

Review

Review and Outlook of Fuel Cell Power Systems for Commercial Vehicles, Buses, and Heavy Trucks

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Abstract

The power system, which is also one of the most crucial parts of fuel cell cars, marks the biggest distinction between them and conventional automobiles. Fuel cell hybrid power systems are reviewed in this paper along with their current state of research. Three different kinds of fuel cell hybrid power systems—fuel cell–battery, fuel cell–supercapacitor, and fuel cell–battery–supercapacitor—are thoroughly compared and analyzed, and they are systematically explained in the three areas of passenger cars, buses, and heavy duty trucks. Existing fuel cell hybrid systems and energy strategies are systematically reviewed and summarized, including predictive control strategies based on game theory, power allocation strategies, fuzzy control strategies, and adaptive super twisted sliding mode control (ASTSMC) energy management techniques. This study offers recommendations and direction for the future direction of fuel cell hybrid power system research and development.

Keywords: fuel cell; mechanical system; energy management strategy; commercial vehicles; town bus; heavy truck



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1. Introduction

The Fuel Cell Electrical Vehicle (FCEV) is a new energy vehicle powered by an electric motor. This fuel cell technique directly produces electricity from the chemical energy of hydrogen and oxygen fuels [1–3]. Currently, single fuel cell drive and fuel cell + auxiliary energy hybrid drive are the two types of primary power systems that are utilized most often in fuel cell automobiles. In contrast to a single battery system based on fuel cells, a system of hybrid electricity that combines both a fuel cell and battery may successfully avoid the consequences of the fuel cell's poor performance. Vehicles that use fuel cells have obvious inherent technological advantages in terms of environmental protection, range, and power. Compared to battery technology, fuel cell (FC) technology is a promising solution to accelerate electrification and achieve zero emissions in heavy duty vehicles (HDVs), medium-duty vehicles (MDVs), and other vehicle segments. Compared to lithium-ion batteries, FCs are remarkably scalable in the sense of energy and power. This may be accomplished through enlarging the hydrogen tanks and fuel cell stack, respectively, with far less extra weight loss to vehicle performance (such as driving range) [4,5]. Compared to pure electric vehicles (BEVs), FCEVs can have a longer range due to the lighter weight and greater energy density of the FC stack. In addition, FCEVs score points for their much shorter refueling time than BEVs. When an FCEV is refueled, hydrogen is injected into an onboard

high-pressure hydrogen tank, which typically takes 3–5 min for light-duty vehicles (LDVs) and 10–15 min for HDVs. As a result, FCEV consumption is comparable to that of traditional internal combustion engine automobiles [6]. When compared to other vehicle types, such as plug-in hybrids, pure electric cars, and conventional internal combustion engines, it is very competitive. Nevertheless, fuel cells include several disadvantages, including sluggish cold start, inadequate dynamic characteristics, and the incapacity for regenerative braking energy recovery. Fuel cell systems (FCS) also have to deal with performance decline and a short lifespan. Gradual performance degradation occurs during long-term operation due to deterioration of the electrode materials, catalyst loss, mechanical damage to membrane electrode modules, and variations in operating circumstances, including temperature, humidity, load fluctuations, etc. In addition to lowering the FC's output power and power production efficiency, such performance deterioration also decreases its service life and significantly raises maintenance and replacement expenses. It has been shown that the combined impacts of complicated operating circumstances and component aging causes the performance of the proton exchange membrane fuel cell (PEMFC) to steadily deteriorate to the lowest tolerable level [7]. In order to effectively slow down performance deterioration and prolong service life, innovative forecasting and health management approaches may be used for real-time monitoring and active intervention of FC's condition. The appropriate alignment of FC vehicle power system parameters and energy management methods may facilitate the coordinated operation of key power system components, enhancing the vehicle's economic performance while ensuring that its dynamic requirements are satisfied [8]. Based on technological reasoning, energy management strategies (EMS) for fuel cell hybrid power systems may now be divided into the following three primary groups: learning approaches, optimization methods, and rule-based strategies. Rule-based methods, such as fuzzy logic control and logic threshold strategies, which have straightforward structures and good real-time performance but little strategic flexibility, accomplish power allocation by presetting logical thresholds or empirical rules. Optimization techniques, such as dynamic programming (DP), model predictive control (MPC), equivalent consumption minimization strategies (ECMS), etc., use mathematical models to optimize energy allocation either locally or globally. While these techniques can produce more accurate energy allocation, some algorithms suffer from high computational complexity. Reinforcement learning (RL), neural networks (NN), heuristic optimization algorithms, and other data-driven or intelligent algorithms are examples of learning methods that automatically optimize strategies. These methods are appropriate for complex dynamic scenarios and can enhance strategy performance through autonomous learning. These three categories of strategies align with the technological instances in the paper's later chapters, providing a theoretical framework for methodically organizing the current research environment and evaluating the strategies' benefits.

Contemporary fuel cell power systems often include several power sources that form hybrid power systems, including FC–battery hybrids, FC–supercapacitor (SC) hybrids, and FC–battery–SC hybrids [9]. These include the FC–battery hybrid system, which uses the battery as an auxiliary energy source and has a high energy density but a slow dynamic response, making it suitable for continuous power output scenarios in passenger cars and buses; the FC–SC hybrid system, which uses the SC's fast charging and discharging characteristics and has a low energy density and a fast dynamic response, making it more appropriate for heavy trucks and other working conditions that require transient high power output; and the three-source hybrid system, which combines the benefits of both the battery and the SC by using the SC to protect the battery and enhance the efficiency of braking energy recovery. The three-source hybrid system combines the benefits of a storage battery and an SC. It can use the SC to protect the storage battery and increase

the efficiency of braking energy recovery, in addition to providing stable power through the storage battery. However, the system is more expensive and has a complex structure, making it appropriate for heavy vehicles with stringent energy management requirements. Every system powered by fuel cells is divided into three groups of passenger cars, buses, and heavy trucks, and the current research status of each type and its energy strategy are systematically discussed. According to the bus connection method, fuel cell hybrid electrical systems may be classified into direct and indirect types, whose structures are shown in Figure 1 [10]. The direct type omits the DC/DC converter, directly linking the fuel cell system to the bus, ensuring simplicity, cost-effectiveness, and excellent dependability. Nonetheless, the total performance is impacted by the voltage differential between the FCS and the bus. Meanwhile, this structure is unable to perform the hybrid system's distributing power, which does not facilitate the application of energy management strategies [11,12]. The indirect structure uses a converter to link the FCS to the bus, permitting the FCS's output voltage to surpass the bus voltage, thereby decoupling the terminal voltages among the composite energy source, the load, and the three components, facilitating optimal power distribution through an energy management strategy. Furthermore, power allocation is executed according to the features of the various sources of energy, enhancing both energy utilization efficiency and the operational performance of the energy sources. The drawbacks of the indirect type encompass increasing the DC/DC converter, increasing system cost, and increasing a certain amount of energy consumption; the complexity of the hybrid system escalates, necessitating more stringent criteria for the control approach.

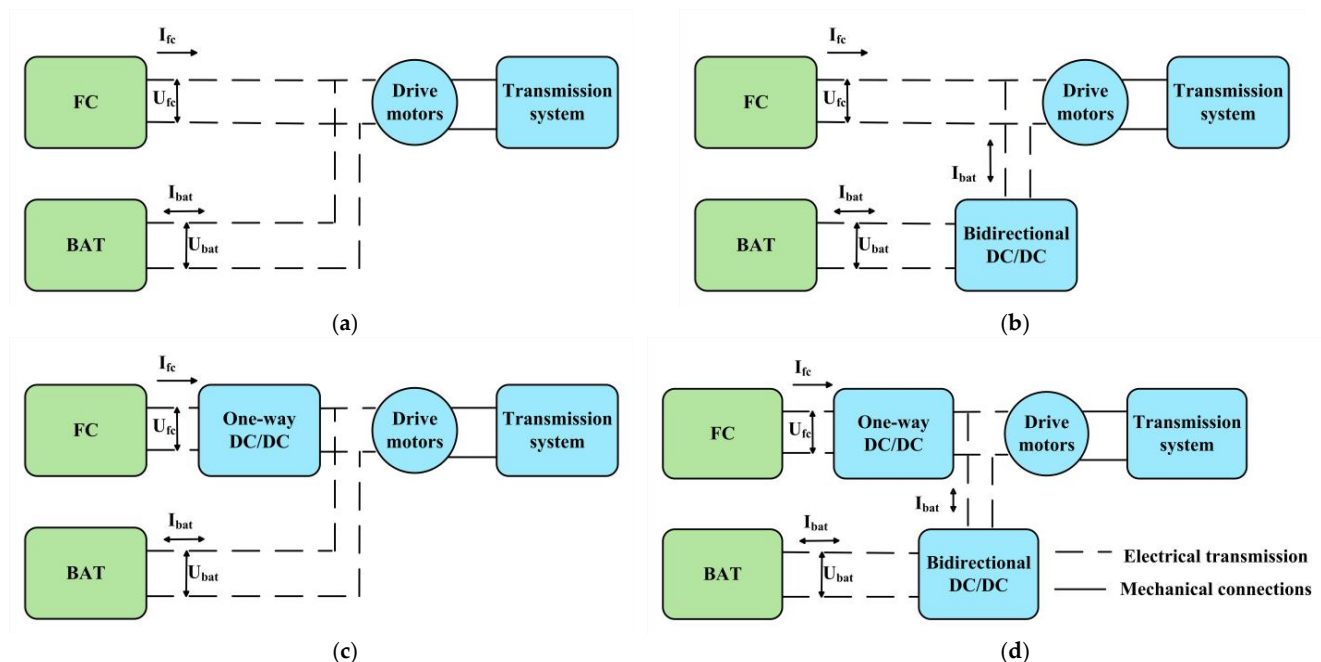


Figure 1. Fuel cell hybrid system structure with different connections: (a) Direct A; (b) Direct B; (c) Indirect A; (d) Indirect B.

The fuel cell power system's motor is a component of the core actuator at the power output end and is the final link in the cycle of energy transfer. The motor is a rotating electromagnetic machine that operates by applying the principle of electromagnetic induction, and it is used to facilitate the transformation of electrical energy into mechanical energy. During operation, it transforms electrical energy into mechanical energy by pulling it from the electrical system for the mechanical system. The motor drive system primarily consists of a motor, controller (inverter), drive motor, and motor controller. They account for the cost ratio of about 1:1. Based on design principles and classifications, the motor's particular

construction and composition costs also change. The motor's control system primarily functions to regulate its working condition, therefore accommodating the many operational needs of the vehicle. For different types of motors, the principles and methods of control systems are very different. The motors in fuel cell vehicles undertake the task of driving the vehicles. Therefore, the drive motors must be able to respond quickly, have a wide speed range, have a large starting torque, have a high backup power, and be efficient. They must also be highly reliable, resistant to high temperatures and moisture, have a simple structure, be inexpensive, require little maintenance, and be suitable for mass production. Permanent magnet synchronous motors, switching reluctance motors, DC motors, and AC asynchronous motors are the primary driving motor types that may be used in fuel cell cars. There are several types of drive motors that can be used in fuel cell vehicles, including DC, alternating current asynchronous, permanent magnet synchronous, and switching reluctance motors. Of these, the most common types of motors are permanent magnetic synchronous and AC asynchronous, while amorphous and memory motors are still being researched. As a relatively mature technology, we do not go into the details of drive motors in this paper.

