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REVIEW PAPER

Optimization and cutting-edge design of fuel-cell hybrid electric vehicles

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Summary

The transportation sector consumes a large amount of fossil fuels consequently exacerbating the global environmental and energy crisis. Fuel-cell hybrid electric vehicles (FCHEVs) are promising alternatives in the continuous transition to clean energy. This article summarizes the recent advances pertaining to the optimization and cutting-edge design of fuel-cell hybrid electric vehicles, especially the fuel cell + battery hybrid topology, and discusses current technological bottlenecks hindering the commercialization of FCHEVs. The development of HEVs, markets, environmental and economic benefits, components, topologies, energy management strategies, degradation mechanisms, and safety standards of FCHEVs are reviewed. Proton exchange membrane fuel cells constitute the mainstream and most mature fuel cell technology for automobile applications. Battery hybridization is currently favored among the available FCHEV topological designs to improve the dynamic response and recover the braking energy. Energy management strategies encompassing logic rule-based simple methods, intelligent control methods, global optimization strategies, and local optimization strategies are described, and issues and challenges encountering FCHEVs are discussed. In addition to promoting the construction of hydrogen supply facilities, future efforts are expected to focus on solving problems such as the high cost, durability of fuel cells, cold start, lifetime of batteries, security and comfort, system optimization, energy management systems, integration, and diagnosis of faults. This review serves as a reference and guide for future technological development and commercialization of FCHEVs.

Highlights

- Advances of the optimization and cutting-edge design of FCHEVs are reviewed.
- Battery hybridization is currently favored among the available topological designs.

- Benefits, components, topologies, and energy management strategies are described.
- Markets, degradation mechanisms, and safety standards of FCHEVs are introduced.
- Technological bottlenecks hindering the commercialization of FCHEVs are discussed.

KEYWORDS

batteries, challenges, energy management strategies, fuel-cell hybrid electric vehicles, topologies

1 | INTRODUCTION

Green technology is in high demand in this century. In particular, the rapid growth of modern cities has led to increased transportation needs giving rise to heavy traffic, consumption of a large amount of fossil fuels, and ensuing environmental problems.[1,2] Therefore, vehicle emissions must be controlled and reduced by implementing cleaner technologies. By reducing carbon emission and other pollutants, electric vehicles (EVs) have a positive impact on the environment. Hybrid vehicles (HVs) such as the Honda Insight and Toyota Prius have been developed to reduce the use of internal combustion engines (ICEs) by combining them with electric motors.[3] With the advent of battery electric vehicles (BEVs), the emission of greenhouse gases has been partly addressed.[4] BEVs are zero-emission vehicles that operate entirely on electricity produced by batteries. However, BEVs do not radically reduce greenhouse gas (GHG) emissions since the electricity is mostly generated by thermal power plants.[5] In addition, BEVs have their own drawbacks such as the limited driving range, long battery charging time, and battery safety.[6] Although the development of near-zero-emission vehicles is still a big challenge, EVs fueled by renewable energy are the desirable choice since they emit only natural byproducts such as water rather than GHGs, consequently improving the air quality and human health.[7]

Recently, fuel-cell electric vehicles (FCEVs) have attracted more and more attention from the automobile industry with strong commercial interest. FCEVs are powered by electric motors that receive power from a fuel cell (FC), and hydrogen combined with oxygen from air is the main energy mover in FCEVs. A comparison of the major emerging energy devices including FCs, batteries, and solar cells is presented in the Ragone plot (Figure 1). FCs have higher energy densities than other energy devices rendering them suitable for long-range vehicular applications, and these benefits have consequently spurred the research and development of FCEVs. Plug-in FC hybrid electric vehicles (FCHEVs)[8] and FC extended electric vehicles have also gained much attention.[9,10] FCs have a number of other benefits, including clean fuel, high efficiency, no harmful emission, and low noise.[11] A startup system is needed when using the FC as the sole power source for an EV. Hence, automakers have developed FCHEVs powered by a FC and either one or more auxiliary power sources such as batteries and supercapacitors. Daimler Mercedes Benz F-Cell, GM Chevrolet Volt, Toyota FCHV, and Honda FCX are all hybrid electric vehicles (HEVs) with the FC + battery configuration.[12] Since the energy source of FCHEVs alternates between the FC and auxiliary power, a reliable energy management system (EMS) is needed. According to the operating mode or power demand, the EMS is required to distribute power between the FC and auxiliary power.[13] A successful EMS not only guarantees the normal operation of vehicles, but also allows each source to supply power efficiently, satisfies physical constraints, prolongs service life, and achieves comprehensive fuel economy.[14]

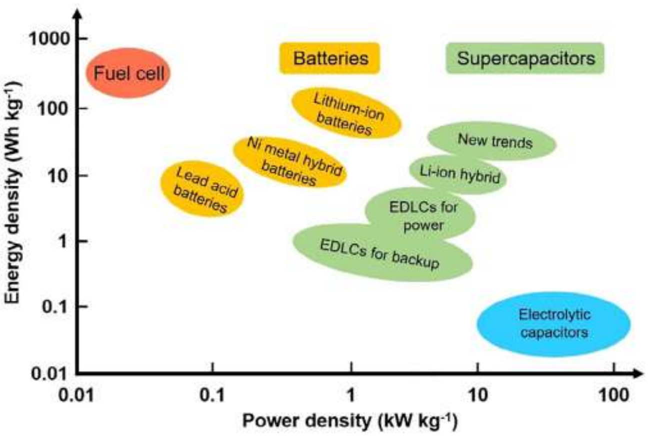

FIGURE 1 Ragone plot of various emerging energy devices [Colour figure can be viewed at wileyonlinelibrary.com]

In this review, the recent development of HEVs, markets of FCHEVs, and environmental and economic benefits of FCHEVs are described. The components, topologies, energy management strategies, and safety standards of FCHEVs are also presented, and finally, current issues and challenges for FCHEVs are discussed.

2 | DEVELOPMENT OF HEVs

The first HEV was introduced by Henri Pieper of Germany in 1899.[15] Dr Ferdinand Porsche produced the world's first series of HEVs in 1900 containing two water-cooled combustion engines with a combined capacity of 5 hp to generate electricity for the wheel hub motors.[16] The main function of these motors was to support the underpowered gasoline engines. However, owing to their high cost, this design was ignored for a long time. Because of concerns about fuel saving and pollution reduction, renowned manufacturers revived their interest in HEVs after 1995 and several HEV models such as micro-HEVs, moderate HEVs, full HEVs, and plug-in HEVs have been developed.[17]

(A) Micro-HEVs: Micro-HEVs have a low level of hybridization, combining the EMS in the form of regenerative braking with electromechanical operation. When a micro-HEV comes to a complete stop or the brake pedal is released, a small integrated alternator/starter kicks in as the electric motor to shut down or start up the engine. However, the kinetic energy recovered during braking is limited because of the small configured motors and batteries. The ICE propels the vehicle when it is moving. A typical generator's capacity falls in the range of 2 to 4 kW, and the conventional battery voltage is ∼12 V. Commercial examples are the A-class of Mercedes-Benz, 1 and 3 series of BMW, SMART car, Focus and Transit of Ford, Peugeot Citroen C3, and Fiat 500.[18] (B) Moderate HEVs: Moderate HEVs are similar to micro-HEVs, but with larger motors of up to 15 kW and batteries that allow for power assistance during propulsion. In real driving, moderate HEVs usually improve the fuel efficiency by 20% to 25% compared with non-hybrids. Economically, the added cost of the bigger motor can be offset by the removal of the starter motor and generator. The production of moderate HEVs does not require major changes to existing manufacturing lines. The Mercedes-Benz S400 BlueHybrid, BMW 7 Series ActiveHybrid, Chevrolet Malibu-eAssist, Buick LaCrosse-eAssist, and Civic and Insight Hybrid of Honda are examples of moderate HEVs.[19] (C) Full HEVs: Full HEVs can run in either conventional ICE mode or electric mode. The electric motors and batteries in full HEVs are considerably larger than those in micro-and moderate HEVs. As a result, the electric motor may be used as the primary power source depending on the power demand. Full HEVs have much smaller engines than micro- and moderate HEVs, and so they require more complicated EMSs. The batteries in HEVs are automatically charged by the motor/generator with the help of proper EMSs. In real driving, full HEVs usually improve the fuel efficiency by 40% to 45% compared with non-hybrids.[20] The Chevrolet Tahoe Hybrid, Prius and Camry Hybrid of Toyota, Honda CR-Z, Ford C-Max, and Kia Optima Hybrid are examples of full HEVs. (D) Plug-in HEVs (PHEVs): PHEVs have the same basic setup as full HEVs, but with additional power grid charging plugs, and they have larger electric motors and batteries but smaller engines.[21] PHEVs can operate on electric power for a longer period of time due to the high-capacity batteries. They have the advantages of less single fuel dependence, lower GHG emissions, higher fuel economy, less dependence on oil, higher energy efficiency, and the combination of vehicle and grid technologies. The Porsche Panamera S E-Hybrid, Chevy Volt, Toyota Prius Plug-in, C-Max Energi and Fusion Energi of Ford, and Fisker Karma are examples of commercial PHEVs.

HEVs have several advantages over traditional vehicles so that the original ICEs can be downsized while satisfying the power demand at the pedal. This benefit is due to the hybrid powertrain ability to deliver power to the wheels concurrently from both the ICE and electric motor, and consequently, fuel consumption is reduced.[22,23] The feature of engine shut-off/startup in full HEVs reduces fuel consumption during idling.[24] The addition of an electric drivetrain to the HEV also enables kinetic braking energy recovery and driving of the wheels solely by the electric propulsion system when the torque demand is low.[25-27] By charging from the grids, a PHEV can emit less pollutants than a conventional HEV, reducing GHGs by 40% to 65%, NOx by 25% to 55%, and gasoline consumption by 45% to 80%. Besides the benefit of reduced fuel consumption, HEVs provide the option of cranking the engine with the electric motor, which removes the starter motor from the powertrain. As for inertia cranking, this new method allows for quicker and smoother cranking,[24] but the proper time management strategy that coordinates onboard power to maximize the fuel efficiency and reduce emission is key to achieving the above merits.

3 | MARKETS OF FCHEVs

The emergence of high-power FC systems for the transportation sector as well as production of commercial/passenger FCHEVs unveils the commercial potential of this new technology. On the heels of the rapid advancement in the automotive industry to improve the fuel economy, interests in the FCHEV technology have grown significantly in recent years.[28]

In fact, big vehicle manufacturers have built more powerful and cleaner powertrains to replace traditional oil-powered ICEs. Vehicle prices have dropped significantly as a result of technological advances pertinent to hydrogen production, storage, and conversion to electricity,[29] for example, FCHEVs models such as commercial passenger vehicles,[30] buses,[31] and trucks.[32-34] Battery hybridization is currently favored among the available FCHEV topological designs. GM, Toyota, and Honda have produced their own FC stacks, whereas DaimlerChrysler, Ford, Mazda, Mazda, Hyundai, Volkswagen, and Fiat purchase them from FC manufacturers.[35] Furthermore, manufacturers such as Mercedes, Hyundai, and Honda have recently developed plug-in FCHEVs and the proton exchange membrane fuel cell (PEMFC) is the mainstream component in FC stacks. They are being improved reaching more than 100 kW.[36]

Since automotive emissions have detrimental effects on the atmosphere and human health, governments worldwide are imposing stringent vehicle emission regulations.[37] Increasing environmental concerns, governments' plans for the construction of hydrogen refueling facilities, and higher performance of hydrogen FCHEVs are factors spurring the development of hydrogen FCHEVs. FCHEVs are projected to be in high demand due to the low emission and compliance with regulations. Moreover, government subsidies for the construction of hydrogen refueling stations and production of FCHEVs are expected to boost the growth.[38] The global sales and holdings of FCHEVs from 2016 to 2019 are shown in Figure 2, but unfortunately, FCHEVs are still costly and the price of hydrogen per kilogram is high as well. These are the two reasons that are limiting the market share of FCHEVs, but there is ongoing research to reduce these costs. The long-range and heavy-duty transportation market is expected to be the largest source of growth for FCs in the coming decades. Modified modularization, higher efficiency, longer driving range, and construction of hydrogen supply for onboard FC systems are the future commercial development directions.

