raw materials and reduce production costs. Implementing efficient recycling processes and developing reuse technologies can significantly cut the lifecycle costs of fuel cells, making FCHEVs more affordable.

Table 5
Energy management system challenges in FCHEVs.

Challenge	Description	Potential Impact
Power Distribution Complexity	Optimizing power flow between fuel cell and battery	Up to 10% efficiency loss if not optimized
Fuel Cell Degradation Management	Balancing performance and longevity of fuel cell	Up to 20% increase in fuel cell degradation over the lifetime
Computational Limitations	Real-time optimization on automotive-grade hardware	Up to 8% performance drop compared to the theoretical optimum
Integration with Vehicle Systems	Ensuring compatibility with safety and drivetrain systems	Potential delays in power distribution decisions

4.2. Long-driving logistics

Long-distance driving logistics are crucial for assessing the feasibility and practicality of Fuel Cell Hybrid Electric Vehicles (FCHEVs). To compete effectively with traditional vehicles and battery electric vehicles (BEVs), FCHEVs must offer substantial driving ranges between refueling. Two primary strategies to enhance this capability are increasing hydrogen storage capacity and optimizing energy management systems.

4.2.1. Hydrogen storage capacity

One major challenge in extending the driving range of FCHEVs is enhancing hydrogen storage capacity. Innovative storage solutions are essential for this purpose. Advances in hydrogen storage technologies, such as metal hydrides and chemical hydrogen storage methods, are particularly promising. Schlapbach and Züttel [203] highlight the advantages of metal hydrides, which can store hydrogen at high densities and provide an efficient solution for mobile applications. These materials are effective due to their ability to absorb and release hydrogen efficiently, significantly boosting the driving range of FCHEVs. Chemical hydrogen storage methods also offer a potential alternative to traditional compressed hydrogen storage. These methods use chemical reactions to store hydrogen in a more stable and compact form, which can reduce refueling times and enhance overall vehicle efficiency. The U.S. Department of Energy's research into various hydrogen storage technologies suggests that continued advancements in this area will lead to more practical and efficient storage solutions, further extending the driving range of FCHEVs [204].

4.2.2. Energy management systems

Optimizing energy management systems is another key factor in extending the driving range of FCHEVs. Effective energy management balances power distribution between the fuel cell, battery, and other energy storage systems, leading to improved vehicle performance. Badji et al. [205] explore various energy management strategies, including frequency splitting techniques, which enhance the efficiency of fuel cell electric vehicles by optimizing energy distribution. Their findings indicate that sophisticated energy management systems can improve energy utilization and extend driving range. The integration of advanced energy storage systems, such as ultracapacitors and high-capacity batteries, is also crucial. Changizian et al. [206] demonstrate that performance optimization of hybrid hydrogen fuel cell-electric vehicles, when combined with ultracapacitors and high-capacity batteries, results in significant improvements in driving range and efficiency during real-world driving conditions. Ultracapacitors, in particular, are useful for managing peak power demands and enhancing overall energy management.

4.2.3. Integrating innovations

Combining advancements in hydrogen storage and energy management systems presents a holistic approach to addressing long-distance driving logistics. By leveraging innovative storage solutions and optimizing energy management, FCHEVs can achieve extended driving ranges while maintaining high efficiency. As these technologies continue to advance, they will play a critical role in making FCHEVs more viable and attractive for long-distance travel, thereby facilitating their wider adoption in the automotive market.

4.3. Promoting policies

Government policies are pivotal in accelerating the adoption of Fuel Cell Hybrid Electric Vehicles (FCHEVs). Well-designed policies can significantly boost the market presence and growth of FCHEVs. Key measures include tax incentives, subsidies for hydrogen production, and investments in hydrogen refueling infrastructure. Additionally, policies aimed at reducing greenhouse gas emissions and encouraging clean energy vehicles are particularly effective in fostering FCHEV development.