Currently, there is a large range of literature about fuel cell hybrid power systems and energy plans, but there are no publications that summarize the current status of their research. This study aims to address this requirement by concentrating on three different kinds of papers, experimental, simulation, and prototype. It also provides a systematic assessment and summary of existing hybrid power plants powered by FCs and energy strategies, as well as recommendations for further study and development trends. In this study, there are two types of FC power systems, direct and indirect. Indirect FC power systems and their energy methods are reviewed in this research, which also breaks them down into the three categories of FC–SC, FC–battery, and FC–battery–SC hybrid power systems. Each system is discussed as per the three categories of passenger cars, buses, and heavy trucks, and the particular categorization is seen in Figure 2. Using topology as the main classification criteria, this study analyzes the research on fuel cell hybrid power systems. In addition to determining the system's energy flow paths and component synergy logic, topology also closely matches the operating circumstances of different vehicle types, including buses, heavy duty vehicles, and passenger automobiles. Moreover, topological categorization serves as a foundational framework in this field of study, facilitating the methodical arrangement of technical advancements and providing a distinct standard for further comparative evaluations. At the same time, the topological classification facilitates the systematic arrangement of technological lineage, provides a clear comparative standard for further analysis, and illustrates the technological characteristics and application differences of each topology, all of which form the basis of field research. These devices can be categorized using a variety of models based on basic differences in their technical specifications and operating characteristics. The primary purpose of passenger cars is urban commuting; they must accelerate from 0 to 100 km/h in 8–10 s, have a range of 500–800 km, and have a short refueling time. The power system's lightweight design must meet strict power density requirements, and the appropriate strategy must maximize energy efficiency to balance the demand for range through power allocation; buses stop and start more than 200 times a day, and more than 30% of their energy is recovered during braking. The braking energy recovery accounts for over 30% of the average daily starting and stopping time of buses, and fixed route operation must consider the fuel cell's resistance to frequent starting and stopping attenuation. The corresponding strategy increases the energy recovery efficiency in starting and stopping conditions by optimizing speed and adjusting power allocation beforehand. Heavy trucks have a lengthy operating cycle, a power requirement of over 300 kW, and a range of 800–1500 km, which necessitates a high energy

density. Their aim is to increase the energy recovery efficiency in heavy load conditions by reducing power fluctuation and maintaining multi-objective optimization. The strategy's multi-objective optimization and power fluctuation limitation increase system endurance in demanding environments. This serves as the rational foundation for the vehicle-type debate.

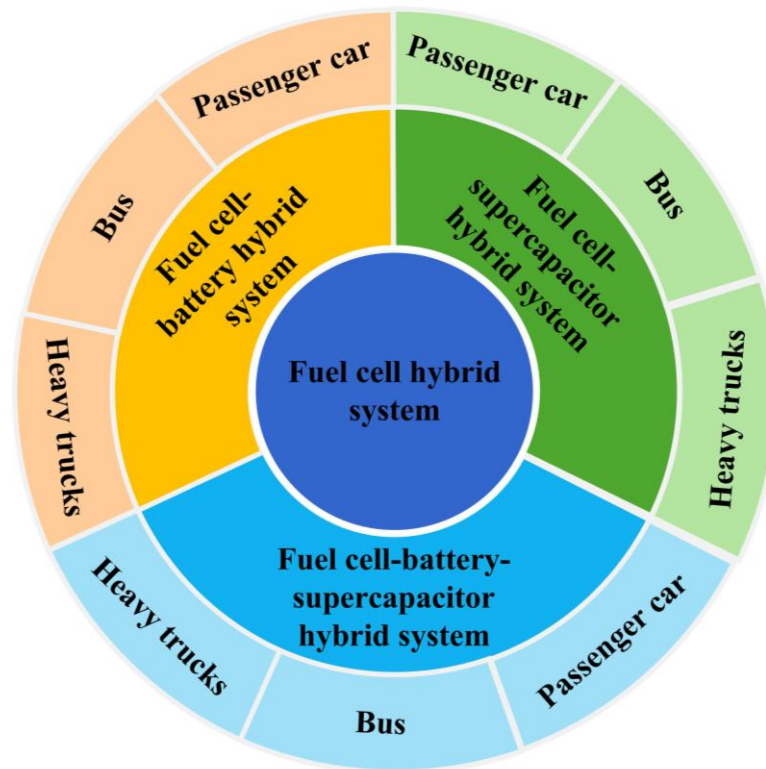


Figure 2. Classification of fuel cell hybrid systems.

2. Fuel Cell–Battery Hybrid System

In Figure 3, the FC–battery hybrid system's construction is shown. Initially, upon activation of the FC hybrid vehicle, the battery supplies energy because the fuel cell system takes a long time to start up. During operation, when power demand is substantial, both the battery and fuel cell can operate concurrently. This combined output diminishes the fuel cell's workload, allowing it to function within its optimal range and enhancing its fuel utilization efficiency [13]. During braking, the battery may recuperate energy to compensate for the fuel cell's inability to recover energy. However, in this structure, although the battery stores a lot of energy, but its regulating ability is limited, the battery will inevitably be affected by the impact of high-current shock when it recovers energy under braking, and its frequent use will greatly decrease the battery's lifespan.

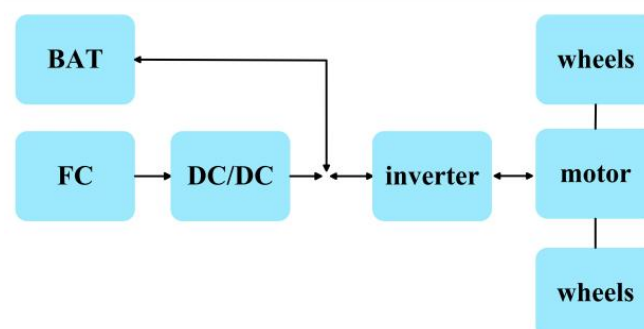


Figure 3. Structure of the indirect fuel cell–battery hybrid system.

2.1. Passenger Cars

Chatterjee et al. [14] suggested a hybrid vehicle bidirectional long short-term memory (Bi-LSTM) model built on an effective EMS. A core function of this EMS involves the real-time acquisition of critical data such as vehicle speed, driver commands, battery state of charge (SOC), engine load, and environmental factors. Based on the continuous monitoring and analysis of these parameters, the system dynamically optimizes power distribution strategies and intelligently selects the most appropriate operating mode. The suggested methodology exhibits enhanced energy efficiency and less environmental impact relative to traditional EMS methods. Insights are offered about the viability of using intelligent EMS techniques to enhance sustainability and efficiency in contemporary energy-efficient settings.

Xu et al. [15] formulated an extensive transient simulation of a battery–fuel cell hybrid drivetrain to examine the output performance and dynamic responsiveness imagining a vehicle powered by fuel cells. The comprehensive capabilities under various typical Chinese normal vehicle driving conditions were examined. The power-following energy management technique was shown to save more energy throughout the vehicle and enabled the FC to operate for an extended amount of time compared to the rule-based energy management approach.

Chen [16] achieved reasonable control of DC/DC duty cycle by designing a reasonable and effective power allocation strategy in order to optimize energy management through control to increase the power system's energy utilization rate, minimize energy loss on the DC/DC converter to minimize energy loss on the lithium battery's reverse charging time and frequency, and achieve reasonable regulation of the FC power output. This allows the electric stack and lithium battery's power output to be controlled close to the desired value without compromising vehicle dynamics. As a result, it is possible to increase the longevity of important power system components and prolong the lifespan of FCs and lithium batteries.

Wang [17] established a mathematical description of the energy optimization problem for the energy management problem of a fuel cell hybrid vehicle and introduced the Pontryagin's minimum principle to solve the optimization problem. An adaptive energy management strategy with the EMS of PMP as a framework was established, and its adaptivity was reflected in the dynamic updating of the co-state variables, which did not use a single co-state variable during the driving process but performed the search of the optimal co-state variables and kept adjusting adaptively according to the working conditions.

A residual lifetime model for FC and batteries in terms of declining in performance was introduced by Feng et al. [18] in the optimization model-based EMS. A flexible balanced equivalent consumption minimization strategy (BCMS) was then used to minimize the total price by accounting for hydrogen consumption, FC, and batteries.

Zhou [19] extended the FC lifespan using a long-term energy management technique that included a reinforcement learning algorithm; nevertheless, the optimization goal did not include energy usage. Meng [20] suggested a dual-q learning-based energy management approach to maximize FC electric cars' total energy use. Yavasoglu [21] suggested an algorithm for machine learning using NN for dual-motor power systems based on FC, batteries, and supercapacitors (SCs) in order to appropriately divide the power between the propulsion engine and technique for storing hybrid energy [22].

Zhou [23] suggested using a profound gradient of deterministic policy to create a self-optimizing power matching technique that takes battery deterioration and energy efficiency into account. This approach enables the hybridization-optimized FCEV powertrain to achieve extended battery and FC life and reduced energy usage.

Ma et al. [24] used a dual-winding motor that was directly powered by the energy source (ES) via an inverter. To save money and energy, the DC/DC converter was taken out of the powertrain. The link between EMS and hybrid energy selection (HESS) was addressed via a two-loop optimization technique. The outer loop optimization used particle swarm optimization to determine the ideal ES size. To find the ideal energy distribution among ESs, the inner loop optimization process used dynamic programming. When comparing the optimized powertrain based on dual-winding motors to the widely used DC/DC converter-based powertrain, the former had reduced production costs and fuel usage.

Ettahir [25] presented an EMS for fuel cell hybrid electric vehicles (FC-HEV). This paper's goal is to make sure that the battery and FC system match while taking the FCs' operating circumstances into account. This study used the adaptive recursive least squares (ARLS) approach to look for models online in order to discover modifications to FCs' performance. The optimal efficiency and power operating point was then determined by applying an optimization algorithm to the modified model. For FC-HEVs, this procedure was used for optimum EMS based on Pontryagin's minimal concept. By examining two FCs with varying degrees of deterioration, the efficacy of the suggested EMS is shown. Wang [26] explained a power management approach that considers fuel use, battery and fuel cell deterioration. By taking into account performance losses brought on by transient electrical loads, start/stop cycles, idling, and high-power loads, a simplified electrochemical model that offers an analytical solution for electrochemical surface area (ECSA) degradation in fuel cells is used to quantify fuel cell deterioration. Ou [27] created a powerful and very effective operating system for a polymer electrolyte membrane (PEM) FC/battery hybrid. The DC/DC step-down converter's power distribution properties and hybrid connection provide the whole system with a quick dynamic reaction. Bendjedia [28] conducted a comparative study on the performance of different energy management strategies for supplying hybrid energy storage sources to electric vehicles and developed a new online strategy to improve the fuel consumption and the lifetime of the hybrid power source.