4 | ENVIRONMENTAL AND ECONOMIC BENEFITS OF FCHEVs

Hydrogen-powered FCHEVs emit just 20% of the gross GHG emissions of ICE vehicles over their entire lifetime.[40] The reduction of GHG emissions is a major motivation for FCs in the transportation sector, and the transportation revolution is ushered by zero-carbon vehicles. In contrast to EVs and ICEs, FCHEVs with renewable fuels have low emissions in all situations.[41] From 2030 to 2050, FCHEVs fueled by renewable hydrogen are supposed to provide 13.9% reduction in the transportation GHG emission and equivalent CO_2 emission of 139.5 mt.[41] Lead-acid batteries, which are now widely used in forklifts and some construction vehicles, produce toxic emissions. Sulfuric acid, used as an electrolyte in lead-acid batteries, is highly corrosive and may transform to sulfide gas during operation, affecting the safety of the working environment and causing harm to humans. When the capacity drops to 80% of the initial value, the EV batteries should be replaced. It will take much more time and cost for the industry to properly handle and recycle the decommissioned batteries. FCHEVs can extend the battery life, significantly mitigating these problems.

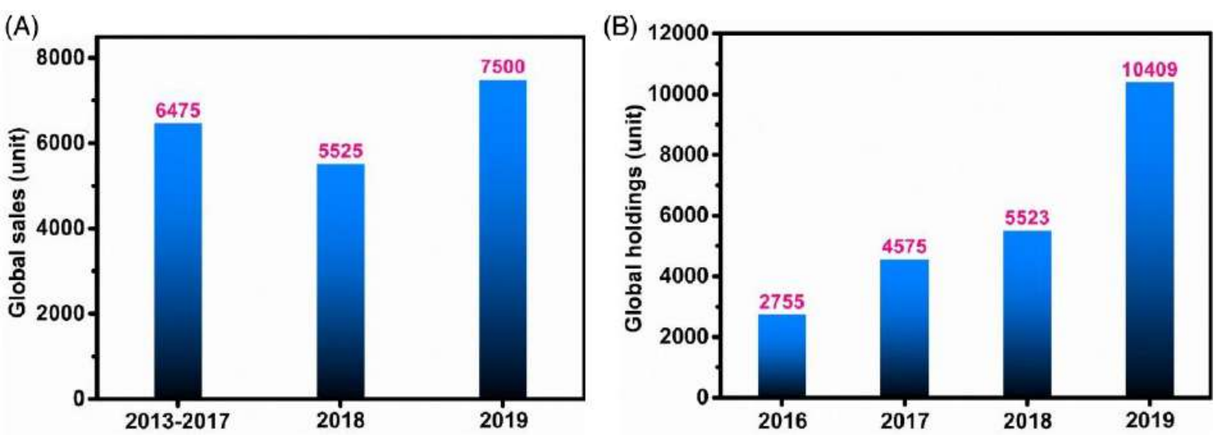

FIGURE 2 (A) Global sales and (B) global holdings of fuel-cell electric vehicles (FCEVs)[39] [Colour figure can be viewed at wileyonlinelibrary.com]

The high cost of FC vehicles is the primary impediment to large-scale deployment, but combining the FC and battery can reduce the overall cost and close the gap. From 2016 to 2050, gross transportation costs are expected to be cut in half.[2] According to International Energy Agency, the operation cost of FC systems will be significantly lowered in the near future, and the price is expected to be just over \$50 per kW in 2030 and below \$50 per kW worldwide in 2050. Currently, the selling price of FCHEV is ~\$74 460, but in the ambitious 2030 projection, it is expected to drop to \$16 350, thus approaching the price of \$14 880 for a conventional ICE vehicle and \$15 580 for an EV.[42] The average hydrogen FC bus consumption of 12.0 kg H_2/100 km and the fuel cost of 3.93 €/kg H_2 will be competitive based on the costs of 47.20 €/100 km and 1 €/L for diesel buses.[43] As zero-emission vehicles, FC vehicles and FCHEVs are the only relevant models that can compete with and even surpass the current mainstream pure EVs. In the future, fossil fuel-powered ICE vehicles will become increasingly expensive and gradually phased out since emission regulations become more and more stringent.

5 | COMPONENTS OF FCHEVs

A full FCEV is powered solely by the FC, but usually, the PEMFC has limitations.[44] The PEMFC's membrane electrode assembly (MEA) is vulnerable to failures such as membrane splits, internal gas leakage, and cell flooding/drying.[45] In addition, PEMFCs have a sluggish dynamic response to load changes, thus decreasing the service life.[46] The efficiency, cost, durability, reliability, fuel access, safety, and performance in transient are important considerations when designing FC vehicles in order to compete with ICE vehicles.[47] Hence, automakers have begun to develop FCHEVs. Starting, cruising, accelerating, and braking are all cases that impact the operation of the FCHEV system.[26,48] The different energy sources in FCHEVs must be controlled in order to ensure that the energy fed to the electric motor is adequate to satisfy the demand or load power. This is because depending on the circumstances, energy can be generated from the FC, battery, supercapacitor, or their hybrid, and in addition, the auxiliary energy sources such as the battery and supercapacitor should be charged at a suitable time.[49]

5.1 | FC stack

The FC is an electrochemical system that uses chemical energy of the fuel to produce electrical energy. It inputs fuel and air and produces energy and water by a chemical reaction.[50] FCs incorporate the benefits of engines and batteries, thus enabling them to run as long as fuel is available.[51] Their properties are identical to those of batteries under loads.[52] In comparison with FCs, conventional heat engines produce electricity through a mechanical energy conversion mechanism, which has lower efficiency. Figure 3 shows the schematic diagram of a simplified FC. Even if different forms of fuels are used, the chemical reactions are similar. The fundamental theory was proposed by Swiss scientist Christian Friedrich Schönbein in 1838,[55] and Sir William Robert Grove created the first fuel cell in 1839.[56] The theoretical voltage provided by the reaction of H_2 and O_2 is 1.23 V, but the voltage is less than this in practice. The voltage decreases and the current increases due to reasons such as activation loss, ohmic loss, and mass transport loss.[57,58] At the rated current, a single cell generates about 0.6 to 0.7 V.

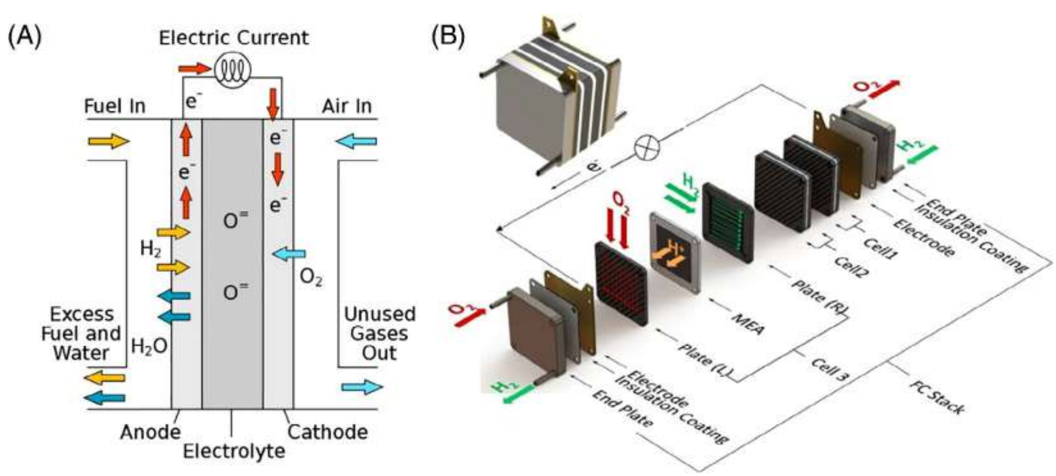

FIGURE 3 Concept of (A) a single fuel cell (FC) and (B) proton exchange membrane fuel cell (PEMFC) stack.[53,54] Copyright © 2021 Wikipedia and 2017 Elsevier [Colour figure can be viewed at wileyonlinelibrary.com]

At present, the development of FC-based applications is underway, and there is an emphasis to reduce the cost and increase the efficiency.

Table 1 shows that FCs are categorized into different classes depending on their chemical properties and operating characteristics. The PEMFC, solid-oxide FC (SOFC), direct methanol FC (DMFC), alkaline FC (AFC), molten carbonate FC (MCFC), and phosphoric acid FC (PAFC) can be used in FCHEVs. The operating temperature and power range of different types of FCs are graphically displayed in. Figure 4. Because of the high power density, a lower working temperature (60°C-80°C), and lower corrosion than other FCs, PEMFCs are widely adopted in vehicles.[59,79]

5.2 | Batteries

The electrodes, electrolyte, and separator make up the battery, and the electrode materials play a particularly significant role.[80] The lead-acid battery, nickel-cadmium battery, nickel-metal hydride battery, and lithium-ion battery are common in automotive applications, as shown in Table 2. The lead-acid battery is a proven technology with a low cost, but it has a low energy density and pollution problems such as lead poisoning.[88] The nickel-metal hydride battery has a high energy density of over 60 Wh/kg and a long lifespan, but has a high self-discharge rate of over 28%.[89] With a high energy density of up to 160 Wh/kg and operational cycle of over 600 hours, the lithium-ion battery is suitable for EVs.[81] A sufficiently high energy density is important to commercial automobile applications. Nearly, all the EVs use lithium-ion batteries, even though a limited number of HEVs are switching from lithium-ion batteries to nickel-metal batteries.[90] To extend the battery lifetime, the battery should be operated within a certain range of state of charge (SOC). The positive electrode limits the energy density, which can be increased by using advanced materials such as lithium iron phosphate, ternary materials, and lithium manganite.[91] LG, for example, achieved a high energy density of up to 284 Wh/kg with nickel-cobalt-aluminum ternary cathode, whereas Panasonic demonstrated an energy density of over 200 Wh/kg with lithium manganese.[92,93]

5.3 | Supercapacitors

The supercapacitor is a high energy density storage device that is a derivative of the standard capacitor. It is also known as an electrochemical capacitor or ultracapacitor.

TABLE 1 Characteristics of different types of FCs[59-78]

Type	PEMFC	SOFC	DMFC	AFC	MCFC	PAFC
Representative electrolyte	Nafion membrane	Yttria stabilized zirconia	Nafion membrane	KOH solution	Lithium, sodium, and/or potassium carbonate solution	Phosphoric acid
Fuel	Pure H_2	H_2, CO, CH_4, etc.	CH_3OH	Pure H_2	H_2, CO, CH_4, etc.	Pure H_2
Efficiency (%)	40-60	~60	~40	~60	~50	~40
Temperature range (°C)	<100	500-1000	60-200	90-100	600-700	150-200
Cell voltage (V)	~1.1	0.8-1	0.2-0.4	~1	0.7-1	~1.1
Stack power (kW)	<1-250	<1-3000	0.001-100	1-100	1-3000	50-1000
Advantages	Lower operating temperature; Fast start; Fewer corrosion and electrolyte problems	Combined heat and power; Higher efficiency; F uel flexibility; Hybrid gas turbine	No need for fuel reformer; Easy fuel storage	Fast start and cathode reaction; Lower material cost; Lower operating temperature	Combined heat and power; Higher efficiency; Fuel flexibility	Higher efficiency; Combined heat and power; Better tolerance for fuel impurity
Disadvantages	Expensive catalyst; Sensitive to fuel impurity	High operation temperature; High corrosion; Poor durability; Slow start	Easy to catalyst poisoning; Low power	Sensitive to CO_2 impurity	High operation temperature; Slow start; Low power	Expensive catalyst; Slow start