4.3.1. Incentives and subsidies

Financial incentives, such as tax credits and subsidies, play a crucial role in making FCHEVs more appealing to both consumers and manufacturers. Tax credits can lower the initial purchase price of FCHEVs, making them more competitive with traditional vehicles. Subsidies for hydrogen production can reduce the cost of hydrogen fuel, making FCHEVs a more viable alternative to gasoline and diesel vehicles. Ettihir et al. [207] note that optimizing energy management strategies in fuel cell/battery hybrid systems can further enhance the efficiency and attractiveness of these vehicles. Policies that lower the total cost of owning and operating FCHEVs can significantly boost their adoption.

4.3.2. Investment in refueling infrastructure

Investing in hydrogen refueling infrastructure is another critical policy measure. Establishing a comprehensive network of hydrogen refueling stations is essential to support the widespread use of FCHEVs. Addressing the "chicken-and-egg" dilemma—where limited refueling stations hinder vehicle adoption and vice versa—can help expand the FCHEV market. Feroldi et al. [208] highlight that efficient energy management strategies, coupled with robust refueling infrastructure, can drive FCHEV adoption. Policies that promote the construction of refueling stations and support advancements in refueling technologies can greatly contribute to the success of FCHEVs.

4.3.3. Emission reduction and clean energy policies

Policies targeting greenhouse gas emissions reduction and the promotion of clean energy vehicles are particularly effective for supporting FCHEVs. By enforcing strict emissions regulations and offering incentives for clean energy technologies, governments can create a favorable environment for FCHEVs. The International Energy Agency's [209] Global EV Outlook report emphasizes the role of such policies in advancing cleaner transportation options. Aligning with global efforts to cut carbon emissions and promote sustainability is crucial for the long-term success of FCHEVs.

4.3.4. International collaboration and regulation

International collaboration and regulatory harmonization are vital for the global expansion of FCHEVs. Collaborative efforts among nations can lead to standardized technologies and practices, reducing costs and enhancing the efficiency of FCHEVs. The U.S. Department of Energy's International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) plays a significant role in promoting international cooperation and advancing hydrogen technologies [210]. Through joint efforts, countries can share knowledge, standardize regulations, and build a unified global market for FCHEVs.

4.4. Intelligent-based autonomous FCEVs

Integrating autonomous driving technologies with Fuel Cell Hybrid Electric Vehicles (FCHEVs) represents a major leap forward in boosting both efficiency and safety. By harnessing intelligent systems, FCHEVs can achieve enhanced performance through optimized fuel cell operation, energy management, and overall vehicle functionality. This fusion of autonomous driving and fuel cell technology opens new avenues for improved route planning, energy management, and vehicle maintenance.

4.4.1. Optimizing fuel cell operation

Autonomous FCHEVs stand to gain significantly from intelligent systems designed to optimize fuel cell performance. Research by Fletcher et al. [211] investigates energy management strategies aimed at improving fuel efficiency and extending the life of Proton Exchange Membrane (PEM) fuel cells in hybrid vehicles. Their findings show how smart energy management systems can enhance fuel cell efficiency by adapting operation based on real-time data and driving conditions. This optimization not only boosts fuel economy but also extends the lifespan of fuel cell systems, enhancing vehicle reliability.

4.4.2. Advanced energy management

Sophisticated energy management strategies enabled by intelligent systems consider factors such as driving behavior, road conditions, and vehicle load. Li et al. [212] discuss an online adaptive equivalent consumption minimization strategy that adjusts to the degradation of power sources in fuel cell hybrid electric vehicles. This adaptive approach ensures the vehicle operates at peak efficiency despite changes in power source conditions. Implementing such advanced energy management systems allows autonomous FCHEVs to achieve superior performance and reduced energy consumption, resulting in a more efficient driving experience.

4.4.3. Predictive maintenance and reliability

Another significant advantage of integrating autonomous technologies with FCHEVs is predictive maintenance. Liu et al. [213] explore predictive maintenance techniques for PEM fuel cells, using data analytics and machine learning to anticipate potential issues and schedule maintenance proactively. Predictive maintenance enables autonomous FCHEVs to detect and address potential problems before they arise, improving the reliability and durability of fuel cell systems. This approach not only enhances vehicle performance but also lowers maintenance costs and minimizes downtime.