2.2. Buses

Han [29] established the convex optimization approach and the power-following approach and confirmed them. The imprecise control regulations were used in the creation of the power following energy management approach, and the convex optimization model was established using the M function according to the best parameter matching results of convex optimization. Calculations were used to examine power battery SOC variations, power battery and fuel cell output power variations, and power distribution under various operating circumstances. The economy of fuel cell buses under different strategies was comparatively analyzed. The findings demonstrated that the convex optimization strategy, which was developed based on actual vehicle construction conditions, clearly outperformed the power following energy management strategy about comparable hydrogen consumption and is capable of successfully resolving the start-stop issue with fuel cell systems. Through the convex optimization strategy, the SOC of the power cell can be adjusted from different initial states to the desired range and finally stabilized within the desired range, and the magnitude of the fluctuations is smoother than using the power-following controlling energy approach. In the meanwhile, the control strategy's equivalent hydrogen consumption will be significantly impacted by the change in the initial SOC.

Wang [30] suggested using the electricity requirement of the vehicle and the cell SOC from the previous control cycle to anticipate the FC's target power in the current control cycle using a predicted half-power power distribution system technique. This

control strategy was compared and examined using SOC's gradual control strategy under C-WTVC operating conditions, as seen in Table 1.

Table 1. Comparison of different strategies on vehicle performance parameters under C-WTVC conditions.

Vehicle Performance Parameters	Stepped Control Strategy for SOC	Half-Power Prediction Energy Management Strategy
Hydrogen energy (kW/h)	68.43	45.84
FC power (kW/h)	35.34	25.16
Battery discharge energy (kW/h)	34.16	37.33
Battery charging energy (kW/h)	−43.37	−36.75
Fuel economy (kg/100 km)	3.72	3.50
Battery cycle time per 100 km	1.16	1.11

The vehicle's fuel efficiency was estimated to be 3.72 kg/100 km utilizing SOC's graduated control approach and 3.50 kg/100 km with the half-power predictive energy management strategy. In comparison to the SOC's stepped control strategy, the car used 5.9% less hydrogen every 100 km. The half-power predictive control technique enabled rapid adjustment of the FC's target power in accordance with the driving cycle instead of depending only on the state of charge for battery charging, thereby lessening the need for the power source. Furthermore, FC's operational point can be adjusted to the high-efficiency range, hence enhancing power production efficiency and decreasing hydrogen consumption. Both the predictive half-power controlling energy method and SOC's stepped control technique have cycle times of 1.11 and 1.16 every 100 km in the driving cycle of an urban bus route, respectively. The battery's lifespan increases with a reduced cycle time. The battery's cycle time per 100 km drops by 4.3% in the half-power predictive EMS compared to the stepped control strategy of the SOC. Therefore, the battery life is longer in the half-power predictive energy management strategy compared to the stepped control strategy of the SOC.

Guo [31] suggested an innovative energy management system for FC engines that incorporates intersection speed planning and mitigates frequent load variations during operation. The primary benefits of this energy management include enhancing the efficiency of road transportation, advancing the objective of reducing hydrogen use, and prolonging the lifespan of the FC engine. The intersection speed planning approach, based on DP, incorporates data on cars preceding the travel path and the state of traffic signals. With intersection speed planning, when the bus is 100 m from the traffic signal, the relevant control variables are implemented for energy management using MPC. Simulation findings indicate that comparable hydrogen savings may be enhanced by about 3.04%, with a 3.4% decrease in idle operational situations, when compared to MPC-based energy management lacking junction speed planning. Hardware-in-the-loop experiments demonstrate that the vehicle speed can accurately track the intended speed, with the corresponding hydrogen consumption error remaining within 2.5%, meeting the permissible error threshold.

A novel cost reduction energy management technique was presented by Jia et al. [32] in order to fully leverage the economic potential of FC hybrid buses. For the first time, the optimization framework incorporated thermal safety and the on-board LIB system's deterioration awareness, and energy durability and hydrogen mass consumption were weighed through fuel cell aging suppression. Furthermore, to increase the forecast accuracy for upcoming driving situations, an improved online self-learning stochastic Markov predictor was suggested in the speed prediction step. Lastly, a comparison was made to verify the effectiveness of the recommended strategy. According to the data, the suggested

approach lowers the overall running cost by 12.3% and the battery aging rate by 34.8% when compared to the method that ignores overheating prevention.

To enhance the performance of energy and heuristic strategies of the current power-train systems used in complicated transit situations in fuel cell hybrid buses, Z Liang [33] suggested an energy management system in real time and a monitoring framework. Specifically, dynamic programming was applied online at cloud level to find the optimal energy management strategies from real cycles based on a monitoring platform. Furthermore, results from simulations and experiments demonstrated that the suggested framework could improve the economic performance of the intended vehicle. In summary, in comparison to the rule-based approach, the amount of hydrogen used decreased from 2.47 kg to 1.97 kg. Regarding the amount of energy used, the online optimization could reduce it to 27.64 kWh, which is 10.28% in CWTVC. Thus, the real-time energy management and monitoring framework has a better energy saving potential compared to the conventional strategy on buses that employ fuel cell hybrids.

He et al. [34] suggested a novel approach to power allocation that minimizes costs while including FC/battery health-aware management to maximize the financial potential of FC/battery hybrid buses. In an effort to reduce the time required to obtain essential lifespan metrics, the suggested framework used a long short-term memory (LSTM) network to quantify FC deterioration over the full working region in a genuine hybrid electric bus. Jia et al. [35] suggested an energy management plan that took into account air conditioning control, considered on-board energy health awareness, combined cockpit comfort with FC/battery durability control to reduce overall vehicle operating costs while maintaining cockpit comfort, and used the most advanced dual-delay deep deterministic policy gradient algorithm to enhance the EMS's training efficiency and optimization capabilities in order to attain the best possible power allocation. Liu et al. [36] developed a stability analysis-based real-time nonlinear adaptive control (NAC) and assessed the effectiveness of the NAC-based strategies using two real-time power management strategies, state machine control (SMC) and fuzzy logic control (FLC).

2.3. Heavy Trucks

Mei [37] introduced a load recognition algorithm to optimize the braking energy recovery control strategy and created a comprehensive gearshift control technique for fuel cell heavy truck design and operation that optimizes energy usage based on the vehicle's overall energy flow characteristics. A composite fuzzy control strategy that accommodates the economy and power stabilization ability and an approach for minimizing hydrogen usage via adaptive equivalence were designed to simulate and analyze the power allocation strategy of fuel cell heavy trucks.

Wang [38] addressed the absence of a developed EMS for high-power FC heavy duty trucks; it is suggested to use the FC protection priority control approach in the formulation of the EMS for these vehicles. By considering the dynamic working condition characteristics and power system characteristics of fuel cell heavy trucks, a composite fuzzy control EMS was founded with the idea of achieving the FC's ideal operating condition and aiming to increase the FC's longevity and heavy truck economy. Based on this, the WAFA composite fuzzy control energy management technique was suggested, which uses the fuel cell variable load rate limiting method and the weighted average filtering algorithm WAFA to lower the frequency of fuel cell breakdown. Ferrara [39] developed an innovative health-oriented energy management system to tackle the durability and efficiency issues of heavy duty long-distance transportation. The suggested technique features a two-stage predictive control framework that facilitates dynamic planning for optimum and anticipatory energy management. The primary innovation of this study is in the multi-objective optimization of

fuel consumption, FC deterioration, and battery degradation, enabling a highly adaptable method that identifies the optimal trade-off among the three goals according to the vehicle's operating circumstances. Figure 4 illustrates the power consumption patterns of SOC and FCS, accompanied with the anticipated reference optimized by dynamic planning.

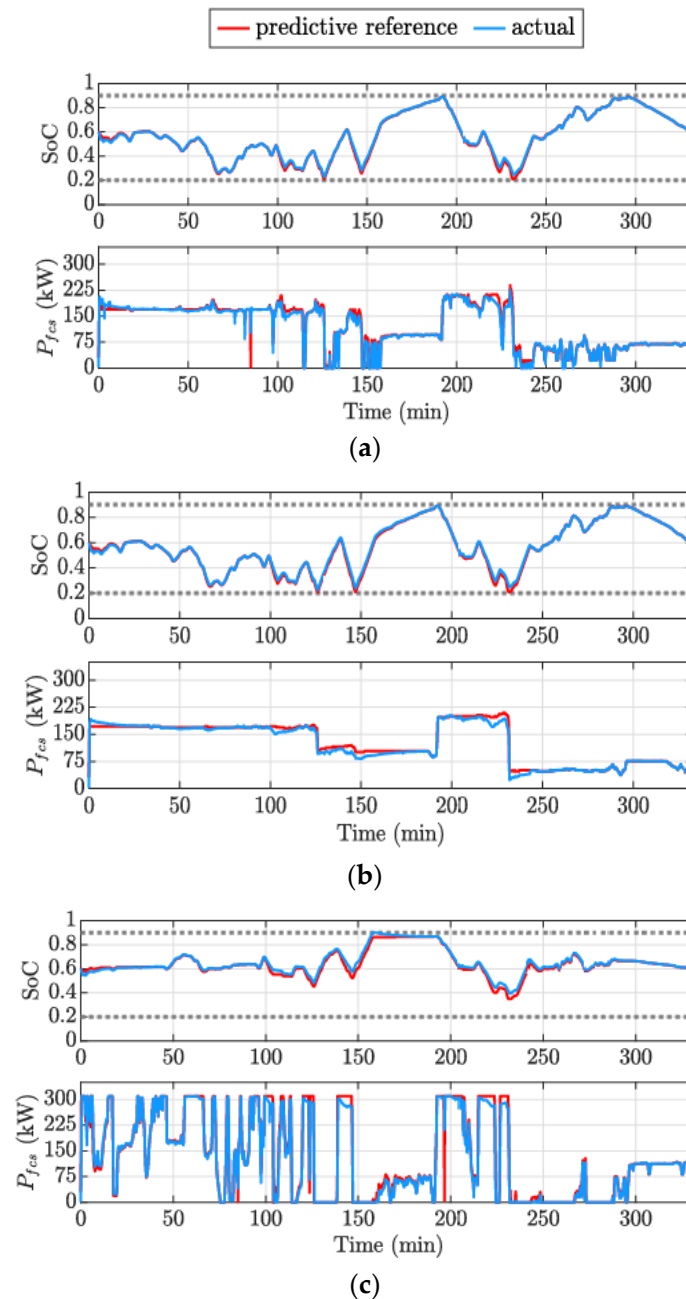


Figure 4. Simulation results of several optimization goals for health-conscious energy management systems [39]: (a) Optimization objective: fuel consumption; (b) Optimization objective: fuel cell degradation; (c) Optimization objective: battery degradation.