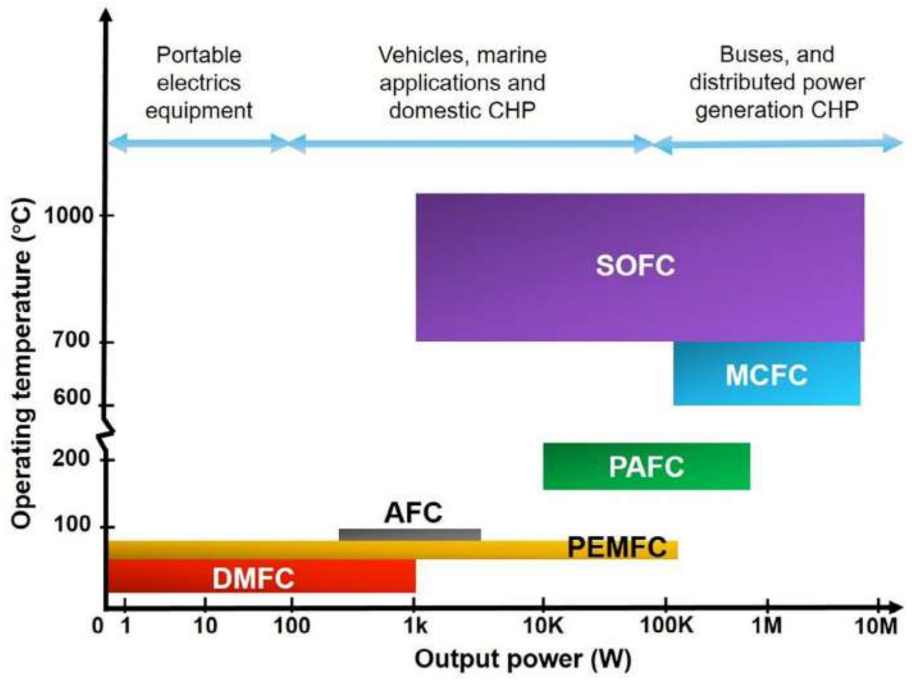

FIGURE 4 Operating temperature and power range of different types of FCs[78] [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Characteristics of different types of batteries[81-87]

Type	Lead-acid battery	Nickel-cadmium battery	Nickel-metal hydride battery	Lithium-ion battery
Energy density (Wh/kg)	20-50	60-100	40-60	100-160
Power density (W/kg)	80-300	200-1500	200-500	80-2000
Service life (cycle)	300-450	~750	~500	600-2000
Self-discharge rate monthly (%)	~5	~28	~20	3-10
Capital cost ($ kWh^{-1})	~70	300-500	~300	200-700

The capacity of a supercapacitor is measured in Farad (F), whereas that of a traditional capacitor is measured in milli-Farad (mF), micro-Farad (μF), and pico-Farad (pF).[94-96] However, in order to maximize the energy density, the supercapacitor's power density is sacrificed. In the traditional capacitor, insulating dielectric materials separate the two conducting electrodes but in a supercapacitor, the electrodes are encased in an electrolyte and separated by a separator.[97,98] Electrolytes are used to store the electrostatic charges in the form of ions. A traditional capacitor has a power density of ~1000 W/m^3 and energy density of ~50 Wh/m^3, whereas a supercapacitor has a power density of ~100 W/m^3 and energy density of ~100 Wh/m^{3}.[99] The supercapacitor electrodes have a much larger surface area than the typical battery or capacitor electrodes.[97,98] The electrodes absorb ions and have a much higher charge density than conventional capacitors. Since ions travel more slowly than electrons in supercapacitors, it takes longer to charge and discharge than electrolytic capacitors, resulting in a higher power.[99,100] The usable energy stored (E) in a supercapacitor is given by

$$E(\mathrm{Wh}) = 0.5CV_r^2(0.75)/3600, \quad (1)$$

where V_r denotes the rated voltage of the supercapacitor cell.

The supercapacitor is used as a battery replacement in a number of applications due to the high efficiency (>90%), high capacity, and wide operating temperature range.[101] The cost of supercapacitors has dropped significantly, and the capacity has increased at the same time as a result of advances in nanomaterial technology and commercial manufacturing. Consequently, the use of supercapacitors has grown in popularity. It was first used militarily to ignite combat tanks and submarine engines.[102] It is currently used in locomotives, diesel engines, actuators, wind turbine pitch control, and memory backup. It is also used in regenerative braking applications because of the fast charging capacity.[55]

Supercapacitors can be classified into three main types: electrochemical double-layer capacitors (EDLCs), pseudocapacitors, and hybrid capacitors.[103] Each class has its own set of characteristics and charge-storage mechanisms. The charge-storage mechanisms are non-Faradaic, Faradaic, or a combination of both, respectively. Charges are spread on the surfaces by a physical mechanism that does not make or break chemical bonds in the non-Faradaic process.[104] Charges are transferred between the electrodes and electrolyte in the Faradaic phase, and oxidative and reductive reactions are examples of this mechanism. Figure 5 presents the supercapacitor classification. Table 3 lists the chemical properties of different forms of supercapacitors as well as their applications. Since the EDL supercapacitor has a higher power density than the other two kinds, it is used in most of the applications.[108] EDLC is produced by many manufacturers such as Maxwell, Panasonic, Asahi Glass, APowerCap, EPCOS, Ness, LS Cable, Fuji, JSR Micro, BatScap, and Power Sys.

5.4 | Flywheels

Flywheel energy storage, also known as FES, is the one that stores and retains rotational energy using a rotating mechanical device.[109] The two states of FES are energy storage and energy release. When a torque is applied to a flywheel, energy is stored. The energy is released in the form of torque in the converse process,[110] and the stored kinetic energy of FES is expressed as

$$E_k = 0.5 I \omega^2, \tag{2}$$

where I is the moment of inertia, and ω is the angular velocity.

The mechanical and electrical outputs are used in FES technology. In most cases, the mechanical output approach is nearly twice as efficient as the electrical output one reaching ~70%.[111] By using frictionless magnetic and vacuum bearings, the mechanical performance efficiency of FES can be increased to 97% and the round-trip efficiency to 85%.[112] The FES device has advantages such as the long lifespan, fast response, low maintenance, short charging time, temperature independence, and nontoxic materials, thereby rendering it ideal for electric vehicle applications.[109,113,114] FES systems with an energy density of 10 to 150 Wh/kg, power density of 2 to 10 kW/kg, and lifetime of about 15 years have been developed.[78] Road cars, rails, uninterruptible power supply (UPS), train electrification, spacecraft energy storage, aircraft launcher systems, motor sports, amusement rides, soft toys, grid energy storage, and wind turbines are among the applications of the FES system.[115-117]

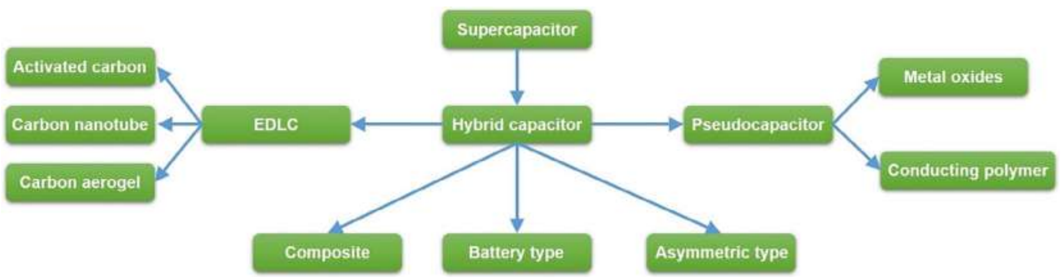

FIGURE 5 Classification of supercapacitors [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Characteristics of different types of supercapacitors[78,100,105-107]

Type	Activated carbon	Graphite	Metal oxides	Carbon/metal oxide	Carbon/metal oxide
Classification	EDLC	EDLC	Pseudocapacitor	Hybrid capacitor	Hybrid capacitor
Energy storage mechanism	Charge separation	Charge transfer/ intercalation	Redox charge transfer	Double layer/ charge transfer	Double layer/ faradaic
Cell voltage (V)	2.5-3	3-3.5	2-3.5	2-3.3	1.5-2.2
Energy density (Wh/kg)	5-7	8-12	10-15	10-15	10-12
Power density (W/kg)	1-3 M	1-2 M	1-2 M	1-2 M	1-2 M
Service life (year)	~40	~40	~40	~40	~40
Efficiency (%)	>95	>95	>95	>95	>95

Gyroscopic force control and safety problems are obstacles to FES systems in EV applications.[118,119]

5.5 | Electric motors

To meet the power density, efficiency, and cost requirements of the drivetrain in HEVs, advanced motors and generators are needed. The most popular motors for passenger vehicles are AC asynchronous motors and AC permanent magnet motors, which are distinguished by the energy conversion performance, high-speed control capability, overload capacity, and torque.[120] The former type, which Tesla employs, has a simple structure and high operational reliability and achieves an efficiency of 90% to 92%.[121] The latter form represented by Honda FC Clarity has improved speed range, power factor, and overload current and can boost the efficiency to 95% to 97%.[122] However, on account of the rare earth magnetic steel, the cost increases by nearly 50%.[123] Table 4 lists the common automotive motor products, and Figure 6 shows the classification of different traction motors.

5.6 | Power converters

Power converters are widely used in a variety of applications in the automotive industry to improve the controllability and performance.[126] DC/AC converters such as single-stage single-phase, single-stage three-phase, and zero-voltage switching inverters have been extensively studied.[127-129] In HVs, the bidirectional converter is needed to convert DC from the FC, battery, supercapacitor, or their combination into AC for the motor drive. Traction inverters have a variety of topologies including the voltage source inverter (VSI), current source inverter (CSI), impedance source converter (ZSI), and soft switching.[130]

TABLE 4 Characteristics of different types of electric motors[78,124]

Brand	SIEMENS	Continental	SHANGHAI EDRIVE	JJE	BorgWarner
Type	Permanent magnet synchronous	Integrated	Permanent magnet synchronous	Permanent magnet synchronous	Integrated
Peak power (kW)	30-170	~140	35-110	90-140	20-150
Peak torque (Nm)	100-265	~400	125-270	165-270	~315
Speed (rpm)	~12 000	~20 000	8500-12 000	~14 000	~10 600
Efficiency (%)	~96.5	~96	—	95-96	96

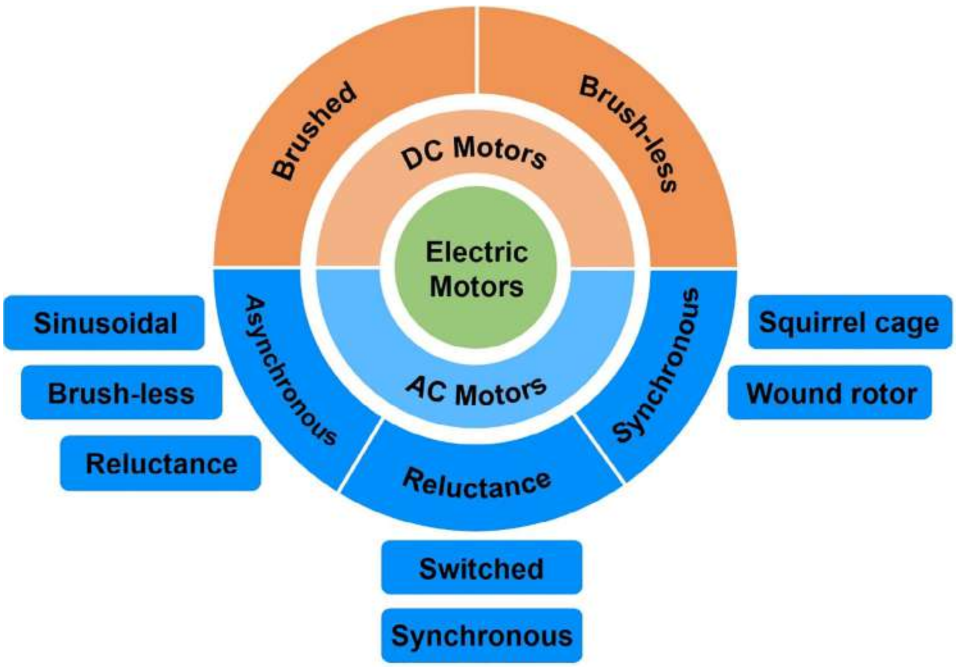

FIGURE 6 Classification of different traction motors[77,125] [Colour figure can be viewed at wileyonlinelibrary.com]

6 | TOPOLOGIES

Figure 7 presents the classification of FCEVs based on the energy units. Aside from sub-energy power supply modules, the main energy generation unit in FCEVs is an FC.[105] The power supplies in FCEVs are divided into two types: generation and storage.[131] Different energy generation/storage units are used to support the FC stacks in hybrid systems, and the supplementary energy units in FCHEVs include batteries, supercapacitors, superconducting magnetic energy storage system (SMES), photovoltaic (PV) panels, and flywheels. Table 5 displays the units of energy generation and storage as well as their characteristic properties. In contrast to other power sources, FCs have a higher energy density and efficiency. Besides, FCs are suitable for EV applications due to the modular construction[133] and the FC's lifespan is estimated to be more than 20 years.[134] The battery is also a common power source for FCEV hybridization as a portable/rechargeable energy storage device. However, its lifetime is short and it is only effective for a short period of time.[60] The supercapacitor is a storage unit in FCEV applications to improve the dynamic response,[135] but rapid discharging is the fundamental flaw.[59] A flywheel