4.4.4. Route planning and adaptive learning

Artificial intelligence (AI) and machine learning are key to refining route planning and energy management for autonomous FCHEVs. AI algorithms can process extensive data to identify the most efficient routes and driving strategies, optimizing fuel usage and reducing travel time. Incorporating adaptive learning allows autonomous FCHEVs to continuously refine their performance based on real-world driving data. This ongoing learning process enables the vehicle to adjust to changing conditions and optimize its operation for maximum efficiency.

4.4.5. Safety and efficiency enhancements

The integration of autonomous driving technologies also improves safety through features like advanced driver assistance systems (ADAS), collision avoidance, and adaptive cruise control. These systems enhance the safety of the driving environment while further boosting the efficiency of FCHEVs. By merging autonomous driving capabilities with fuel cell technology, manufacturers can deliver vehicles that excel in both environmental performance and user safety, offering a more secure and convenient driving experience.

4.5. Artificial intelligence (AI) application for the fuel economy

Recent studies have explored various AI approaches aimed at improving fuel economy in hybrid and electric vehicles. Oladosu et al. [214] focused on AI-based energy management systems (EMS) in Hydrogen Fuel Cell Electric Vehicles (HFCEVs), where reinforcement learning and genetic algorithms were highlighted as having the potential to significantly enhance fuel efficiency. Projections suggest achieving \$30/kW power by 2050 and a power density of 3 kW/L. In a similar vein, Hu et al. [215] examined reinforcement learning-based EMS in Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Electric Vehicles (FCEVs), finding that optimization of perception granularity and reward functions contributed to an increase in fuel efficiency and SOC performance by as much as 10%. The use of Artificial Neural Networks (ANN) in Hybrid Electric Vehicles (HEVs) by Kalaivani and Joice [216] led to a reduction in hydrogen consumption between 2.4% and 6.7%, with SOC maintained in the range of 62%–68%. In another study, Singh et al. [217] evaluated an ANN-based system for integrating solar and fuel cells in electric vehicles, achieving voltage stability at 430V and optimized

SOC performance. Saleem et al. [218] implemented ANN and Super Twisting Sliding Mode Control (STSMC) in PHEVs, enhancing power management efficiency, validated by Lyapunov analysis. This approach reduced transient response error by 15% and improved SOC by 8%. Gao et al. [211] proposed a Model Predictive Control (MPC) strategy combined with Pontryagin's Maximum Principle for FCHEVs, resulting in a reduction in hydrogen consumption by 8.44% and an improvement in fuel cell durability. Similarly, Liu et al. [212] utilized MPC along with deep learning techniques to optimize PEMFC performance, resulting in a 109.53% increase in efficiency and a 13.56% reduction in hydrogen consumption. Khan et al. [213] investigated machine learning techniques in microgrids and electric vehicles, focusing on AI's ability to optimize energy management, though specific numerical data were not provided. Sheeja et al. [214] introduced an AI-based braking system for electric vehicles, which improved energy recovery and overall efficiency, while Musa [215] explored AI control strategies in both Hybrid Electric Vehicles (HEVs) and Battery Electric Vehicles (BEVs), where reductions in energy consumption and extensions of battery lifespan were achieved through the application of reinforcement learning (RL), LSTM, and GRU models. A summary of the applications of AI techniques for various types of vehicle are presented in Table 6.

5. Major challenges and future directions

The broader adoption of Fuel Cell Hybrid Electric Vehicles (FCHEVs) is hindered by several major challenges that must be overcome to ensure widespread market acceptance and long-term viability. The primary obstacles include high hydrogen production costs, the need for improved fuel cell durability and lifespan, and the development of a comprehensive hydrogen infrastructure. Addressing these challenges requires targeted research, development, and cooperation among industry, academia, and government sectors. Future efforts should also address public awareness and acceptance of hydrogen technologies.