Figure 4b shows the results associated with the minimization of FC degradation. The power curve of the fuel cells is significantly more stable in this instance, as transients and load cycling adversely affect the lifespan of the FCs. The average power profile of FCs is like that shown in Figure 4a. However, the above behavior is avoided because EMS prioritizes fuel cell degradation over gasoline consumption. Normally, the power decreases to zero. It maximizes the use of regenerative braking energy when braking or going downhill, minimizing fuel consumption. The results regarding battery degradation minimization are

displayed in Figure 4c. In this instance, the EMS minimizes performance degradation by reducing cell usage and maintaining it within a narrow SOC range; however, the SOC range remains relatively large. In contrast, the EMS performs FCs in a load-following manner, which leads to high fuel consumption and fuel cell degradation.

Shiledar [40] examined range-extended electric vehicles (REEVs) for medium-duty Class 6 pickups and delivery trucks. The hybrid structure combined an internal combustion engine range extender with an electric powertrain. To maximize the efficiency of an REEV, an EMS was needed to achieve optimal distribution between the two power sources. In this endeavor, the layered EMS was developed using a model-based design and verified through hardware-in-the-loop (HIL) simulation. By using dynamic programming, the suggested EMS maintained emissions and engine start frequency equivalent to the top EMS benchmarks in the world while reducing fuel consumption by 7% when compared to the baseline management method. Additionally, the HIL results validated the feasibility of the real-time implementation strategy, highlighting the practical feasibility of the controller.

Fuel cell hybrid trucks (FCHTs), which have low speed, are heavy duty, and have frequent start-stop characteristics, may be a promising solution for port logistics. However, the effective energy management of refrigerated reefer containers in ports is critical. Environmental degradation and proposals for carbon neutrality are driving a change in port freight transportation. Wang et al. [41] examined how DP strategies affect FCHT energy management. The FCHT structure and each component were modeled to determine the power demand. As state variables, choice variables, and objective functions, respectively, the DP technique took into account the battery's SOC, power output, and hydrogen fuel consumption. By lowering the hydrogen fuel usage by over 10%, simulation findings under two distinct typical operating situations at the port showed that the suggested DP worked better than current genetic algorithms (GA) and rule-based techniques. Additionally, a set of examples from multiple FCHTs with varying parameters and conditions indicated that the key characterization parameters have varying effects on SOC and hydrogen fuel consumption. At current prices, the cost of FCHT in the Quay-to-yard (QCY) cycle was reduced by nearly 50%, indicating that FCHT has a wide range of applications. Finally, the results under various circumstances reaffirmed that DP is a great method for managing the energy of FCHTs at ports under scenarios with large loads and frequent start-stops.

Dual fuel cell hybrid systems present appealing propulsion alternatives for transportation, particularly for HDVs. Nonetheless, the increased weight of larger vehicles heightens the sensitivity of power demands to driving conditions and the capacity of the vehicle to navigate, complicating the sizing process. This work aims to illustrate multi-objective and multi-parameter optimization for the series development of heavy duty vehicles utilizing dual fuel cell hybrid systems. Zhang [42] suggested an integrated model that amalgamates the degradation models of the FCS and the battery system. Pareto theory was employed to assess three-dimensional objectives, including equivalent hydrogen consumption, mass objectives, and vehicle dynamics, which were obtained using a two-layer optimization framework and a variety of six-dimensional parameters. The proposed methodology allowed for obtaining a reasonable set of selected solutions in an optimization space with high-dimensional parameters. Taking the product's serialization into account, improved solutions and corresponding upper bounds of performance were also identified under different weight levels according to the proposed method.

3. Fuel Cell–Supercapacitor Hybrid System

Supercapacitors have the benefit of being able to release a large quantity of power instantly and have a rapid reaction time, while fuel cells have a relatively sluggish response time and are unable to produce a significant amount of power instantly. However, SCs have

relatively low energy density and cannot provide long-lasting power output, requiring frequent recharging [43]. Therefore, a power system that combines SCs with fuel cells can make full use of their respective advantages and compensate for their shortcomings, as seen in Figure 5.

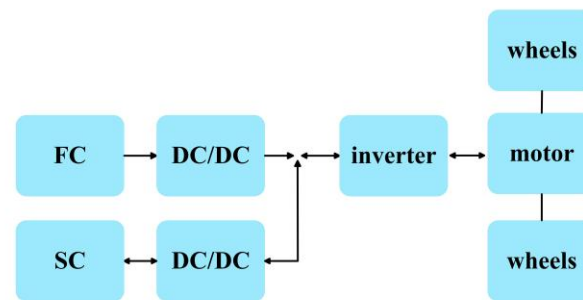


Figure 5. Structure of the indirect FC–SC hybrid power system.

3.1. Passenger Cars

Oksuztepe [44] proposed a four-wheel-drive electric vehicle (4WDEV) hybrid system that consists of a FC and SC. Since an EV's energy consumption is dependent on its route, a geographic information system (GIS) can be used to create a framework for effective energy management. The power demand of the EV can be estimated based on the road trajectory, which will help reduce energy consumption.

Lin [45] focused on the FC and SC hybrid vehicle to achieve real-time performance, economic efficiency, and FC durability. The research encompassed the selection of key components and parameters for the FC hybrid vehicle, modeling of the FC hybrid system, and real-time energy control. The findings indicate that the MLD-MPC EMS significantly enhances the durability of the FC, as illustrated in Figure 6.

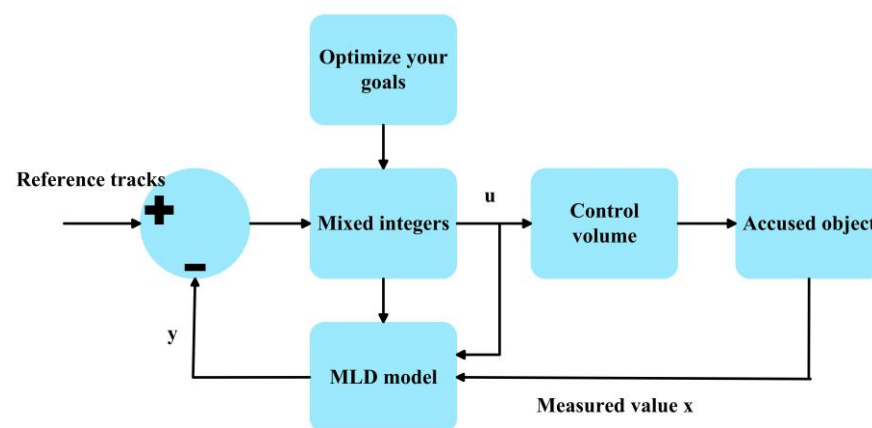


Figure 6. MLD–MPC strategy [45].

Adel et al. [46] created a secure power management plan for hybrid cars that combines fuel cells and SCs. The suggested power management strategy may identify the cause of failure and reconfigure the control scheme in addition to identifying when issues arise with the vehicle's power supply, which guarantees the stability of the bus voltage and the vehicle's traction even when issues arise. By using the particle swarm optimization algorithm and using the newly proposed cost function, torque and speed pulsations are automatically minimized, which makes the design of the controller easier.

Hamlat et al. [47] developed a resilient nonlinear control strategy integrating backstepping with super-twisted sliding mode control for the seamless execution and ongoing synchronization of an FC–SC hybrid powertrain concerning the output converter, set-

point generation, and power monitoring. Numerical simulations were used to compare a standard performance index linked to a deterministic rule-based energy management system with a backstepping super-twisted sliding mode control integrated with fuzzy logic, applied to an out-of-town driving cycle test scenario for a fuel cell electric car. The research indicates that the suggested regulation lowers the hydrogen consumption of the FC while preserving an optimal state of charge of the SC.

3.2. Buses

Li et al. [48] evaluated the following two MPC frameworks using distinct error compensation methodologies for power management in FC hybrid electric buses: the MPC framework with adaptive compensation (AC-MPC) and the MPC framework with Gaussian process regression compensation (GPRC-MPC). The AC-MPC fixes issues related to the linearization of the nonlinear FC/SC HESS and uses adaptive weights based on the SC's SOC. Gaussian process regression is used by the GPRC-MPC to predict and correct load-disturbance errors and residuals. The AC-MPC and GPRC-MPC were assessed using New York Bus (NYBus) driving cycles and driving cycles obtained from the Swedish GBG17 bus route. In contrast to the linear MPC scheme, AC-MPC and GPRC-MPC enhanced the performance of the hydrogen system by decreasing hydrogen consumption and minimizing the fluctuation of maximum fuel cell current without requiring correction, while preserving the SC state of charge within specified limits.

Yan et al. [49] proposed a hierarchical EMS for fuel cell buses (FCBs) that integrates traffic information at bus stops. During the upper trajectory planning phase, the ideal state of charge trajectory is determined using dynamic programming, considering diverse historical traffic situations. The use of BiLSTM for mapping traffic data and ideal SOC trajectories facilitates the rapid, actual time extended SOC reference. The smaller-scale actual time predictive energy management method used the optimal state of charge as a benchmark to guide the predictive energy management of the FCB upon its arrival at a bus stop. Simulation findings indicate that the life cycle cost of the suggested strategy is diminished by 13.8%, while the overall cost is decreased by 3.61% in comparison to the plan without the SOC trajectory reference. The SOC of the suggested technique is nearer to the DP optimum solution.

Guo et al. [50] presented an economically driven energy management system (EDEM) for FCBs based on the cyclical nature of the driving cycle and traditional speed-predictive energy management methodologies. In EDEM, the following two scenarios are established for bus route conditions: in the absence of a bus in the bus lane (primary scenario), FCB can utilize trapezoidal planning curve (TPC)-based speed planning for entering and exiting bus stops, thereby minimizing intersection stopping conditions and integrating the speed planning into the MPC-based EMS; conversely, in the presence of a bus, speed prediction is employed within the MPC-based EMS (secondary scenario). This minimizes junction halting situations and incorporates speed planning as an input to the MPC-based EMS; alternatively, conventional speed prediction is used in the MPC-based EMS (contingency scenario). In addition, this EDEM cost function adds bus load variations at bus stops, allowing for the accurate calculation of energy usage and optimum energy distribution.

Siangsano et al. [51] suggested a new converter design for applications combining SCs and FCs, where the FC is coupled with a set of SCs. The advantages include high efficiency and maximization of SC energy. The functioning and modeling of the converter are delineated. An indirect sliding mode technique is used for the internal current loop for closed-loop control, while a disturbance estimator is used for energy management in the external loop.

Broatch et al. [52] examined several approaches or setups for the fuel cell electric bus's (FCEB) integrated thermal management system (ITMS). A thermal model of the fundamental parts is part of a new global model of FCEB. In order to replicate the driving cycle of a public transportation system in Valencia, Spain, during the winter, several strategies in the FCEB integrated thermal management system were evaluated using the model. The first method achieved up to 7% savings by using the heat produced by the FC to heat the car's cab. The second method warmed the battery by using the FC's waste heat. It was discovered that using the waste heat to warm the batteries may save 4% of energy when the FC is subjected to high power demands. Lastly, a hybrid approach was suggested, which saved 10% on energy costs by using the FC's waste heat to heat the batteries and the cabin.

Farsi et al. [53] presented a PEMFC input air heating system for FCEVs that cools the battery before sending it to the PEMFC's cathode side. A PEMFC using warmed air demonstrated power densities of 450 W/m² more than the baseline arrangement when it was freezing outside without heating. Yang et al. [54] developed an ITMS for FCEVs including various control methodologies and energy management integration.