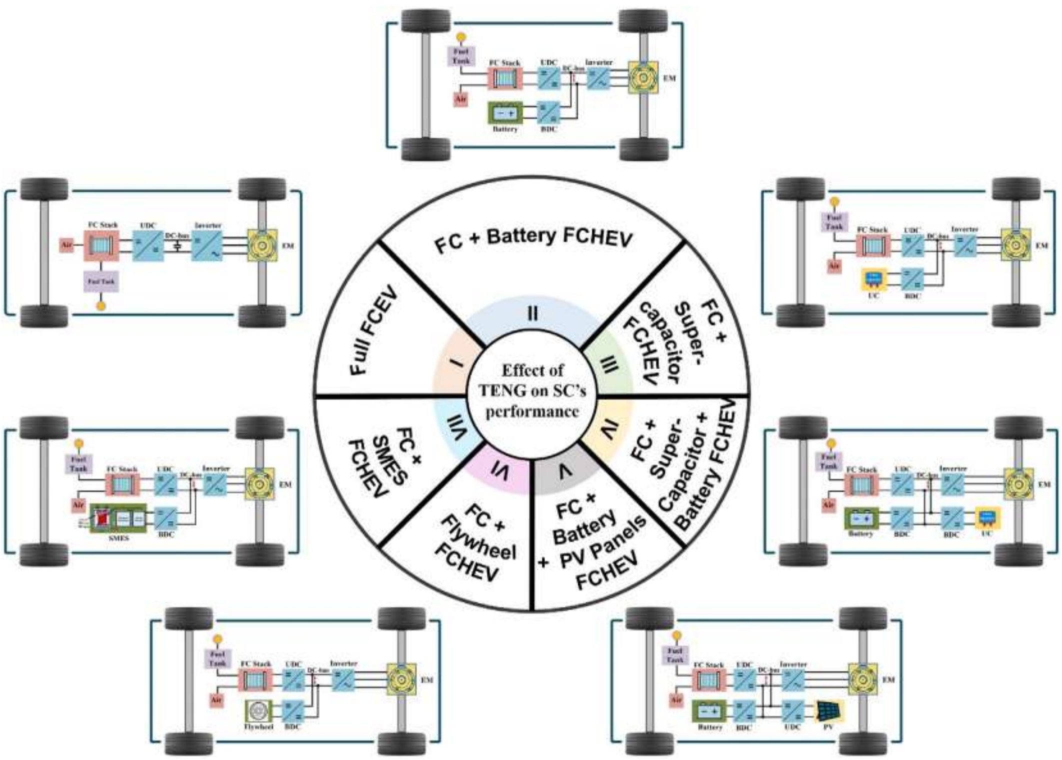

FIGURE 7 Topologies of fuel-cell hybrid electric vehicles (FCHEVs) according to the power sources[77] [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Characteristics of different types of power units[77,132]

Unit	FC	Battery	Supercapacitor	PV panels	Flywheel	SMES
Function	Generation	Storage	Storage	Generation	Storage	Storage
Energy density level	Very high	High	Very low	Medium	High	Low
Lifetime (year)	20-25	4-6	20-40	10-20	5-10	25-30
Advantages	High efficiency; Modular; compact; Stable output	Portable	Rapid response	Silent	Swift charging; high power rating	High power output
Disadvantages	Slow start and response; High cost	Limited service time; long charging time	Short-term service time	Intermittent output; Large volume	Long charging time; high weight	Short-term service time; high cost

is a high-energy density energy storage device, but it is heavy and bulky and also takes a long time to charge. The PV panel is an energy-generating unit but too large for transportation applications.[135] The SMES produces a high power in the output, but has a low energy density. It also has a short energy storage term and high cost.[136] The FC-powered vehicles are divided into several topologies: (a) full FCEVs, (b) FC + battery HEVs, (c) FC + supercapacitor HEVs, (d) FC + battery + supercapacitor HEVs, (e) FC + battery + PV panel HEVs, (f) FC + flywheel HEVs, and (g) FC + SMES HEVs.

6.1 | Full FCEVs

The full FCEV is one of the types (Type I shown in Figure 6) that uses a stack of FCs as the energy source. Low-speed vehicles such as forklifts, buses, airline vehicles, trams, and marine vehicles are suitable candidates for full FCEV applications.[137] This topology only uses an FC stack without other power sources. The FC stack, fuel tank, DC-DC power converter, inverter, and electric motor make up the basic structure.[133] Besides the structural simplicity, these vehicles have a long driving range, short charging time, cold-start capability, silent operation due to the lack of moving parts, continuous energy supply, and no polluting emission.[138] This topology is difficult to meet the instantaneous high power required by vehicles, and the use of a single DC/DC makes the excess energy of the system wasted.

6.2 | FC + battery HEVs

The most common hybridization topology for FCHEVs is a combination of FC + battery units (Type II).[139-141] In general, the FC is connected to the DC bus through a unidirectional DC-DC converter (UDC) and the battery is connected to a bidirectional DC-DC converter.[142,143] An initial startup with the battery is provided in this hybridization to preserve FC lifetime and avoid its unnecessary start and stop. As a consequence, it produces a significant amount of current to start the electric motor. The FC is turned on after the startup of the vehicle to keep the electric motor running,[60] and the battery is charged at this time in compliance with the charge status provision.[60] Figure 8 is a typical optimized sample of this topology. In the hybrid system, the FC stack is the primary power unit to deliver consistent power to the vehicle, while the lithium battery acts as an auxiliary power unit to handle additional power needs such as system startup, acceleration, climbing, and even backup power

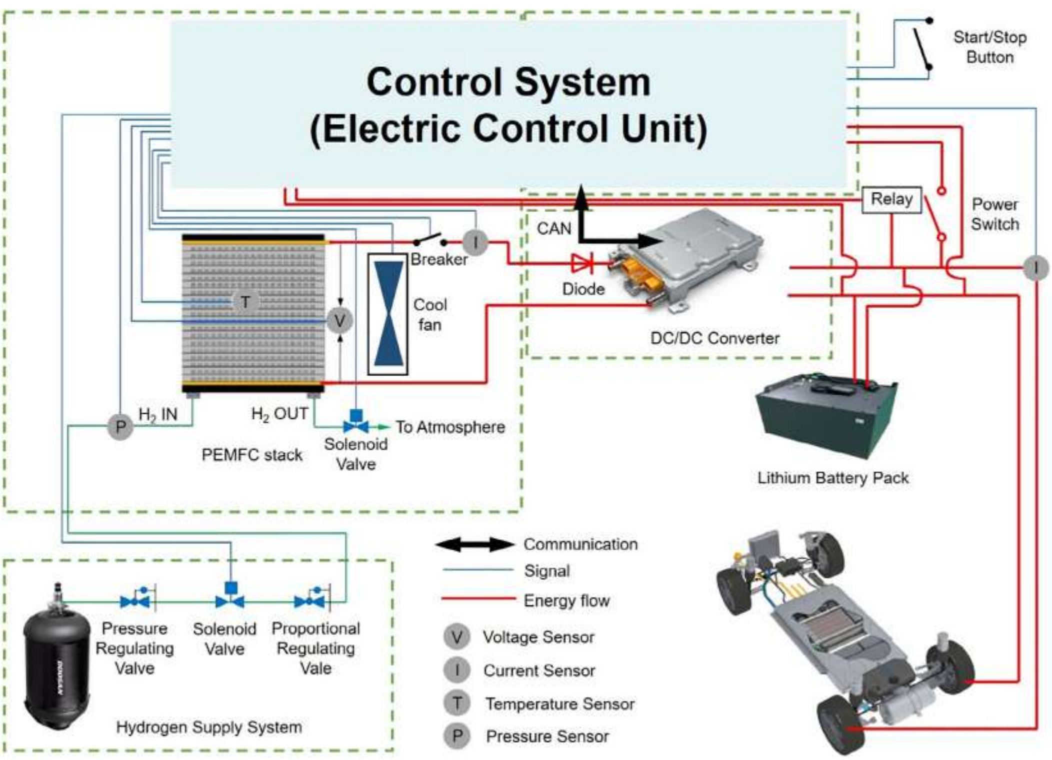

FIGURE 8 Typical optimized architecture of hydrogen FC hybrid power system [Colour figure can be viewed at wileyonlinelibrary.com]

to track the vehicle to the hydrogen refueling equipment when the hydrogen runs out. An electronic control unit (ECU) is designed to monitor and analyze the complicated interactive data between various systems. The control strategy is integrated in the ECU to control the overall FC hybrid system to improve the working performance of the system. Such hybrid system significantly improves the performance of the overall system and is especially suitable for frequent start and stop scenarios.

According to the connection mode of the FC and auxiliary battery system, the structure can control the output power of the FC indirectly by controlling the output current of the DC/DC converter, and the battery is directly connected in parallel with the DC bus in the topology, so its voltage level must be matched with the load voltage. This kind of topology is easy to control not only the hybrid energy management but also the charging and discharging of the battery. According to the topology, the control system is the main and core component to control different subsystems. The hydrogen FC hybrid system block diagram is shown in Figure 9A, and the FC stack control flowchart is shown in Figure 9B.

6.3 | FC + supercapacitor HEVs

The Type III topology uses a supercapacitor instead of a battery.[59,62] The FC + supercapacitor type only meets the transient power demand in emergency situations.[59] However, since the supercapacitor has a low energy density, it is not used to provide the energy and power in the long term. In the process of charging and discharging the supercapacitor, severe voltage fluctuations often occur. To avoid such fluctuations, impedance components need to be added to the system, which will increase the complexity of the system architecture. In addition, the increase in system complexity will increase the difficulty of controlling the power sources, so this topology has very few practical applications.

6.4 | FC + battery + supercapacitor HEVs

In contrast to the aforementioned hybridization topologies, the FC + battery + supercapacitor topology (Type IV) has the primary energy source (FC) and two

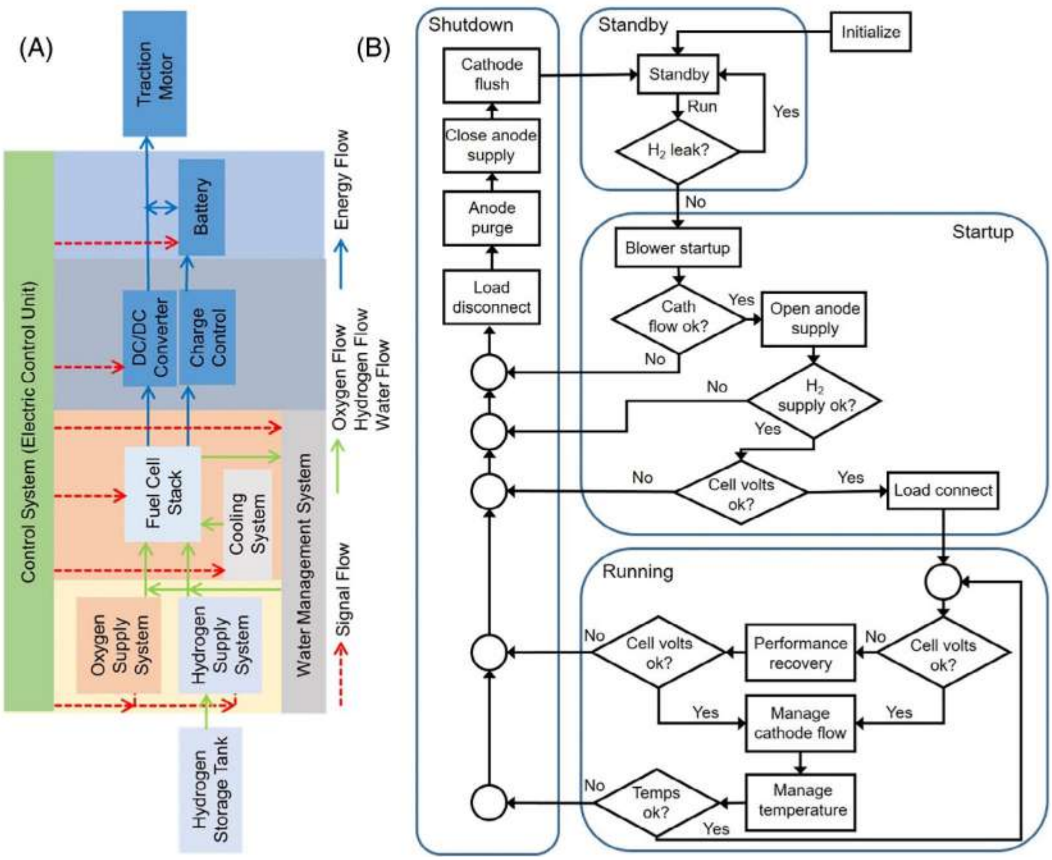

FIGURE 9 (A) Hydrogen FC hybrid system block diagram and (B) control flowchart of the FC stack [Colour figure can be viewed at wileyonlinelibrary.com]

supplementary units (battery and supercapacitor).[61] A one-way DC-DC converter connects the FC to the DC bus in this architecture, and the bidirectional DC-DC converters (BDCs) link the battery and supercapacitor to the DC bus.[61,144,145] This topology combines the benefits of FC + battery and FC + supercapacitor configurations, providing continuous energy and improving the FC dynamic response under transient conditions.[145] However, multiple power sources mean a more complex control system and an extremely complex vehicle structure, which makes this kind of topology difficult to achieve.