5.1. Reducing hydrogen production costs

One of the biggest hurdles for FCHEV adoption is the high cost of hydrogen production. Making hydrogen more affordable is essential to position it as a viable alternative to conventional fuels. Advancements in production methods, particularly electrolysis using renewable energy, hold promise for reducing costs. Pei and Chen [216] emphasize the importance of ongoing research into factors affecting Proton Exchange Membrane (PEM) fuel cell longevity and the influence of hydrogen production costs on fuel cell efficiency. Developing more cost-effective and efficient hydrogen production technologies is crucial for the success of FCHEVs in the long term.

5.2. Enhancing fuel cell durability and lifespan

The reliability and cost-effectiveness of FCHEVs depend significantly on the durability and lifespan of their fuel cells. Progress in materials science and engineering is essential to improve fuel cell performance and longevity. Yue et al. [217] review strategies and models for energy management in fuel cell hybrid electric vehicles, highlighting the need to address fuel cell degradation. Research into new materials and innovative design approaches could lead to substantial gains in fuel cell durability, thereby reducing the overall ownership costs of FCHEVs.

5.3. Building a comprehensive hydrogen infrastructure

Creating a robust hydrogen infrastructure is another crucial challenge. A widespread network of hydrogen refueling stations is necessary to support the extensive use of FCHEVs. Investments in infrastructure, coupled with advancements in hydrogen storage and distribution technologies, are required to establish a reliable and accessible refueling network. This infrastructure development is vital to solving the

Table 6
Summary of the applications of AI techniques for various types of vehicle.

Author(s)	Vehicle Type/ Technology	AI Technique Used	Key Findings	Numerical Results
Oladosu et al. [214]	HFCEV (Hydrogen Fuel Cell Electric Vehicle)	Reinforcement learning, genetic algorithms	AI-based EMS algorithms improve fuel economy and performance, multi-objective algorithms show potential.	Efficiency predictions: $30/kW power by 2050, 3 kW/L power density.
Hu et al. [215]	PHEV and FCEV	Reinforcement learning, deep reinforcement learning	Off-policy RL-based EMS improves fuel economy, perception granularity optimization reduces energy consumption.	Improved fuel efficiency and SOC performance by up to 10%
Kalaivani and Joice [216]	HEV (Hybrid Electric Vehicle)	ANN (Artificial Neural Network)	ANN-based EMS reduces hydrogen consumption by 2.4%–6.7%, SOC maintained between 62% and 68%.	Hydrogen consumption reduced by 10g–100g during testing.
Singh et al. [217]	Electric Vehicle (EV)	Artificial Neural Network (ANN), Bi-directional converters	Efficient power management through ANN-based system for solar and fuel cell integration.	Maintained voltage stability at 430V, optimal SOC performance
Saleem et al. [218]	PHEV	ANN, Super Twisting Sliding Mode Control (STSMC)	Enhanced power management efficiency through ANN, stability validated via Lyapunov analysis.	Reduced transient response error by 15%, SOC improved by 8%
Gao et al. [211]	FCHEV	MPC, Pontryagin's Maximum Principle	Improved fuel cell efficiency by reducing hydrogen consumption by 8.44% using predictive control.	Hydrogen consumption reduced by 8.44%, enhanced durability of fuel cells
Liu et al. [212]	FCHEV	Model Predictive Control (MPC), LSTM deep learning	Optimization of PEMFC efficiency by 109%, reducing hydrogen consumption by 13.56%.	PEMFC efficiency improved by 109.53%, reduced hydrogen consumption by 13.56%
Khan et al. [213]	Microgrid, Electric Vehicle (EV)	Machine Learning (ML)	AI techniques optimize energy management, reducing uncertainties in power load management.	Efficiency improved, but no specific numerical data provided
Sheeja et al. [214]	Electric Vehicle (EV)	AI-based braking system optimization	AI-enhanced braking system increases energy recovery and efficiency.	Improved energy recovery by an unspecified amount

(continued on next page)

Table 6 (*continued*)

Author(s)	Vehicle Type/ Technology	AI Technique Used	Key Findings	Numerical Results
Musa [215]	HEV, BEV	RL, LSTM, GRU	AI-based control strategies enhance fuel economy and operational efficiency, trajectory optimization reduces energy consumption.	Energy consumption reduced significantly, battery lifespan extended

"chicken-and-egg" problem of insufficient refueling stations and limited vehicle availability.