A viable electrified transportation system might be the fuel cell hybrid electric bus (FCHEB), which uses an SC as a buffer for energy and a hydrogen FC as the primary power source. Li et al. [55] suggested a method for model predictive control including Gaussian process regression compensation (GPRC-MPC) for the FC and SC HESS. To enhance the precision of the linear MPC model, GPRC-MPC incorporates Gaussian process regression to forecast and mitigate load disturbance errors and residuals.

3.3. Heavy Trucks

Noone et al. [56] presented an approach for the design and sizing of a hybrid powertrain for HDVs. The methodology employs the following two-stage approach: first, a viable hybrid configuration is identified by pure simulation using a genetic algorithm, followed by a multi-criteria optimization including design of experiments (DoE) on an engine-in-the-loop test bed. The electrical components of the hybrid assembly are optimized for dimensions in this procedure. The suggested technique is fundamentally adaptable to altering the goal variables and boundary conditions, making it highly suitable for hybrid system design. Variable degrees of detail may be delineated to obtain the best outcomes for each application. Furthermore, a model optimization is shown, whereby only the corresponding values during CO₂ operation are minimized to serve as a cost function. In the subsequent phase, NO_x and particle emissions are also taken into account. The example is derived from actual and previously recorded long-haul vehicles.

Li et al. [57] proposed a technique for energy management and cost analysis of an excavator fueled by FCs and SCs. The operational parameters and energy dynamics of the hydraulic excavator were examined, and the determinants influencing the longevity of FCs under these settings were deliberated. Substantial load fluctuations provide a considerable challenge to the efficacy of the FCs, necessitating an adequate EMS for the FCHE. Three typical EMSs based on dynamic planning, Pontryagin's minimal principle, and model predictive control were created while taking hydrogen consumption and FC durability into account. The MATLAB environment's simulation of an excavator's cyclic loads demonstrates the advantages of the suggested EMS. The durability of FCs can be improved with the introduction of FC power variation limits. An economic study of the FCHE is provided, including the impact of FCs and SC dimensions on hydrogen consumption, along with existing and projected costs of use. The size of the FCs is the primary determinant influencing the fuel efficiency of the FCHE. As costs decline, FCHE will become increasingly attractive.

The use of fuel cell hybrid construction equipment (FCHCE) is a promising alternative for prospective industrial advancement. Construction machinery exhibits extremely repetitive operational patterns suitable for predictive control. Nevertheless, the loads often fluctuate considerably, resulting in suboptimal energy management. Li et al. [58] proposed a predictive energy management technique using the MPC of FCHCE architecture to address this issue. The supervisory energy management goals were used to control fast fluctuations in building equipment loads while reducing fuel consumption, enhancing FC longevity, and keeping the SCs' state of charge within acceptable bounds. To enhance the efficacy and functionality of the prediction controller, we provide two approaches for predicting power demand that make use of neural networks and Markov chains. The findings indicate that the neural network model yields superior predictions compared to the Markov chain model, but the Markov chain model is more suitable for modeling integrated driving cycles. Corral-Vega et al. [59] suggested a rubber-tired gantry (RTG) crane that is "all-green" by using an SC as an energy storage system (ESS) and an FC unit. When loads are accelerated during lifting motions, the SC supplies the necessary high current and power requirement. Upon reaching a stable power demand (elevation at a steady velocity), the FC supplies the necessary energy for the remainder of the movement. The spinal column is also engaged during raising and lowering actions. In this instance, the regenerative energy may be retained in the SC rather than dissipated in the brake resistor, as is typical in a standard RTG crane. The novel hybrid system using fuel cells and SCs was developed and assessed using actual driving cycles of rubber-tired gantry cranes. Simulation results, including a comparison analysis that used the current RTG crane design (which is only powered by a diesel engine), demonstrated the technical feasibility of an RTG crane powered by SCs and FCs. This hybrid system is costlier than a diesel-powered system, although it is more energy efficient and has superior environmental benefits.

Wang et al. [60] suggested a method for allocating online power that is not optimum, based on the concepts of classical cybernetics. The offline dynamic programming approach serves as the ideal benchmark for comparison with the suggested suboptimal online power allocation strategy. Subsequently, to assess the effectiveness of the proposed power distribution strategy, simulations were run. An experimental investigation was undertaken using a semi-physical experimental platform to examine the fuel efficiency and dynamic properties of several hybrid constructions. The hybrid structures of FCs and SCs exhibited enhancements of 21.03–26.70% with the PID-based power allocation approach and 21.86–30.48% with the rule-based approach to electricity distribution, in comparison to the hybrid structures of fuel cells and batteries. The findings demonstrate that the suggested rule-based approach may achieve near-optimal performance and is easy to be applied online compared to dynamic programming algorithms.

4. Fuel Cell–Battery–Supercapacitor Hybrid Power System

In the structure of FC + battery + SC in Figure 7, the battery and SC serve as supplemental energy sources, while the FC serves as the primary energy source. The battery and SC have a good complementarity, the SC can protect the battery from the impact of high current and improve the service life of the battery, and at the same time, the battery can provide a stable output power in the demand of high power and recover peak power through the SC under the situation of brake, so that the secondary energy source can better provide power demand and absorb energy. The battery can simultaneously provide consistent output power under high power demand, and can recover the peak power through SC under braking situation, so that the secondary energy source can better provide power demand and absorb energy, and the mixing of the three of them can build up a three-energy-source high-efficiency hybrid system with high performance and low

emission, but the configuration and control system design of this three-energy-source hybrid system is more complex, and the cost is also relatively more expensive.

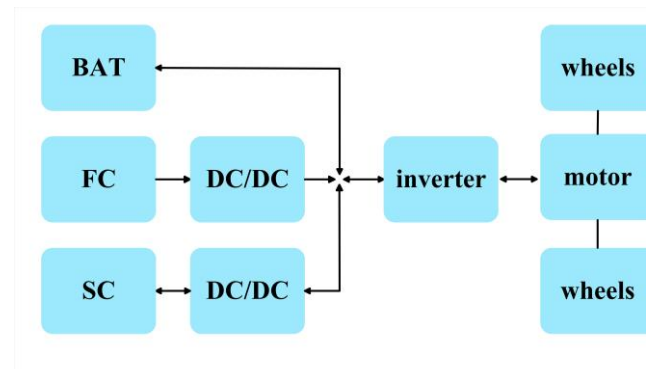


Figure 7. Structure of indirect FC+ battery + SC hybrid system.

4.1. Passenger Vehicles

Han et al. [61] partitioned the battery and supercapacitor SOC to control the output value of each energy source and suggested a method for controlling state machines. Chen et al. [62] analyzed the power for different working conditions and created an energy management plan to prolong the power stack's service life by modifying the power following factor in real time via the power battery SOC. Li et al. [63] used the particle swarm optimization algorithm in the swarm intelligence optimization algorithm to improve the fuzzy logic-based parameter selection of the affiliation function to optimize the energy distribution among the SC, FC, and lithium-ion battery in accordance with power requirements to enhance system performance and extend component longevity. Fu et al. [64] suggested a fuzzy controller that is tuned using genetic algorithms using a wavelet transform and adaptive low-pass filter to divide the necessary power into three bands of frequencies. This decreases fuel cell power fluctuation and increases fuel cell life.

Lei [65] suggested a double fuzzy control-based Pareto multi-objective optimum energy management strategy, as shown in Figure 8. Aiming at the problems of fuzzy control relying on subjective experience and the difficulty of fusion of multiple performance indicators, the multi-objective problem is addressed through an enhanced non-dominated sequential genetic algorithm (NSGA-II), focusing on the comparable energy use of three energy sources and the performance degradation of these sources, resulting in improved fuel economy compared to power-following control and single fuzzy control strategies. Yuan et al. [66] reduced power usage using a dynamic allocation-based logic threshold filtering technique. Depending on the vehicle's specifications, to confirm the efficacy of the present method under the urban dynamometer driving scheme (UDDS), a power system model was built and compared to the traditional control strategy. Hydrogen consumption decreased by 1.9% with the improved energy management approach; the proportion of power beyond 10 kW decreased by around 20%; and the battery terminal SOC values under the pre- and post-improvement control techniques were 51.64 and 50.91, respectively.

Nie et al. [67] suggested a hierarchical control approach for energy management and speed improvement using a sequence-based nonlinear model predictive control algorithm to minimize the degradation of the power source using a multi-objective performance function to prolong operating life and reduce energy consumption. Hassan [68] proposed a nonlinear controller that was designed for an FC hybrid vehicle's HESS. All of these energy sources are connected to a motor, a DC-DC power converter, and a DC-AC inverter. The suggested nonlinear controller based on Liapunov achieves tight regulation of the DC bus, good monitoring of the source currents, and global closed-loop system asymptotic stability.

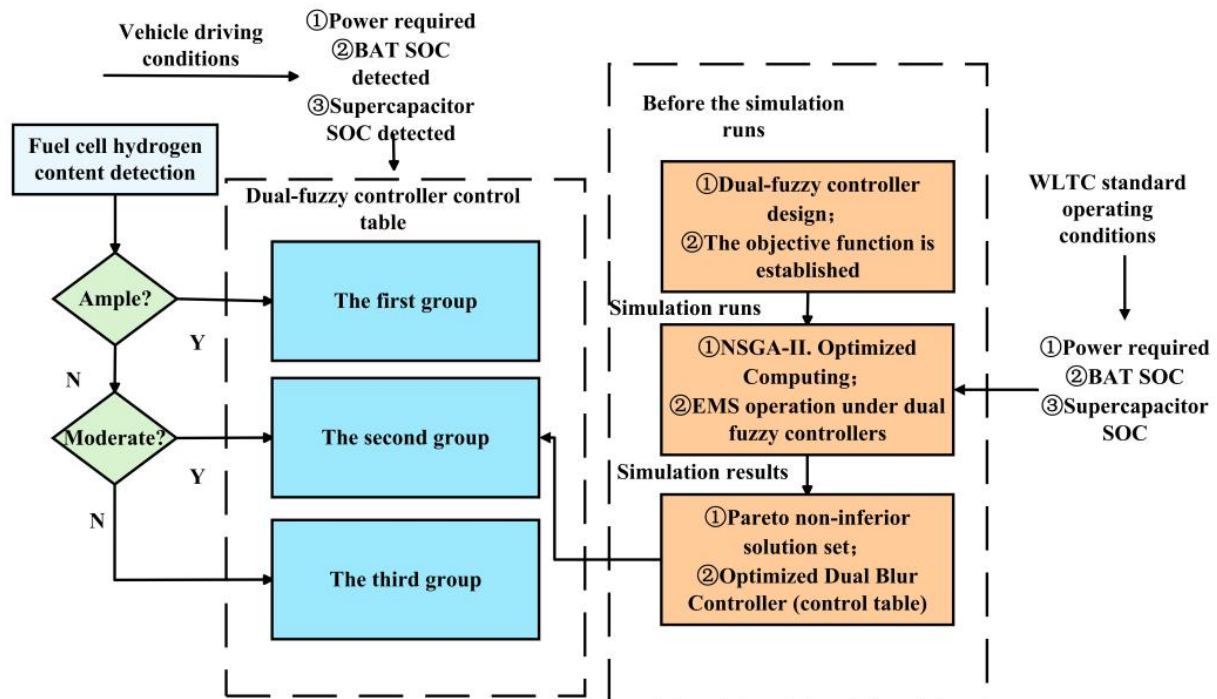


Figure 8. Pareto-based double fuzzy control multi-objective optimum energy management approach [65].