6.5 | FC + battery + PV panel HEVs

PV panels have been combined with the FC for FCHEVs in recent years. The PV panels produce variable power depending on the strength of solar radiation, temperature, and light direction. In this configuration, the FC acts as the primary energy source and the PV panel is the backup.[146,147] PV panels produce DC voltages that are connected to the DC bus through a unidirectional converter in FC + battery + PV panel hybridization. Unidirectional converters link both the FC and PV panel to the DC bus, and the battery is connected to the DC bus via a bidirectional converter. As a result, the PV power is fed directly into the electric motor or used to charge the battery. The supercapacitor can absorb sudden fluctuations from PV panels due to the high power density and low power fluctuations result. Such a topology is still at the conceptual stage.

6.6 | FC + flywheel HEVs

In comparison with the other topologies, Type VI uses a new topology of the FC + flywheel configuration. The FC is used as the primary energy source analogous to Type II, and the flywheel is attached as an alternative to the battery for energy storage. Compared to batteries, flywheels have a high charging speed, high efficiency, and high power level.[148] Flywheels are also eco-friendly having a wide operating temperature range, high energy storage capacity, and long lifespan.[148] Flywheels are attached to store energy mechanically at a high rotational speed and convert the mechanical energy into electricity through a generator when the electric motor demands more energy.[149] Compared with the battery, the FES system has the advantages of high power density, long life, lightweight, and no chemical pollution, but it also has problems such as difficult gyroscopic force control and security risks. In addition, further research is needed to determine the ideal operating temperature range. Induction motors are currently designed with lower manufacturing costs and are not suitable for high-speed operation. Therefore, the coupling of brushless DC motors and permanent magnet synchronous motors with FES systems should be focused in the future. Active magnetic bearings can also be used with mechanical bearings to reduce the complexity of the control system, thus making the entire system more cost-effective.

6.7 | FC + SMES HEVs

In the realm of FCHEV implementation, this topology is still under development. However, in the near future, the SMES unit is expected to be used in conjunction with an FC stack. In contrast to other storage systems, the SMES takes less time to charge and discharge. The SMES stores electricity by creating a magnetic field through direct current on a superconducting coil. It also has long charge/discharge cycles and power conversion ratio of nearly 95%.[136] However, the high cost of SMES limits its use in FCHEVs.

7 | ENERGY MANAGEMENT STRATEGIES

7.1 | Logic rule-based simple methods

Based on engineering experience, simple EMS methods usually adopt static control strategies by simplifying the hybrid system model and providing practical logic rules for the control objectives.[77] Owing to the good robustness and less computation, they are well implemented in realistic engineering. According to the power demand division among different power sources, some rules and operations are pre-programmed, which is straightforward and easy to comprehend. However, due to a lack of the dynamic response, the real-time fuel consumption and emission cannot be optimized. The thermostat control strategy and the load follower strategy are two commonly used control mechanisms for HEVs and FCHEVs. When the SOC is below the lower threshold, the thermostat control strategy runs the FC at full efficiency to charge the battery and stops and then the SOC reaches the upper limit. The disadvantage of this control strategy is that the life of FCs and batteries is shortened due to the frequent start/stop and possible deep discharge, respectively. The load follower strategy takes into account both the SOC and power load, which helps overcome the problem that occurs in the thermostat control strategy. Stiffness coefficient model (SCM), operating mode model (OCM), and state machine model (SMM) are some other deterministic rule control strategies. In the series configuration, switching and power monitoring control strategy is widely adopted, whereas in the parallel configuration, power-assisted control is common.[150] An energy management strategy based on the SCM has been proposed, which can dynamically distribute power flow under different energy sources according to the logical relationship between the output and power demand at the peak FC efficiency.[151] The hydrogen economy of the FCHEV can be maximized by making the FC system work in an efficient field. To ensure power consistency and equilibrium, two algorithms of power management control (PMC) focusing on power balance and energy recovery have been proposed.[152] The EMS that has four switches and eight modes is dependable and reliable. An online ASM-based EMS for multi-stack FCHEVs has been developed to enhance the fuel economy and FC lifetime.[153] To distribute power among four FC systems and a battery pack, a two-layer strategy is used, resulting in a significant increase in the overall performance of the FCHEV.

7.2 | Intelligent control methods

For online applications with simplified architectures, intelligent control methods such as predictive control, fuzzy control, and multi-model switching control are appropriate.[154] To obtain the proper functions and control rules, the fuzzy logic control mode needs sufficient training experience and data.[155] The strategy based on fuzzy rules is an extension of the strategy of logic rules. Its rules are in "if-then" form described by various member functions. It does not rely on accurate system models, making it suitable for the system and dynamic processes, particularly nonlinear time-varying cases like vehicles. The inputs and outputs are different for different fuzzy logic strategies. Predictive control and multi-model control are heavily dependent on the system model, and in the case of an inappropriate model, the control effect will deviate from the actual object.[156] An adaptive fuzzy logic for the FC + battery topology can be evaluated by Simulink and MATLAB to increase the independence of fuzzy control and driving conditions on the system model. An adaptive control strategy with fuzzy logic parameter tuning (AFLPT) was proposed to make FCHEVs adaptive to variable driving scenarios including routine running, regenerative braking, and overload conditions.[157] The power flow between the FC and the battery is specifically regulated in real time to satisfy the dynamic constraints of the FC while maintaining the SOC of the battery at an optimal level. By considering the constraints of the FC slow response and battery SOC, the fuzzy controller can perform a reasonable energy splitting between two power sources, improving the comprehensive performance of FCHEVs and the life of power supply.[60] An EMS based on fuzzy rules was designed to regulate FC operating with high efficiency, so that it is not affected by the rapid change in load power. By accumulating the FC power increment, the FC power can be determined in real time, making FC power always within the high-efficiency zone limited by the slope of maximum power.[158] The development of a novel EMS of model predictive control based on fuzzy C-means clustering and Markov chain methods results in 40.04% reduction in the FC power dynamics and 3.79% reduction in the equivalent hydrogen consumption.[8] Combined with the predicted speed and SOC reference, the ideal control action is derived by minimizing the performance metrics in each finite time range. A cost-optimal and predictive control focusing on minimizing the overall running cost has been suggested to remedy the deficiency of the FC and battery degradation.[159] Owing to the design of the controller, selecting the required horizon size necessitates a trade-off between optimality and computational performance, and the driving conditions, uncertainty in speed prediction, and hydrogen consumption affect the optimization cost.

7.3 | Dynamic optimization methods

7.3.1 | Global optimization strategies

The real-time global control needs to know the complete driving conditions and precise road information in advance and so calculation is heavy. Some global optimization strategies are adopted only to optimize powertrain sizes and strategy parameters. Offline control and online control are two types of global optimization strategies. Dynamic programming (DP), genetic algorithm (GA), particle swarm optimization (PSO), simulated annealing (SA), and convex programming (CP) are some of the approaches for offline control.

The DP is one of the most effective solutions for global optimization problems, and its purpose is to find the optimal control strategy using the multiple stage decision processes. Although DP requires a predesigned cycle model, the stochastic DP (SDP), discrete DP (DDP), and weighted improved DP (WIDP) can quantify the uncertain driving cycle and further improve the fuel economy. Aiming at the problems of interpolation leakage, dimension disaster, standardization, and Markov, a unified DP model was established, proving that the proposed algorithm is superior to basic DP and level-set DP in both computation time and computation precision.[160] The GA is a kind of algorithm based on the Darwinian evolution theory, which is often used to search for optimal optimization schemes for problems. The GA has a strong global search efficiency with low algorithm complexity, and focus on the structure, cost, and system optimization. The integrated optimization control achieves the best overall system efficiency. With the GA searching global optimum controls and deep learning (DL) training the neural network model, an adaptive hierarchical EMS of DL and GA enhances the fuel economy significantly.[161] The literature has analyzed and summarized the optimization effects of GA in various EMSs, which is helpful to select and implement optimization rules, objectives, objects, and parameters.[162] To simulate the FCHEV behavior at various velocities, a nonlinear autoregressive neural network (NARANN) has been developed for the FCHEV, making GA and DP easily applied to the vehicle to improve energy storage efficiency and performance.[163] The PSO is a heuristic algorithm, starting from a population and searching for the next optimal movement by iteratively trying a given quality measure. This process is repeated until an optimal solution is found. The PSO is suitable for multi-objectives and multi-constrained optimization because of the higher convergence speed and good compatibility with other algorithms. The PSO-based multi-objective optimization architecture has been suggested to balance the vehicle expense and fuel utilization in the rational hybridization range.[164] The dynamic PSO was used to optimize the control strategy of bivariate energy management and gear-shifting of FCHEV, realizing an improvement in the maximum fuel economy of more than 30% and energy consumption of more than 59%.[165] The SA is able to resist a local minimum and ultimately tends to the global optimum. The SA was used to monitor the maximum power point and improve the stability of the FC power to minimize fluctuations.[166] Both the parameters and control feedbacks can be optimized quickly and easily by the CP. The SA algorithm has been applied to the calculation of engine starting power, battery SOH, and maximum current coefficient, and the simulation results revealed that the proposed algorithm would significantly minimize fuel consumption.[167] A CP system was designed to minimize the sum of energy and power costs, while meeting the requirements of FCHEV power and battery health for different drive cycles.[168] Based on the convex programming control law and the parameter optimization, the power distribution under different hydrogen prices was investigated, and it was found that the power distribution has a significant impact on the fuel economy. Artificial neural networks (ANN) are commonly used in online EMS control because of the self-learning capability and ability to easily discover optimal solutions. The ANN has been tested in a variety of driving cycles and compared with the DP's offline power with the goal of reducing hydrogen consumption and battery degradation.[169]

7.3.2 | Local optimization strategies

Local optimization strategies use instantaneous cost function to replace global cost function for calculating the instantaneous optimal power distribution scheme between different energy sources, solving the issues of relying on road data and heavy computation. The equivalent consumption minimization strategy (ECMS) converts electricity stored in the energy storage system (ESS) into equivalent hydrogen consumption, with the goal of minimizing the sum of hydrogen and equivalent hydrogen consumption. An equivalent coefficient is very important to ECMS, and its value is co-determined by driving cycle, battery SOC limit, and other factors. The hydrogen consumption can be minimized, and the power sources' service life can be extended by adjusting the equivalent coefficient. The Pontryagin's minimum principle (PMP) is based on the optimal control strategy. It's a series of optimal conditions of state variables that are confined within a finite boundary and its optimal values that are closer to DP. The ECMS and PMP, which do not fully rely on the model to achieve discrete dynamic optimization, are widely used in hybrid systems, but they are ineffective in online applications due to the large computational requirement. Model predictive control (MPC) excels at forecasting potential changes from current values, dynamic states, and process variable targets in optimization problems with many constraints. Linear programming (LP), also known as linear optimization, is especially suitable for the optimization of linear relations. The nonlinear power-hydrogen consumption relationship of the FC can be simplified into three linear parts. Optimal control theory (OCT) is an alternative, which is based on mathematical optimization. An online adaptive equivalent consumption minimum strategy (AECMS) for FCHEVs was designed to decrease hydrogen consumption and degradation of power sources.[170] Real-time and approximately optimal EMS based on the PMP can control the SOC of the battery within a certain range and determine the approximately optimal hydrogen consumption, thereby improving FC durability and reducing the average daily operating cost.[171] To lower the average daily running cost and improve the FC life, a real-time EMS based on the PMP that considers the fuel efficiency and power source durability has been introduced.[172] The ECMS has been demonstrated to boost fuel economy and prolong the battery life of the FCHEV by simulation on the ADVISOR and Simulink.[173] The ECMS has been tested in real driving scenarios including rural, urban, and highway driving, and the maximum battery usage is 50-80%.[174] A MPC method was developed to regulate the circulation of hydrogen and achieve the stable and efficient operation of the PEMFC.[175] The LP was used to optimize energy flow in the FCHEV to achieve an optimal power distribution between energy sources, while satisfying component requirements and maintaining necessary operating performance, thereby reducing hydrogen consumption and operating costs.[176]

Predecessors have studied a variety of control strategies, even including related simulation analyses, and a small number of EMSs have also been tested in hardware or real vehicle applications. However, most of the EMSs proposed at present are only studied through simulation, and the real-time monitoring and testing of real-life scenes are insufficient. The reliability and feasibility of some newly proposed EMSs are still to be further verified. In addition, the EMS that can minimize hydrogen consumption without affecting power load distribution and performance is still a direction that needs to be focused in the future.