5.4. Fostering collaboration and innovation

Addressing these challenges demands collaboration between industry, academia, and government. Joint research initiatives can foster innovation in fuel cell technology, hydrogen production, and infrastructure. Hanley et al. [218] discuss the role of hydrogen in low-carbon energy futures and stress the importance of interdisciplinary cooperation to advance hydrogen technologies. By pooling knowledge, resources, and expertise, stakeholders can accelerate progress toward sustainable transportation solutions.

5.5. Increasing public awareness and acceptance

Public awareness and acceptance are key to the successful adoption of FCHEVs. Gu et al. [219] examine public perceptions of hydrogen and fuel cell vehicles in China, underscoring the need for enhanced education and outreach efforts. Building public trust in hydrogen technologies through awareness campaigns, educational initiatives, and demonstration projects can help mitigate skepticism and create a more favorable market environment.

5.6. Future research directions

Future research should focus on several critical areas to overcome the challenges facing FCHEVs.

- Advanced Materials: Develop new materials for fuel cells that offer improved performance, durability, and cost-effectiveness.
- Hydrogen Storage Solutions: Innovate hydrogen storage technologies to enhance capacity and reduce refueling times.
- Energy Management Systems: Investigate advanced energy management strategies to optimize fuel cell performance and vehicle efficiency.
- Infrastructure Development: Promote research and investment in hydrogen refueling infrastructure to build a comprehensive and accessible network.

6. Conclusions

Fuel Cell Hybrid Electric Vehicles (FCHEVs) represent a critical step toward achieving cleaner and more sustainable modes of transportation. By integrating hydrogen fuel cells with electric vehicle technologies, FCHEVs stand as a promising alternative to traditional internal combustion engine vehicles. Their unique combination of zero-emission hydrogen power and the high efficiency of electric drivetrains positions FCHEVs as key players in reducing the automotive sector's environmental footprint. Compared to ICE vehicles, FCHEVs can cut greenhouse gas emissions by as much as 40–50%, offering a tangible solution to combat climate change.

6.1. Current advancements and status

Recent technological advancements have significantly improved the fuel economy and performance of FCHEVs. For example, innovations in catalyst materials and energy management systems have boosted fuel cell efficiency by 10–15%, while new hydrogen storage methods, such as metal hydrides, have increased storage capacity by 20%. As a result, FCHEVs are now capable of covering over 400 miles per hydrogen fill, a notable 25–30% improvement over many battery electric vehicles (BEVs). Additionally, manufacturing advancements have contributed to a 30% reduction in fuel cell production costs, moving FCHEVs closer to mass-market viability.

6.2. Ongoing challenges

Despite these achievements, there are several key challenges that need to be addressed for FCHEVs to gain widespread acceptance.

- **Cost Reduction**: The cost of fuel cells remains relatively high at around $60 per kW, whereas battery systems cost approximately $45 per kW. Furthermore, hydrogen production—especially from renewable sources—still adds about 15% to the overall vehicle cost. Reducing these costs by 20–30% is essential to make FCHEVs more competitive in the market.
- **Durability and Reliability**: Fuel cells typically last for 5000–8000 h, which is considerably shorter than the 15,000-h lifespan of internal combustion engines. Improving fuel cell durability by 30–50% is a major focus of current research to enhance vehicle longevity.
- **Infrastructure Development**: Currently, fewer than 500 hydrogen refueling stations exist worldwide, compared to more than 1 million EV charging stations. Expanding the global hydrogen refueling infrastructure by 500–700% by 2030 will be crucial for the widespread adoption of FCHEVs.

6.3. Future outlook

The future for FCHEVs appears bright, with global sales expected to reach 1.2 million units annually by 2030, representing a 10-fold increase from current levels. However, for FCHEVs to achieve this growth, it will be necessary to address critical challenges such as hydrogen production costs and the scaling of refueling infrastructure. If these hurdles are overcome, FCHEVs could account for 15–20% of the global vehicle market by 2040.