Omer et al. [69] introduced a novel design technique for an EMS using adaptive super-twisted sliding mode control (ASTSMC) for FC/battery/SC hybrid electric vehicles (FCHEV). Hal's Wavelet Transform (HWT), an adaptive low-pass filter, and fuzzy logic control (FLC) are used in the proposed EMS's frequency decoupling technique to separate the necessary power into low-, medium-, and high-frequency components for the battery, FC, and SC, respectively. The suggested frequency decoupling method enhances the vehicle's power output while reducing power fluctuations and load stress in the FC. To attain robustness and precise control, ASTSMC was formulated on a nonlinear disturbance observer (NDOB) to stabilize the energy source's DC bus voltages and currents to guarantee that the ultracapacitors, batteries, and FCs all operate within their specified reference ranges. The following three common driving cycles were used to evaluate the FCHEV system, which includes the suggested EMS, using MATLAB/Simulink: HWFET, UDDS, and WLTP; They were compared with other current methodologies such as ECMS, state machines (SMs), and FLC-based EMS as shown in Table 2. From the table, it can be seen that the Δ SOC (battery), representing the difference between the initial 75% and the ultimate state of charge for three typical driving circumstances, derived from the SM, FLC, and ECMS, exceeded that of the proposed EMS. Under HWFET, UDDS, and WLTP driving cycles, the suggested EMS used around 10.2%, 20.3%, and 7.9% less fuel than the FLC. In comparison to the SM, the suggested EMS even reduced fuel consumption by about 11.6%, 28.7%, and 17.7% for HWFET, UDDS, and WLTP driving cycles, respectively. Furthermore, as compared to the ECMS-based EMS, the suggested EMS even reduced fuel consumption by around 7.1%, 14.64%, and 5.2% for HWFET, UDDS, and WLTP driving cycles, respectively. In addition, the suggested EMS may outperform ECMS, FLC, and SM in terms of lowering fuel cell power fluctuation and consumption.

Table 2. Comparison of vehicle performance parameters under four different energy management strategies.

Parameters	Driving Cycle	SMs	FLC	ECMS	ASTSMC
SOC final value (%)	HWFET	76.15	75.71	75.51	74.6
	UDDS	80.68	79.54	78.53	77.36
	WLTP	78.1	77	77.1	76
Hydrogen consumption (L)	HWFET	12.5	12.3	11.89	11.05
	UDDS	13.64	12.2	11.4	9.73
	WLTP	22.4	20.02	19.45	18.44
FC power fluctuation (W/s)	HWFET	±900	±500	±400	±250
	UDDS	±1000	±600	±500	±300
	WLTP	±1000	±600	±500	±300

Liu et al. [70] created a predictive EMS with several objectives. NSGA-II reduces the economic cost of fuel cells and batteries while increasing their durability in a predictive control framework. A fuzzy logic method filters the data from the Pareto frontier produced by NSGA-II, which optimizes the cost function in real time to provide the best control solution. The NSGA-II compared with FMPC and PMPC, the proposed EMS, has excellent feasibility and effectiveness, as seen in Figure 9. Figure 9a demonstrates the FCS power. The FCS delivers 10 kW as the lowest power and 100 kW as the maximum power throughout the drive cycle. In general, the FCS power falls within the low power range. Heavy loads and lower battery/supercapacitor SOC circumstances result in the FCS's peak power. Compared to the suggested EMS, the FMPC and PMPC's FCS power trajectories fluctuate more often. The FMPC's FCS power swings and changes the greatest compared to other FMPCs. This is due to the lack of operating condition prediction in FMPC. It results in the discrepancy between the demand pressures that are projected and those that are present (constant prediction). In contrast, PMPC utilizes preexisting information about future circumstances and adequately responds to changes in operating conditions. As a result, PMPC is more variable than the proposed EMS. It is noteworthy that the FCS's power trajectory is less pronounced under the suggested EMS, indicating that the FCS's longevity may be successfully increased. Figure 9b,c shows the battery's SOC and power. The battery SOC varies from around 0.382 to 0.8, and the power range is from −96.7 to 96.5 kW. The FMPC's development trajectory exhibits the least amount of volatility, with a power range from −74.8 to 65 kW and an SOC range from 0.523 to 0.8. The suggested EMS's battery power and SOC trajectories resemble those of the PMPC. The SC power supply and state of charge for SC are seen in Figure 9d,e. The PMPC's trajectory has the least variable range, whereas the FMPC's has the greatest dynamic range, much like the battery performance. The FMPC has a power range from −146.1 to 98.9 kW and an SOC range from 0.527 to 0.8, whereas the PMPC has a power range from −83.2 to 97.9 kW and an SOC range from 0.589 to 0.8. Notably, the battery and ultracapacitor trajectories are similar, and the recommended EMS is in the middle of the other EMSs. The SOC of the battery and ultracapacitor both drop with each cycle. Given the high load circumstances for which the EMS was designed, the power supply's SOC must be kept to a minimum.

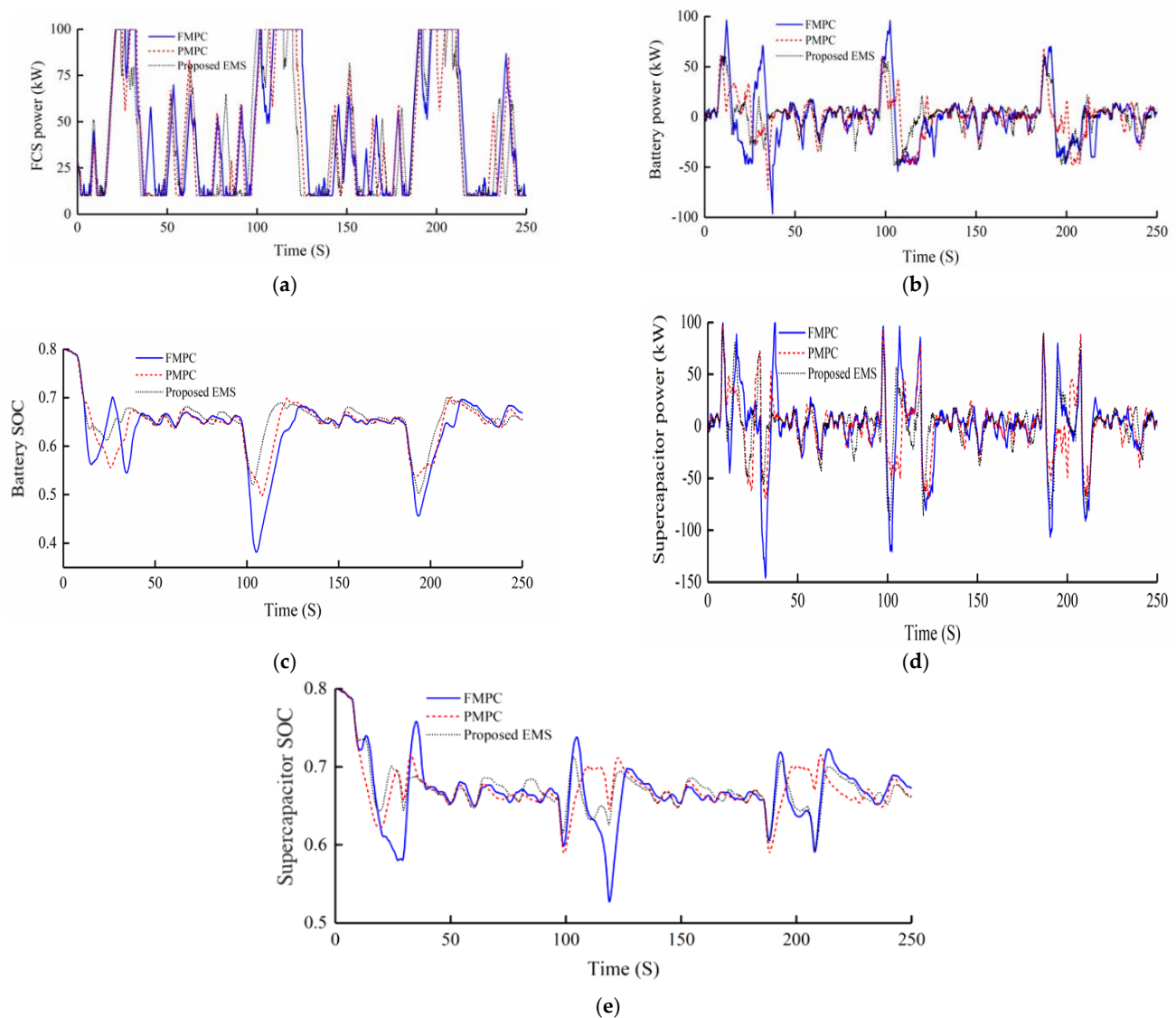


Figure 9. Proposed EMS compared to FMPC and PMPC [70]: (a) FCS power; (b) Battery power; (c) Battery SOC; (d) SC power; (e) SOC of SC.

According to the simulation findings, the FMPC, PMPC, and the suggested EMS had equal hydrogen consumptions of 242.94 g, 230.7 g, and 232.16 g, respectively. The battery and SC modifications in relation to the original state were included in the equivalent hydrogen consumption. Overall, the suggested EMS is comparable to PMPC and superior to FMPC. Thus, the superiority of the suggested EMS is confirmed by its excellent cost economics and SOC operating range.

A comparison of Lei's Pareto multi-objective optimal energy management technique based on dual-fuzzy control with our multi-objective predictive EMS was performed [67]. Figure 10 displays each energy source's output power map under dual-fuzzy management. As the primary energy source, the FC's output was reasonably smooth, and it only stopped twice during operation, which promoted the FC's lifespan. However, at 1600 s, the vehicle's overall power demand rose, and the output power of the Li-ion battery and super capacitor also rose. The super capacitor can better provide the peak power during acceleration, which has the effect of "peak shaving and valley filling", effectively reducing the burden of FC and lithium battery. The optimized dual-fuzzy control enabled hydrogen fuel cell vehicles to consume less hydrogen, reduce equivalent energy consumption by an average of 1.8%, and reduce the equivalent performance degradation of the energy source by an average of

85.4%, whereas the multi-objective predictive EMS effectively saved 4.43% of hydrogen consumption. Its greater utilization of SCs and decreased battery contribution are among its benefits. This advantage translates into extended battery life, ensuring that the hybrid FC/battery/SC engineering vehicle extends the life of these devices and guarantees high efficiency by not only receiving enough power under challenging working circumstances but also allocating the power demand among the FCs, batteries, and SCs in an appropriate manner.