8 | DEGRADATION OF FCS

A PEMFC system includes the PEMFC stack and accessories such as reactant storage, and pumps. The electrodes, membrane, gas diffusion layers (GDLs), and bipolar plates in the PEMFC stack suffer from degradation, and the degradation mechanisms associated with these components are summarized in Table 6.

The performance of a PEMFC stack is affected by several factors, such as FC design and assembly, degradation of the materials, operational conditions, and impurities or contaminants present in the feedstocks. Performance degradation is unavoidable, but it can be partially limited within time to increase its lifetime. DOE-suggested degradation targets usually require less than 10% loss in the efficiency of an FC system at the end of its lifetime. The degradation mechanisms can basically be subdivided into two families: FC component degradation (membrane, electrocatalysts and catalyst loading or CL, GDL, gaskets, bipolar plates or BPs, sealing) and degradation effects due to operative conditions (air/fuel impurities, load cycle, startup/shutdown, environmental subfreezing conditions).[177-179] Membranes can degrade mechanically, thermally, or chemically electrochemically.[143] Mechanical degradation usually causes early life failure, due to perforations, cracks, tears, or pinholes, which may result from inherent membrane defects or from improper MEA manufacturing processes. The membrane protonic conductivity drops significantly with a decrease in the water content when the FC is operated at a high temperature and under low humidity. Membrane thinning may be caused by a chemical attack from hydrogen peroxide formed by electrochemical reaction of oxygen and hydrogen that have crossed the membrane. Pt-based catalysts are usually used in PEMFCs: Pt is in the form of highly dispersed metal particles at a nanometer scale, usually in the 2 to 6 nm range. Considering the extremely harsh conditions in which PEMFCs operate, the corrosion of Pt/C catalysts (both catalytic metals and the support materials) is a problem. Nanoparticles inherently show a strong tendency to agglomerate, because of their high specific surface energy. Consequently, when Pt nanoparticles agglomerate to larger ones, the electrochemical surface area of the Pt-based catalysts decreases, and consequently, the performance of the PEMFC degrades. The degradation of catalysts involves the two different features of the catalytic metal (Pt or Pt alloys) and the carbon support that influence each other: The

TABLE 6 Major failure modes of different components in PEMFCs[177-179]

Component	PEM	Electrodes	GDLs	Bipolar plates	Sealing gasket
Failure mode	Mechanical degradation; Thermal degradation; Chemical degradation	Catalyst loss; Conductivity decrease; Decreased transportation; Reformate tolerance loss; Deteriorated water management	Mechanical degradation; Conductivity decrease; Deteriorated water management	Mechanical degradation; Conductivity decrease	Mechanical degradation
Causes	Uneven mechanical stress; Inadequate humidification; Corrosion of catalysts and seal materials; Thermal stress and cycles; Contamination; Radical attack	Catalyst sintering; Corrosion of catalysts or supports; Mechanical stress; Contamination; Change in hydrophobicity	Degradation of backing materials; Chemical corrosion; Mechanical stress; Change in the hydrophobicity; Chemical corrosion	Corrosion; Oxidation; Mechanical stress; Thermal stress and cycles	Corrosion; Mechanical stress

catalytic metal, especially Pt, catalyzes the oxidation of carbon, and the oxidation of carbon accelerates Pt sintering. The PEMFC-operating environment gradually changes the GDL from hydrophobic to hydrophilic. Likes all other PEMFC components, BPs also suffer from corrosion failure, mainly due to pinhole formation especially when metal plates are used. In addition, the degradation of FC auxiliary materials is insufficient, although the degradation mechanisms have been clear, but the evolution of their properties is still a research goal to be explored. Various simulation approaches on the degradation pathways have been reported in the literature, and several data-driven and physical model-based methods are utilized to simulate the deterioration of FEMFCs similar to battery degradation models.[180,181] Data-driven methods rely on data laws, but the parameters must be changed as the operating conditions are altered. Physical models take into account chemical reactions that affect the FC degradation rate such as carbon support loss and Pt surface area loss.

Degradation of the PEMFC in FCHEVs is unavoidable and has a large impact on the system lifetime. The deterioration mechanism in vehicle applications is much more complicated and difficult to describe accurately with a theoretical model.[182] However, in the design of a health-conscious EMS, the deterioration of the FC is roughly considered by a theoretical model, which cannot be applied to all real driving conditions.[179,183] This is primarily due to the FC's complex architectures and reactions as well as modeling challenges. Although some prognostic works have been performed to assess FC degradation, the actions or control configurations are lacking. As a result, it is needed to design a health-conscious EMS based on state estimation and prognostics, which can not only solve the modeling inaccuracy, but also implement automatic corrective control.[184] Presently, health-conscious EMSs are basically divided into the rule-based EMSs and optimization-based EMSs, as shown in Figure 10. Degradation model simulation and optimization are two major concerns in developing health-conscious EMSs for FCHEVs. Future works should focus on putting forward practical degradation models and estimation methods, constructing multi-objective problems with degradation and striking a good balance between complexity and optimality.

9 | SAFETY STANDARDS OF FCHEVs

Safety standards are developed by transportation organizations in world. The most widely used vehicle standard is SAE established by the United States. ISO from the international community, EC from the European Union,

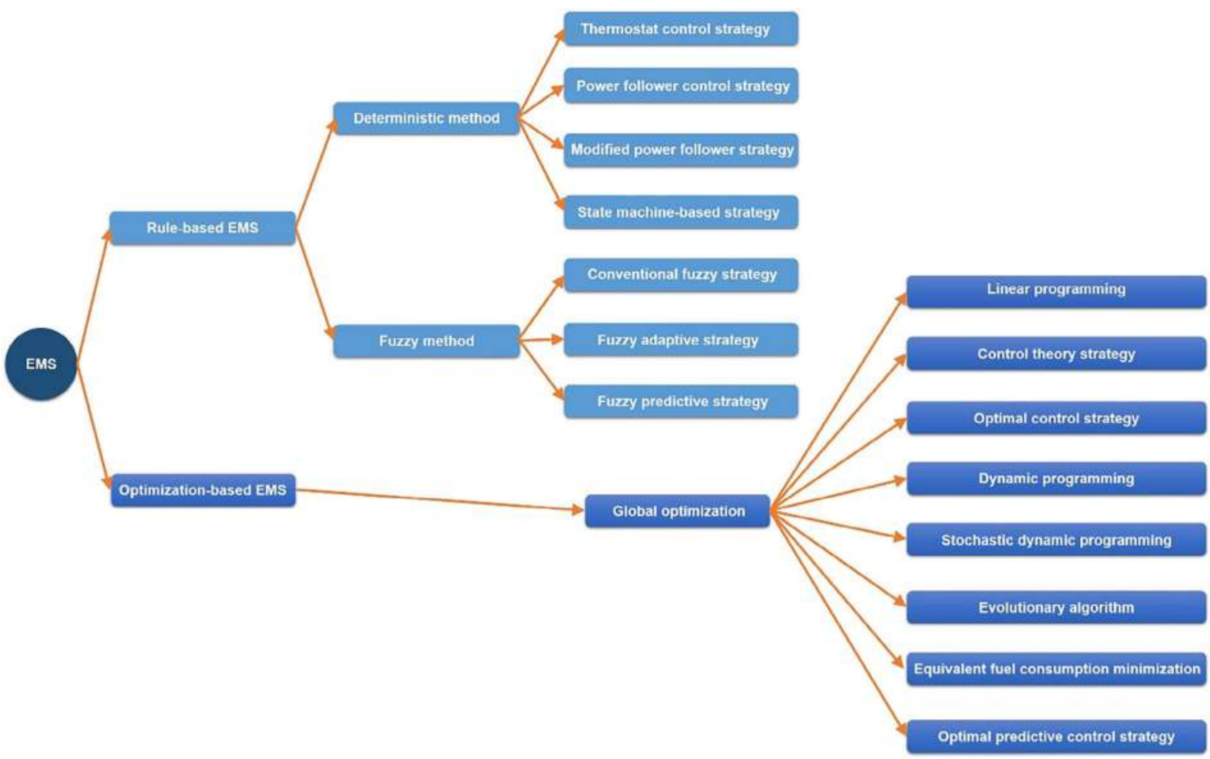

FIGURE 10 Health-conscious EMSs for FCHEVs[162] [Colour figure can be viewed at wileyonlinelibrary.com]

CNS Japan and Taiwan, KS from Korea, CGA and CSA from the United States, and GB/T from China are the other standards. All of these standards regulate the system design and testing of FCHEVs in addition to safety considerations, efficiency, fuel systems, performance, and durability. The same factors for the FC stack are also governed by these standards. The automotive standards and requirements are summarized in Table 7. The safety problems including hydrogen leakage and subsequent fire, explosion, and other consequences need to be considered in the promotion of hydrogen FCHEVs. In addition, leak monitoring and control systems including regulations and standards applicable to the field and various sensors need to be improved. In general, each type of sensor is suitable for a specific application, and the optimal sensor should be selected by the comprehensive evaluation of sensor characteristics and operating conditions.

10 | ISSUES AND CHALLENGES

Progress of FCHEVs is anticipated with the installation of more hydrogen refueling stations. However, there are some inherent drawbacks that can potentially impede commercialization.

10.1 | Cost

The cost of an FC stack is the highest among vehicle parts according to the US Department of Energy (DOE) (Figure 11),[187] and lowering the cost of the FC stack is crucial to the competitiveness. The catalytic layer made of the precious metal Pt accounts for the bulk of the price, and so decreasing the Pt loading, increasing the Pt utilization efficiency, and designing non-Pt catalysts can pare the cost. Pt loading can be minimized by modifying the catalyst structures such as core-shell structures[188] and hollow morphologies[189] and creating binary Pt alloy catalysts such as Pt-Co[190] and Pt-Ni,[191] which have synergistic catalytic effects on the electronic state and catalytic activity of Pt. Improved catalyst substrates such as nitrogen-doped carbon,[192] carbon nanotubes,[193] graphene,[194] and titanium oxides[195] can improve Pt dispersion and utilization efficiency. The performance of non-noble metal catalysts is also close to that of platinum-based catalysts. However, it is not easy to achieve their performance in FCEVs because the high activity is largely dependent on the fine surface structure of the nanocatalysts, and therefore, the catalyst degradation becomes a big problem, especially for the shape-controlled catalysts.[196]

The cost of bipolar plates is currently 5-10 \$/kW, with a target of below 3 \$/kW by 2022.[197,198] Current research is focusing on reducing the cost without compromising the conductivity and corrosion resistance. Metal bipolar plates are less costly than graphite and composite ones, but the passivation layer on the metal surface limits the power density and lifespan.[199] Stainless steel with metal nitride[200] and carbon-doped polymer[201] coatings has recently demonstrated to have high chemical stability, low interfacial contact resistance, and reasonable cost. As proton exchange membranes (PEMs), perfluoro sulfonyl fluoride ethyl-propyl-vinyl ether (Nafion) membrane produced by DuPont is quite expensive (120 \$/kW).[202] Similar PEMs have been developed by other manufacturers including Flemion from Asahi Glass,[203] Aciplex from Asahi Chemical,[204] "C" membrane from Chlorine Engineers,[205] Dow from Dow Chemical,[206] and Aquivion from Solvay.[207] To provide more affordable FCEVs, it is also necessary to recover valuable FC materials and components from obsolete ones.