6.4. Technological innovation

Further advancements in FCHEV technology are key to improving both performance and cost-effectiveness. Researchers are focusing on increasing fuel cell power density by 20%, reducing the weight of hydrogen storage systems by 15%, and improving energy management systems to cut hydrogen consumption by 10–15%. Collaboration between industry, academia, and government is essential to drive these innovations forward, ensuring that FCHEVs can compete effectively with BEVs and internal combustion vehicles.

6.5. Supportive policies

Government policies will play a pivotal role in the adoption of FCHEVs. Financial incentives, such as tax credits and subsidies, could lower consumer costs by 15–20%. Moreover, global investments in hydrogen infrastructure, projected to require over $70 billion by 2030, will be crucial for enabling widespread FCHEV use. Policies promoting clean energy and zero-emission vehicles will create a favorable environment for FCHEVs to thrive.

6.6. Collaborative efforts

Collaboration between different stakeholders—including industry players, researchers, and policymakers—will be crucial in overcoming the barriers to FCHEV adoption. Working together could lead to a 20% reduction in hydrogen production costs and a 25% improvement in fuel cell efficiency, helping to unlock the full potential of FCHEVs. Such efforts will drive innovation and contribute to a more sustainable and efficient transportation sector, with the potential to cut global vehicle emissions by 50% by 2050.

6.7. Environmental impact and sustainability

FCHEVs offer substantial potential to reduce the environmental impact of transportation. They produce no tailpipe emissions, which could lead to a 40% reduction in CO2 emissions when compared to traditional internal combustion vehicles, especially if hydrogen is produced using renewable energy. Fuel cells are also highly efficient, converting 60–70% of the energy in hydrogen into useable power, significantly higher than the 20–25% efficiency of conventional engines. By promoting the widespread adoption of FCHEVs, the transportation sector could achieve a 30–40% reduction in emissions over the next two decades.

6.8. Future research directions

Future research should continue focusing on several key areas to further optimize FCHEV technology.

- **Hydrogen Production**: Finding more cost-effective and sustainable ways to produce hydrogen, such as renewable-energy-driven electrolysis, could reduce costs by 15–20%.
- **Fuel Cell Materials**: Developing new catalyst materials that reduce reliance on platinum could lead to a 25–30% decrease in fuel cell production costs.
- **Energy Storage**: Further advancements in hybrid energy storage systems, combining ultracapacitors with fuel cells, could boost overall energy efficiency by 10–15%, enabling longer vehicle ranges.

6.9. Comparative studies and global impact

Comparative studies show that FCHEVs offer clear advantages over BEVs in terms of refueling time and driving range. FCHEVs can travel over 400 miles on a single fill-up, while BEVs typically have ranges of 250–300 miles. Moreover, refueling an FCHEV takes just 3–5 min, compared to the 30 min to several hours required to recharge a BEV. This makes FCHEVs particularly well-suited for long-haul transportation and commercial fleets. Widespread adoption of FCHEVs in these sectors could reduce heavy-duty vehicle emissions by 25–30% by 2035.

6.10. Economic considerations

The economic feasibility of FCHEVs depends on reducing fuel cell and hydrogen production costs. Current estimates suggest that hydrogen fuel prices could drop to $3 per kilogram by 2030, making FCHEVs more competitive with gasoline-powered vehicles. Additionally, as economies of scale are achieved, FCHEV production costs are expected to fall by 30–40%, making them more accessible to the general public.

CRediT authorship contribution statement

Hussein Togun: Writing – review & editing, Writing – original draft, Supervision. **Hakim S. Sultan Aljibori:** Conceptualization. **Azher M. Abed:** Data curation. **Nirmalendu Biswas:** Writing – review & editing, Writing – original draft. **Maher T. Alshamkhani:** Formal analysis. **Hakeem Niyas:** Funding acquisition. **Hayder I. Mohammed:** Funding acquisition. **Farhan Lafta Rashid:** Writing – review & editing, Writing – original draft. **Jameel M. dhabab:** Methodology. **Dipankar Paul:** Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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