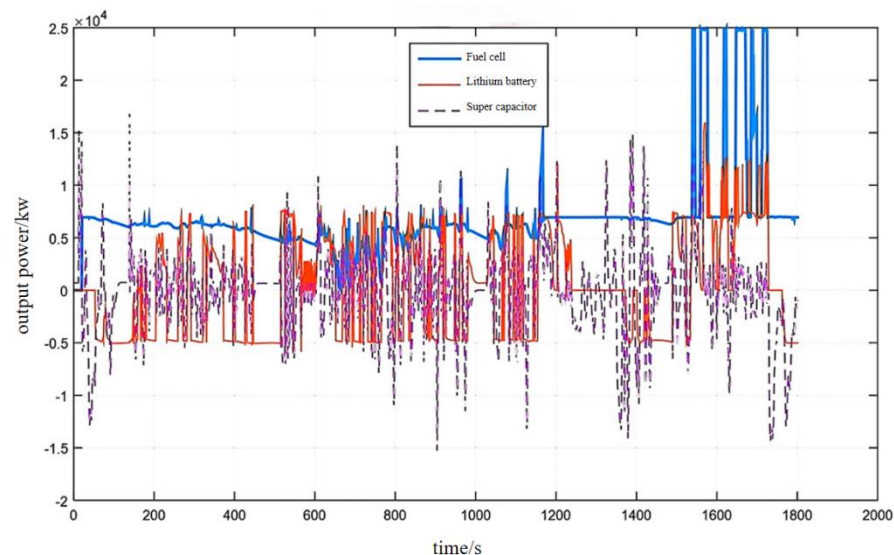


Figure 10. Each energy source's output power plot under double fuzzy control [67].

Abdelqawee et al. [71] introduced a draft EMS that uses an improved proportional integral (PI) controller that takes into account the FC efficiency to make sure the FC stack runs in its maximum efficiency zone and lowers its stresses, which lowers the amount of hydrogen it uses. In order to balance the exploration and development phases, a hybrid meta-heuristic optimization technique called JPSOBAT is proposed for the tuning of the PI controller gain (K_p , K_i). This technique combines the BAT Optimizer, the Particle Swarm Optimizer (PSO), and the jellyfish (JS) optimizer. A comparison analysis with various single and hybrid meta-heuristic optimization strategies is offered by evaluating 50 difficult benchmark functions so as to first confirm the efficacy of the JPSOBAT methodology. The controller gain of the suggested PI controller is then chosen using JPSOBAT. It makes use of a 30 min More Electric Aircraft (MEA) load profile.

4.2. Buses

Li et al. [72] suggested an FC three-source hybrid bus management technique under life cycle game optimization. In order to increase forecast accuracy, a driving cycle prediction approach under learning vector quantization (LVQ) and back-propagation (BP) neural networks was first suggested. Second, a novel FC degradation model was created by further deriving the expression of the link between hydrogen efficiency and fuel cell state of health (SOH) deterioration, which accommodates the different degradation rates of FCs under various operational circumstances. Finally, the competitive-cooperative mechanism between the FC and the battery was described as a non-cooperative game theory-based dual-source lifespan degradation game optimization technique. In order for the strategy to achieve the degrading adaptive property, the hydrogen efficiency degradation was computed in real time using the most recent SOH during the game optimization phase. The findings indicate that, in comparison to the rule-based technique, the suggested approach improved the economy by 81.64%. In comparison to the traditional model predictive

control energy management technique, the economic cost decreased by 76.99%, fuel cell degradation decreased by 76.83%, and battery deterioration improved by 49.28%.

Rezk et al. [73] provided an extensive evaluation of several energy management techniques for FC, SC, and battery energy storage devices. These solutions are used to effectively regulate the reaction of hybrid systems to energy demand under significantly variable load situations. Rezk introduced two novel tactics using the salp swarm algorithm (SSA) and burst optimization. These tactics' outcomes were contrasted with those of other widely used tactics. Hydrogen fuel economy and overall efficiency were used to evaluate these different solutions. The results of the study showed that the proposed SSA management technique outperforms the other alternative strategies in terms of hydrogen fuel economy and overall efficiency. Hydrogen consumption was the lowest, and efficiency was the highest, with 19.4 g and 85.61%, respectively.

Odeim et al. [74] investigated the offline and real-time optimization of power management techniques for FC/battery/ultracapacitor hybrid vehicle systems. First, a comparison was made between two offline optimization algorithms, Pontryagin's minimal principle and dynamic programming. Since the offline optimum lacks real-time capabilities and is only focused on reducing hydrogen consumption, which might cause needless battery overloading, it is inevitable that the offline optimum be utilized as a benchmark for creating a real-time strategy. A multi-objective genetic algorithm was used in the real-time strategy's creation and optimization while considering other important factors in addition to hydrogen consumption, such as reducing the battery power load and the fuel cell system's sluggish dynamics. Consequently, it was discovered that the real-time approach greatly increased system durability while using a little more hydrogen than the offline optimum solution.

Kwan et al. [75] suggested optimizing an FC–battery–SC based FC power system using a multi-objective optimization approach based on NSGA-II. The optimization goals were to minimize the FC's fuel consumption, the necessary dimensions of the cell and SC, and the rate of cell deterioration. More significantly, the optimization approach was predicated on a combination of hardware component size and EMS software settings, which is crucial to guaranteeing a dynamically stable response. By placing restrictions on the transient time response, the DC-BUS capacitor voltage, and the function of the electrical parameters during general step changes in load power, this feature was accomplished. The findings demonstrated that suitable hardware and software parameter combinations may provide dynamic stability without requiring any compromises to the optimization goal. Furthermore, the goals of battery deterioration and system quality are trade-offs that are independent of hydrogen consumption.

The cost, effectiveness, energy consumption, carbon emissions, and other aspects of hydrogen fuel cell public transportation have been the subject of much domestic and international inquiry by scholars. Ribau et al. [76] investigated the significance of driving circumstances, investment costs, effectiveness, and life cycle effects in the design of the fuel cell vehicle powertrain by employing single-objective and multi-objective genetic algorithms, and they ultimately found an optimization scheme that can achieve lower life cycle impacts and lower costs. Wang et al. [77] investigated and proposed a comprehensive life cycle evaluation technique based on costs to analyze the financial and environmental advantages of long-distance transportation systems fueled by hydrogen. Thanh et al. [78] analyzed key performance metrics, including cumulative mileage, availability, fuel economy, and fuel cost, for a North American and European hydrogen fuel cell bus demonstration project in light of the background and current status of the project. McKenzie et al. [79] analyzed the findings of a life cycle analysis of transit costs and GHG emissions using a hybrid input–output model, and they found that hydrogen fuel

cells provide a higher level of GHG emission reduction. Munoz et al. [80] developed a composite index to characterize the effectiveness of the cost, energy use, and emissions of greenhouse gases from the energy mix and transportation technology. Their study found that replacing the entire fleet with hydrogen fuel cell buses could reduce emissions by 1.3 million tons of equivalent carbon dioxide, which is very friendly to the environment. Bubna et al. [81] examined the upkeep and operation of hydrogen fuel cell and battery series hybrid buses within the framework of an FCHB route in the FCHB project at the University of Delaware. Additionally, it proved that fuel cell cars might be used in the transportation sector.

4.3. Heavy Trucks

Ding et al. [82] presented an event-triggered control method for an FC heavy duty truck hybrid powertrain. The strategy of event-triggered control was incorporated into a traditional proportional-integral (PI) control approach to create the suggested event-triggered technique. The PI control scheme is engaged if the trigger condition is met; if not, it will be stopped and the control signals will stay unchanged. The following benefits are inherited by the suggested event-triggered method: (i) the computational load is lessened without compromising regulatory performance, and (ii) the switching action is lessened to avoid switching loss. Anselma et al. [83] proposed an EMS (real-time energy management technique) that may increase the efficiency of heavy duty fuel cell electric trucks in terms of hydrogen. First, the Simulink environment was used to represent the heavy duty vehicle under consideration. Then, a controller that instantaneously regulates the power distribution between the heavy duty truck's high-voltage battery pack and FCS was kept. This controller was based on a baseline heuristic mapping. Therefore, the characteristics of the EMS under consideration are optimally tuned by the use of particle swarm optimization (PSO). To achieve this study, the calibrated optimization objectives included using a Simulink model to simulate a heavy duty vehicle in order to minimize the anticipated hydrogen consumption. The VECTO program, a European tool used to verify the CO₂ emissions of new HDVs, was utilized to produce some of the driving jobs that were necessary for the simulation. Furthermore, by understanding the whole driving job ahead of time, the trajectory of the global optimum control over time may be found using DP, an offline reference EMS technique. The PSO-calibrated real-time EMS proved to have significant hydrogen saving potential, with results differing by only about 5% compared to the best global benchmark provided by DP.

Dao et al. [84] proposed an innovative optimum EMS for a hybrid hydraulic excavator system to improve power efficiency, extend power source longevity, and increase fuel efficiency. FC serves as the primary energy source, whereas SCs and batteries are regarded as energy storage systems. A suggested energy management system utilizes fuzzy logic control and rule-based algorithms to facilitate the efficient allocation of power among the three sources and the reutilization of renewable energy. Furthermore, the parameters of the fuzzy logic system are optimized by a combination of backtracking search algorithm and sequential dynamic programming as a local search method, which offers a useful orientation to the global optimum area for fine-tuning the ideal solution to lower hydrogen consumption and increase power source longevity.

Trinh et al. [85] presented the best possible EMS for a fuel cell hybrid excavator (FCHE) that has FC technology for power and an ES device made up of a bank of SCs and a lithium-ion battery pack. An ECMS, which guarantees load power adaptability while reducing hydrogen consumption and enhancing fuel cell stack operating efficiency, is suggested as a way to satisfy fuel-saving criteria.

Electrification and hydrogen generation for automobile applications have drawn a lot of research interest in order to achieve decarbonization goals. In an excellent review, Abul et al. [86] explained the particular design specifications for off-road hybrid and all-electric cars. Masrur evaluated the benefits and drawbacks of the underlying design choices and offered a framework for judgments on vehicle deployment. Liukkonen et al. [87] evaluated five distinct FC hybrid topologies and came to the conclusion that the DC-DC converter's efficiency might make the difference between a workable and impractical (under-efficient) powertrain based on the duty cycle. Munoz et al. [88] analyzed vehicle power losses under various operating circumstances and terrains by modeling a hybrid off-road engine. Hermann et al. [89] reviewed and compared components for on-road automobiles' electric powertrains with the advantages of electric powertrain components.

5. Summary and Outlook

FC hybrid power systems realize efficient, clean, and high dynamic response energy supply by combining FC with a secondary energy storage device. This paper mainly reviews the classification, working principle, and positive and negative aspects of system of fuel cell hybrid electricity; analyzes the research status of three kinds of FC hybrid power systems in detail from passenger cars, buses, and heavy duty trucks; and reviews and summarizes the existing system of FC hybrid electricity and energy strategy. This offers a point of reference for the subsequent line of inquiry.