10.2 | Durability of FCs

FCs must be as reliable and robust as conventional engines. The important environmental factors that affect the lifespan of FCs are freezing, start, shutdown, oxygen pressure, humidity, and temperature.[208-210] The FC is also subjected to complex operating conditions such as variable start/braking and different loads.[211] Therefore, the lifespan of FCs in full FCEVs is less than that of FCs in other hybrid topologies.[212,213] Drastically variable temperature, voltage, relative humidity, and partial pressure of gases affect the states of the FC stacks.[214] Membrane degradation is also a challenge for PEMFC durability, since the PEMFC lifetime depends on the PEM durability.[143] Pinhole formation is caused by distortion in the membrane working process and may produce a stack problem.[215] Physical and chemical changes can occur during the cycle and cause terrible consequences.[216,217] As a result, the FC performance inevitably deteriorates. Towards the end of its life, the FC is predicted to have lost less than 20% of its productivity under normal conditions.[174] For a more precise lifetime forecast, the attenuation mechanism, failure mechanism, and life prediction methods must be thoroughly understood and developed.[218,219] Experimental methods for studying durability and degradation include steady-state performance-time tests and accelerated stress tests. Steady-state testing is simple but time-consuming and high cost. Therefore, the accelerated stress testing has been more widely adopted. Simulation-based prediction is also an effective way to improve the durability of the system, including physical

TABLE 7 Automotive standards and requirements for FCHEVs[185,186]

Standards	Issue	Contents
Japanese government regulations	Vehicles-system design/testing	Hydrogen fuel cell vehicles
GB/T 23645-2009	Vehicles-system design/testing	Test method of fuel cell power system for passenger car
GB/T 25319-2010	Vehicles-system design/testing	Fuel cell test system used for motor vehicles—technical specification
GB/T 28183-2011	Vehicles-system design/testing	Test methods of fuel cell power system for bus
SAE J1766	Vehicles-safety	Recommended practice for electric and hybrid electric vehicle battery systems crash integrity testing
SAE J2578	Vehicles-safety	Recommended practice for general fuel cell vehicle safety
ISO 6469-1	Vehicles-safety	Electrically propelled road vehicles—safety specifications—Part 1: On-board rechargeable energy storage systems (RESS)
ISO 6469-2	Vehicles-safety	Part 2: Vehicle operational safety means and protection against failures
ISO 6469-3:2011	Vehicles-safety	Part 3: Protection of persons against electric shock
ISO 6469-4:2015	Vehicles-safety	Part 4: Post crash electrical safety requirements
ISO 23273:2013	Vehicles-safety	Fuel cell road vehicle—safety specifications—protection against hydrogen hazards for vehicles fueled with compressed hydrogen
KS R ISO 23273-1	Vehicles-safety	Fuel cell road vehicles—safety specification—Part 1: Vehicle functional safety
KS R ISO 23273-2	Vehicles-safety	Part 2: Protection against hydrogen hazard for vehicles fueled with compressed hydrogen
KS R ISO 23273-3	Vehicles-safety	Part 3: Protection of persons against electric shock
CNS 15499-1	Vehicles-safety	Electrically propelled road vehicles—safety specifications Part 1: On-board rechargeable energy storage systems (RESS)
CNS 15499-2	Vehicles-safety	Part 2: Vehicle operational safety means and protection against failure
CNS 15499-3	Vehicles-safety	Part 3: Protection of persons against electric shock
SAE J2572	Vehicles-performance (efficiency, emissions, durability)	Recommended practice for measuring the exhaust emissions, energy consumption, and range of fuel cell-powered electric vehicles using compressed hydrogen
ISO 23828:2013	Vehicles-performance (efficiency, emissions, durability)	Fuel cell road vehicle—energy consumption measurement—Part 1: Vehicles fueled with compressed hydrogen
ISO/TR 11954	Vehicles-performance (efficiency, emissions, durability)	Fuel cell road vehicles—road maximum speed measurement
SAE J2754	Vehicles-terminology	Fuel cell electric vehicle terminology
SAE J2760-TIR	Vehicles-terminology	Pressure terminology used in fuel cells and other hydrogen vehicle applications
ISO/TR 8713:2012	Vehicles-terminology	Electrically propelled road vehicles—vocabulary
CSA America HGV3.1	Vehicles-fuel systems	Fuel system components for hydrogen gas-powered vehicles
NFPA 52	Vehicles-fuel systems	Vehicle fuel system code
SAE J2579	Vehicles-fuel systems	Standard for fuel systems in fuel cell and other hydrogen vehicles

(Continues)

TABLE 7 (Continued)

Standards	Issue	Contents
CGA Publication PS31	Vehicles-fuel systems	Cleanliness for PEM hydrogen piping/components
EC No. 79/2009	Vehicles-fuel systems	Type-approval of hydrogen-powered motor vehicles
ISO 12619-1 Road vehicles	Vehicles-fuel systems	Compressed gaseous hydrogen and hydrogen/methane blends fuel components—Part 1: General requirements and definitions
ISO 12619-2 Road vehicles	Vehicles-fuel systems	Part 2: Performance and general test methods
ISO 12619-3 Road vehicles	Vehicles-fuel systems	Part 3: Pressure regulator

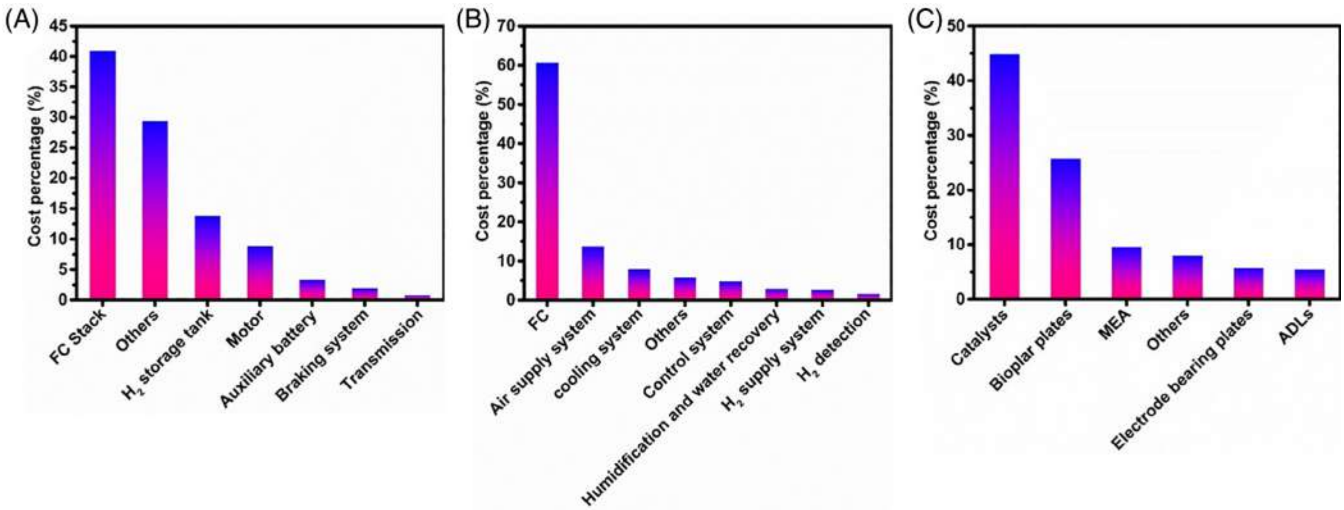

FIGURE 11 Cost breakdown of the FCHEV: (A) vehicle, (B) FC stack, and (C) FC cell[186,187] [Colour figure can be viewed at wileyonlinelibrary.com]

models, chemical models, data-driven models, and hybrid models that match the actual system.

10.3 | Cold start

Cold start can be problematic for PEMFC stacks when internal water freezes, as ice can block the flow channels of the electrodes and damage the MEA resulting in performance degradation.[220] Therefore, a subfreezing cold start is essential for PEMFC commercialization, and the critical components, cold-start techniques, and auxiliary powers should be optimized to improve the low-temperature performance.[221] The membrane conductivity is reduced at low temperature, and the voltage suffers as well. Therefore, the primary optimization focus is to enhance the water uptake ability and conductivity at subfreezing temperatures. The SPEEK/PVA/PA composite membrane showed a high and stable proton conductivity of 5.30×10^{-2} S/cm at $-30°$C after seven temperature cycles from $-30°$C to 30°C, and retained 3.33×10^{-2} S/cm at $-30°$C after 980 hours of continuous testing at $-30°$C.[222] The POM-based acid-base adduct in SBA-15 called HPW-HSN@SBA-15 has been reported to have a high proton conductivity of 6.8×10^{-5} S cm^{-}1 at $-40°$C.[223] The cold start may be affected by the ionomer content and thickness of the catalyst layers. A high Nafion ionomer content can inhibit gas transfer to the catalytic active sites, whereas a low content can result in weak catalyst particle-to-electrolyte connection. It has been shown that a Nafion content of 25 wt% is optimal.[224] The effects of ionomer/carbon (I/C) ratio on the cold start of PEMFCs were systematically investigated by experiments and theoretical calculations.[225] When the ionomer/carbon (I/C) ratio is between 0.7 and 1.7, both the increase in the I/C ratio and the decrease in the temperature will lead to the deterioration of cold-start performance. However, at temperatures below $-5°$C, the total product water is nearly the same regardless of the I/C ratio due to rapid freezing before the water adsorption of membranes. The operation time of PEMFCs is extended at a temperature range of $-4.2°$C to $-10.0°$C using a new form of the microporous layer with plane-distributed wettability, in which hydrophilic and hydrophobic rows are arrayed alternately in the in-plane direction.[226] Ice melting can be accelerated during the cold start by reducing the porosity of the GDL.[227] When the porosity is high, the number of carbon fiber layers has a greater impact on the ice melting than the fiber length, whereas when the porosity is low, the effect is opposite. The cold-start ability may also be improved by designing the materials and structures of the bipolar plates. Vanadium oxide thin films fabricated onto metallic bipolar plates such as 316 L and 446 M stainless steel can deliver a competitive cold start output at −20°C.[228] Optimized power control strategies provide effective cold-start methods.[229] With regard to the heating time, the constant voltage cold-start strategy outperforms the constant current strategy.[230] Real-time control of the operating current is possible thanks to an internal-based adaptive strategy that maximizes the produced heat flux.[231] The performance of maximum power mode-based real-time adaptive cold-start strategies in a PEMFC stack highly depends on the selection of a precise model, and suitable model selection will enhance the cold startup performance.[232] Power off purging and heating are two effective ways to the cold start of PEMFC systems, and according to different heating sources, the heating schemes can be divided into self-heating strategy and auxiliary heating strategy.[233] The aim of purging the solution is to reduce the amount of residual water in the PEMFC before the next start. In order to improve the temperature uniformity during the cold-start process, a reverse air supply device (RFU) was designed to start the PEMFC reactor within 79 seconds with a uniform temperature distribution of −32°C.[234] The transport phenomenon as well as the spatial distribution of water and temperature can be analyzed by multidimensional cold-start models. An online self cold startup methodology consisting of a water extraction step after the PEMFC shutdown and a self-heating step during the cold startup was invented, which maximizes the internal heat of the PEMFC according to the variation of operating parameters, attempts to maintain a high current density, and improves the performance by increasing the hydration and temperature of the PEM.[235] The cold-start processes of PEMFCs with zigzag-channeled flow field (ZZFF) has been numerically studied, and it was found that ZZFF can better distribute the reactants/products and current density within PEMFCs because ZZFF enhances the flow direction transport between under-land and under-channel areas.[236] It has been reported that it is easier to realize the success of cold start by current ramping mode than by constant voltage or constant current strategies.[237] Hot air blowing, batteries, and catalytic furnaces can be used to achieve fast heating both internally and externally.[233] In general, the cold-start problem can be concerned from two aspects. On the one hand, it is the transmission phenomenon of water in the FC system, including supercooling, phase change, and transmission. On the other hand, it is the control strategy, including component design, unit structure, material selection, startup mode, and load control. In fact, the two aspects are complementary. All effective control strategies for cold-start problems stem from a clear understanding of the transmission mechanism during the cold-start process. It is recommended to adopt more advanced real-time monitoring methods of water transmission to verify new models and control strategies in the future.