Fuel cells' green energy is a competitive advantage for the automobile sector and serves as an optimal alternative to internal combustion engines [90]. Presently, within the green energy industry, battery electric vehicles (BEVs) possess a cost advantage in manufacturing over FCEVs in both small and medium market segments [91]. Because of this, the market for fuel cell electric cars for light-duty vehicles seems to be quite promising by 2030, making up half of the current competitive categories [92]. Their distinct benefits, which include compatibility with renewable energy sources, high energy density, zero emissions, and quick fuel replenishment, have led them to be considered as an important pillar of the future energy system. However, current fuel cell systems still face challenges such as high cost, short lifetime, and insufficient hydrogen infrastructure. In order to realize its large-scale application, it needs to be synergistically promoted from the following four dimensions: technological breakthrough, system optimization, application expansion, and policy support. In the following, we discuss in detail the development path and key breakthrough directions in the next decade from these four aspects.

5.1. Technological Breakthroughs: From Material Innovation to the Upgrading of the Entire Hydrogen Energy Chain

Fuel cell electric car research and commercialization are expanding across the board [93]. In 2020, in the Asian market, Hyundai introduced the new NEXO model with an estimated driving range of 380 miles, and BMW developed SUV concepts for future models of the premium X series. The main challenges faced by developers in the automotive industry to improve FCEVs and increase global sales are durability and cost [94,95]. Proton exchange membrane FCSs' catalysts are most impacted in terms of durability, and they are constantly looking for solutions to improve electrochemical properties, structure, and morphology [96]. Based on 2D nanomaterials, advanced electrocatalytic technologies have been developed [97]. Meanwhile, with a maximum lifespan of ten years, the battery system is another component that compromises the longevity of FCEVs. The primary causes of this degradation include high discharge/charge rates, overheating, and the local environment [98].

The technological breakthrough of FC hybrid systems is the foundation of industrialization, and it needs to achieve leapfrog development in the fields of core materials, hydrogen production technology and storage and transportation technology. First of all, the core materials should be iterated to low cost and high performance. Currently, more than 40% of the fuel cell cost comes from platinum-based catalysts, and reducing platinum loading and developing non-precious metal catalysts are the key directions of technology research. The atomic level-dispersed Fe-N-C material developed by Argonne National Laboratory in the U.S. has an oxygen reduction reaction (ORR) mass activity close to 90% of that of platinum catalysts, with a cost of only 1/20 of platinum-based catalysts. Then, hydrogen energy preparation should be conducted by a parallel approach of green hydrogen scaling up and distributed hydrogen production. The PEM electrolyzer should be scaled up to save expenses and boost productivity, e.g., the use of titanium-plated stainless steel in the bipolar plate instead of pure titanium. For example, the application of stainless steel with a titanium coating instead of pure titanium for the bipolar plates reduces the manufacturing cost of the electrolyzer; according to the National Renewable Energy Laboratory (NREL), the efficiency of the PEM electrolyzer has been increased from 60% to 75% through high-temperature and high-pressure operation (90 °C, 30 bar). The III-V semiconductor PEC device developed by the U.S. NREL has an efficiency of 19.3% and a lifespan of more than 1000 h, which provides a possibility for distributed hydrogen production. Finally, research has been conducted on storage and transportation technology, cracking the hydrogen energy “last kilometer” problem. The storage and delivery of hydrogen using high-pressure gas has been investigated, such as the European hydrogen backbone network plans to build 28,000 km of pipeline hydrogen transmission in 2030, with the proportion of hydrogen doped up to 20%, reducing the cost of transmission. Innovative solid-state hydrogen storage materials and $\text{MgH}_2\text{-TiMn}_2$ composite materials were developed by Tohoku University in Japan, decreasing hydrogen absorption and discharge temperature down to below 150 °C.

5.2. System Optimization: Multi-Energy Coupling and Intelligent Control Reconstructing Power Architecture

The hybrid power system using fuel cells needs to evolve from a single power source to a multi-energy complementary, intelligent, and synergistic energy hub, and its optimization should cover the three major dimensions of energy management, thermal management, lightweighting, and structural integration design. First of all, energy management adopts the method of combining hybrid topology and intelligent algorithms to innovate hybrid architecture, and the SOFC micro gas turbine system developed by Bloom Energy in the U.S., with a power generation efficiency exceeding 70%, is used as a backup power source for data centers. The deep reinforcement learning (DRL) algorithm is used to dynamically adjust power allocation according to road conditions and SOC to adapt to complex working conditions. This has been combined with digital twin technology to realize the dynamic monitoring of system life, and fuel cell waste heat has been used to improve comprehensive energy efficiency. Second, the thermal management system allows for waste heat recovery and precise temperature control. The step-by-step utilization of waste heat, low-temperature waste heat-driven refrigeration, and the fuel cell 80 °C waste heat-driven ammonia absorption chiller provide a −18 °C freezing capacity for cold chain logistic vehicles (Hyundai pilot project). Medium-temperature waste heat-driven power generation, with 150 °C waste heat driving Organic Rankine Cycle (ORC) power generation, increases the total system efficiency by 5% (Mitsubishi Heavy Industries case in Japan). Micro-channel cooling panels developed by UTC in the U.S. increased heat dissipation capacity by 50%, with the temperature difference of the power stack controlled within ± 1 °C. A variable flow cooling system is used to dynamically adjust the coolant

flow according to the load. Then, lightweight and structural integration design is applied, and a magnesium alloy battery frame is adopted to reduce weight and improve impact resistance. By integrating the design of the electrostack–air compressor module, Germany’s Bosch integrated the air compressor into the electrostack end plate, reducing the length of the pipeline by 80% and the weight by 15%. By adopting the 3D printed flow field structure, General Electric utilized additive manufacturing to prepare bionic tree-like flow channels to enhance gas distribution uniformity.

5.3. Application Scenarios: Full Scenario Penetration from Transportation to Energy Networks

Utilizing a hybrid fuel cell system should break through the traditional transportation field and penetrate into diversified scenarios such as energy network, industrial process, building energy supply, etc., so as to form a complete ecosystem of “Hydrogen Energy Society”.

Regarding heavy duty, long-distance, and all-area development transportation, in heavy trucks and long-distance transportation, for example, Daimler GenH2 hydrogen heavy duty trucks equipped with a 2×150 kW fuel cell system and range of 1000 km, the whole life cycle cost (TCO) is expected to be the same as diesel vehicles in 2030. In shipping and aviation, the Norwegian MF Hydra ferry adopts a 3.2 MW fuel cell set, reducing CO₂ emissions by 95% after replacing diesel power.

In the energy sector, we are building a resilient network with hydrogen electricity integration and increasing efforts to utilize off-grid power supply systems. Huawei’s fuel cell–PV hybrid microgrid deployed in Tibet provides 24 h power supply for 5G base stations, improving overall efficiency and reducing operation and maintenance costs. The adoption of combined heat and power supply and the establishment of household CHP systems, with Japan’s ENE-FARM series SOFC system generating electricity with an efficiency of 65% and using waste heat for heating, reduce household energy costs. By participating in data center energy supply, Microsoft cooperates with Plug Power to deploy 3 MW fuel cell backup power in data centers with high reliability.

In the industrial sector, the iron and steel industry can adopt hydrogen-based direct reduction iron technology to reduce steel carbon emissions and accelerate the pace of commercialization. Hydrogen fuel cells are utilized to power electric arc furnaces, replacing natural gas and reducing emissions. Green hydrogen may replace gray hydrogen in the chemical industry’s ammonia production process. Methanol may also be made by hydrogenating carbon dioxide. The Carbon Recycling International (CRI) plant in Iceland, which synthesizes methanol from hydrogen + CO₂ using geothermal heat, has an annual production capacity of 4000 tons, with a carbon reduction efficiency of 90%.

5.4. Policy Support: From Single-Point Subsidy to Full Ecological Construction

Policies need to be laid out in an all-round way from technology R&D, infrastructure, and market cultivation to international cooperation to build a sustainable industrial ecology. In terms of financial incentives and market mechanisms, China provides a maximum of CNY 500,000/vehicle purchase subsidy for hydrogen fuel cell heavy trucks and incorporates the carbon trading market, with a gain of CNY 80 per ton of CO₂ emission reduction. The EU Carbon Border Adjustment Mechanism (CBAM) levies a hydrogen substitution spread on imported steel, forcing enterprises to transform. An infrastructure-first strategy should be implemented to accelerate the construction of a network of hydrogen refueling stations to cover the country’s major logistics corridors. The construction of hydrogen pipelines should also be accelerated. The European Hydrogen Backbone (EHB) plans to complete 28,000 km of hydrogen pipelines by 2030, connecting wind power hydrogen production bases in the North Sea with industrial centers. In terms of standardization and international

collaboration, the Chinese-led “Low Temperature Cold Start Specification for Fuel Cell Vehicles” has become an international reference, and IPHE (International Partnership for Hydrogen Energy) promotes the joint research of China, the United States, Europe, and Japan on common technologies such as membrane electrodes and high-pressure hydrogen storage. At the level of vehicle purchase incentives, Germany links the efficiency of the entire vehicle (range ≥ 800 km, hydrogen refueling ≤ 15 min) to 60% of the vehicle purchase subsidy, forcing a high degree of standardization of the technology. Meanwhile, China’s Jiulongpo, Chongqing, is offering a special subsidy of 1 RMB/W to the high-power system of 180 kW or more. The current policy design is moving from a single subsidy to a multi-level synergy, and the models of other nations provide unique references for our nation. Henan is the first province to implement a highway toll-free policy for hydrogen energy-heavy trucks, which lowers the total cost of ownership of long-distance transportation by 30%. Seven provinces have adopted this strategy, which links the green hydrogen-carbon market by linking subsidies for hydrogen refueling stations to carbon intensity thresholds and imposing limits on carbon intensity thresholds. The system is given a special subsidy of RMB 1/W to promote the power density of heavy trucks by 40%. A “subsidy regression-green hydrogen energy cost reduction” closed loop serves as an empirical reference. At the level of green hydrogen-carbon market linkage, the EU links subsidies for hydrogen refueling stations to the carbon intensity threshold (≤ 1 kgCO₂e/kgH₂), while China’s Liokengdao encourages the use of hydrogen refueling stations through hydrogen refueling volume step subsidies ($\leq 30,000$ kg: RMB 40/kg; $>30,000$ kg: RMB 25/kg).

The creation of a hybrid FCS is a systematic revolution covering material science, energy engineering, policy and economy, and social collaboration. Technological breakthroughs need to focus on catalysts, electrolyte membranes, and other “choke points”; system optimization needs to solve the problem of multi-energy coupling and intelligent control; application expansion needs to tap into the depth of demand for transportation, energy, and industry; and policy support should be built to cover the whole ecological support system of research and development, infrastructure, and finance. Fuel cell hybrid systems will move from demonstration applications to large-scale commercialization and become the core energy carriers in the carbon neutral era. This process requires not only the wisdom of scientists and engineers, but also the vision of policy makers and the synergy of the global industry. Only in this way can the hydrogen society truly move from blueprint to reality.

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