10.4 | Lifetime of batteries

Batteries are required in FCHEVs because they provide the energy storage required for regenerative braking,[238] and the service life of the battery, which depends on the SOC and depth of discharge, must be carefully examined in the design stage. There are several types of batteries on the market, and Li-ion and NiMH batteries are the most widely used in electric vehicles.[239] NiMH batteries are considered to be environmentally friendly and have low maintenance while offering high power and energy density and relatively low cost. Lithium-ion batteries are lightweight and compact and have higher energy densities than NiMH. They also operate in a wide temperature range, but the raw materials are scarce. When choosing batteries, a balance of cost and technological performance should be taken into account.[47] Circuit modeling seems to be the most suitable method for battery modeling because it does not require redundant data and calculations and can reproduce the dynamic behavior of the battery. Based on this, battery health indicators such as internal impedance and available capacity can be evaluated in real time. In addition, machine learning models provide good accuracy, but such models require a large database. In short, model simulation is very important to optimize the battery device and overall system.

10.5 | Security and comfort

The FCHEV safety is important as hydrogen is the main energy source. Hydrogen as a clean fuel has a lot of potential in the automotive market, but it is flammable and explosive in the presence of oxygen. Hence, the main task is to store hydrogen safely.[240] A special hydrogen storage tank is important, and hydrogenation stations should also meet safety requirements.[241] Actually, automobile manufacturers have carried out a series of safety tests before launching new models. However, these theoretical data are not convincing enough for consumers due to the small market share of FCEVs and lack of actual support. Therefore, the commercialization of FCEVs is still limited. Driving comfort is derived in part from the vehicle's dynamic performance and in part from humanization. Therefore, it is necessary to continue to improve the EMS design and strive to bring FCHEV performance closer to that of conventional diesel ones in terms of high power, high efficiency, and driving comfort.[242]

10.6 | System optimization

In FC-powered engines, system optimization is critical.[243] Regardless of the optimization algorithms such as EMS, there are a number of concerns and problems. The fuel economy, minimum cost, proper component sizing, suitable parameter selection, power management, maximum FC lifetime, and system weight are all important aspects in optimization studies.[244-249] As previously mentioned, load changes and start-stop cycles affect the lifespan of the FC. The design of an optimized FCHEV system may ease the impact of load changes and start-stop cycles. By incorporating other power sources with FC, extreme load changes can be avoided. Furthermore, by using storage components, the start-stop cycles can be reduced and the FC operation can continue to charge the storage device at the lowest speed while the vehicle stops.[243] Most simulations are theoretical, and some of them do not even indicate the corresponding application or tool. The ant colony algorithm and dynamic programming, as well as a combination of proportional integration (PI) with LP, are used to solve optimization problems related to simulation.[151] Prioritization of hardware sizing over the life and degradation of ESS components can be found in the literature.[250-253]

10.7 | EMS

When selecting a battery and supercapacitor for hybridization, there should be an optimal balance between the cost and performance. The development of a suitable EMS for FCHEVs is critical because it has a direct impact on vehicle maintenance and operating costs.[46,245] Owing to the proper integration of systems in the vehicle, one of the challenges is to optimize the setup and design of the appropriate controller.[254] The goal of the EMS is to control multiple power sources. In the hybrid system, controlling the flow of power is vital to the market demand.[255] The EMS ensures that energy is distributed efficiently among the FC, ESS, and electric motor in order to avoid FC power irregularities and extend the life of the FC and other energy storage devices. The EMS aims at reducing hydrogen consumption and improving ESS coordination.[47] During regenerative braking, maximum energy recycling is expected and SOC restriction, maximum energy recovery during regenerative braking, and FC support during high loads should be considered.[47] Conditions such as the FC oxygen pressure as well as the life of the battery and supercapacitor should be investigated. Since the lifetime of ESS components is affected by SOC and discharge depth, they should be thoroughly examined prior to use.[47] Except simulation, experiments have been performed for EMS.[151] As mentioned above, although there have been many studies on the optimization of EMSs, most of them are limited to simulation and not verified by real-time or actual experimental applications. Therefore, the future simulation of EMS must be verified through real-time applications or experimental settings.

10.8 | Integration

FCHEVs are integrated in the same way as conventional ICE vehicles. A passenger car can be integrated with a highly powerful drivetrain using existing FC vehicle technology. In addition, there are no technical barriers against possible integration of FC systems and their scalability allows them to be adapted to different vehicle dimensions in manufacturing. The FC stack size and weight need to be further reduced in order to commercialize the technology.[30,256] The ideal location of the hydrogen storage tank in the vehicle is on the bottom of the seat and trunk[257] (see Figure 12A,B), but the most significant disadvantage is that the tank cannot store an excessive amount of hydrogen due to the additional space required by the increased volume.[258] The high-pressure onboard hydrogen tank is customized by carbon fiber reinforced plastics (CFRPs) to provide 35 or 70 MPa pressure level storage for hydrogen. Other specifications such as tank weight, storage volume, intake pressure, discharge pressure, and temperature should be designed in accordance with the hydrogen pressure vessel standards. The size of the hydrogen tank needs to be designed to maximize the utilization of hydrogen for vehicles with different purposes. The hydrogen refueling interface also needs to be developed in accordance with SAE or other standards; that is, hydrogen is compressed from low pressure to high pressure and then injected into the onboard hydrogen storage tank. The control flowchart of the hydrogen refueling process is displayed in Figure 12C. Refueling tests under different working conditions are also required to record refueling data. The power of the DC-DC converters and DC-AC inverters used in the power transfer stage is calculated using the peak value of

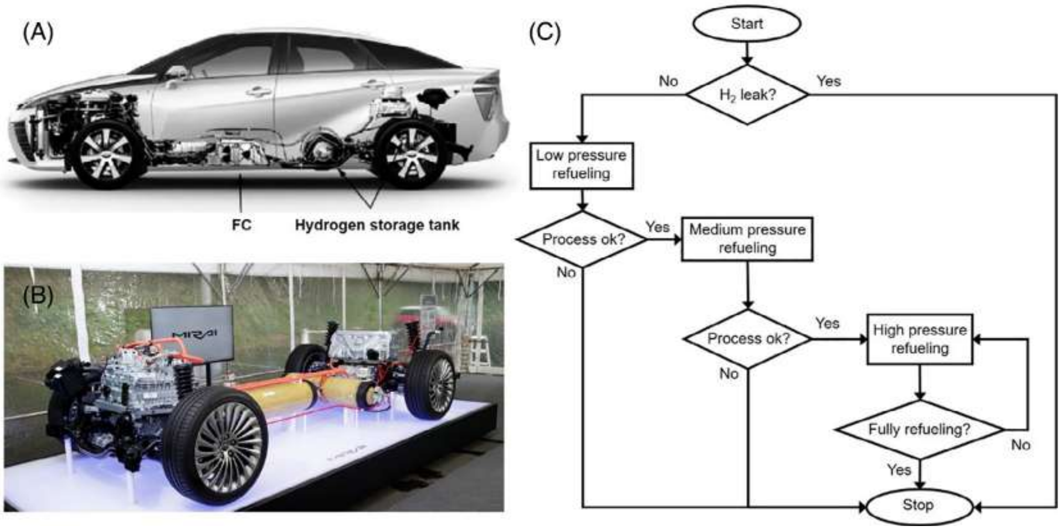

FIGURE 12 (A) Suggested location of the hydrogen storage tank in the vehicle, (B) FC and hydrogen storage tank location in the Toyota Mirai, and (C) control flowchart of the hydrogen refueling process [Colour figure can be viewed at wileyonlinelibrary.com]

the electrical load. At a specific switching frequency, it is combined based on optimum current and voltage degrees. Integration of online electrochemical impedance spectroscopy (EIS) functionality into a FC stack connected to a DC-DC booster converter is a promising approach for real-time monitoring of the FC stack health that requires no additional measuring equipment.[259] An electric motor, which may be either AC or DC, is responsible for transferring the electric energy to rotation. The low pole number requirement for induction motors necessitates large copper winding ends in the motor integration. This needs an outer iron coating on the stator, which adds to the weight. The electromagnetic compatibility issue caused by high frequencies and high peak currents should be considered in switched reluctance motors. In addition, the stator and electronic structure of the SRM differs from existing built-in technologies. It also produces a lot of noise and has a low efficiency.[260,261] The current cost of energy magnets in PMSM motors, which are commonly used in EV applications, is high and a fixed flux and, on the other hand, produces a narrow speed range at fixed speeds.[262]

10.9 | Diagnosis of faults

When a device in the EV runs outside of standard conditions, a fault occurs. This flaw will lead to a loss of dynamic stability or costly breakdown.[263,264] Therefore, it is critical to monitor the operation to ensure the safety and stability of vehicles. Faults may occur in the FC stack, power converters, storage tanks, electric motors, or measuring instruments.[265,266] The fault may be electronic, electrical, mechanical, or software,[267] and electric and electronic components have the highest failure rate of nearly 42%.[268,269] Overcharging of the storage device, overloading of the FC, short-circuit or open circuit of the motor stator windings, overheating of electronics, open or short switch in power converter components, and so on are examples of defects. Some of these flaws will compromise the vehicle performance, cause vibration and noise, and even harm the vehicle dynamic system.[270] There are two ways of fault diagnosis: online and offline.[269] The controller area network (CAN)-based systems are commonly used in FCHEVs for control and communication.[271] Due to the need for diagnostics of the FCHEV's electronic control system, they are critical in terms of vehicle safety and reliability.[272] The code defined for warning is sent to the vehicle management system through the CAN data when a possible fault is detected in any part of the online diagnostic system. The fault information received is shown on the screen, and an audible warning is provided along with the alarm fault code on the screen. Offline diagnostics refers to reading previous faults when the vehicle is parked. When a probable malfunction happens, the offline diagnostics function of the vehicle management system kicks in to perform the operation that refers to the malfunctioning condition. In the opening and closing instances, the system controls the storing and retrieval of error information.[273] Failures in storage devices, motor systems, diagnosis system, sensors, and converters must be identified as soon as possible to ensure the safety of both the driver and vehicle. In addition, the existing fault coupling mechanisms are mainly for two faults, and the coupling mechanisms of three or more faults are less studied. The investigation methods are mainly simulations, and there are few experimental verifications. In order to improve the accuracy of fault diagnosis, it is also necessary to use the comprehensive technologies of multi-physical fields including electricity, flow, electromagnetics, temperature, and stress to diagnose FCHEVs.

11 | CONCLUSION

FCHEVs are expected to play important roles in mitigating environmental degradation and demand for fossil fuels. This review summarizes recent advances in optimization and cutting-edge design of FCHEVs, especially the fuel cell + battery hybrid topology, and discusses current technological bottlenecks that hamper commercialization of FCHEVs. The development of HEVs, markets, environmental and economic benefits, components, topologies, energy management strategies, degradation mechanisms, and safety standards of FCHEVs are reviewed. The PEMFC constitutes the mainstream and most mature fuel cell technology for automobile applications. The main components of FCHEVs include the FC stack, battery, supercapacitor, electric motor, and power converter. FC + battery hybridization is currently favored among the six available FCHEV topological designs to improve the dynamic response and recover the braking energy. The energy management strategies include the logic rule-based simple methods, intelligent control methods, global optimization strategies, and local optimization strategies. In addition to promoting the construction of hydrogen supply facilities, further adoption of FCHEVs by consumers continues to face challenges including the unsatisfactory cost, durability of FCs, cold start, lifetime of batteries, security, comfort, system optimization, EMS, integration, and diagnosis of faults. It is projected that FCHEVs will undergo rapid development and be accepted by customers after these shortcomings have been addressed.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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