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Review

A comprehensive review of the key technologies for pure electric vehicles

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ABSTRACT

Nowadays, the emissions from conventional vehicles significantly contribute to increasingly serious environmental issues. In addition, the energy crisis and the low energy efficiency of conventional vehicles also offer a good opportunity to develop electric vehicles. Hybrid electric vehicles have better fuel economy compared to conventional vehicles, but they are just an interim step in vehicle development and pure electric vehicles are the ultimate goal. Currently, the technologies of hybrid electric vehicles can be found in numerous literature surveys, however there is a lack of published papers to present a comprehensive technical review for pure electric vehicles. In this study, the characteristics and typical models of energy sources of pure electric vehicles are firstly described. Then the existing pure electric vehicle types are depicted and the environmental impacts of the typical pure electric vehicles are evaluated. Moreover, energy management strategies for pure electric vehicles and charging technologies are investigated. The main challenges faced by pure electric vehicles and corresponding solutions are discussed, whilst the latest developments of pure electric vehicles are presented. The awareness of environmental issues and the energy crisis as well as the incentives from the governments of many countries continuously enhance the rapid development of pure electric vehicles.

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1. Introduction

The conventional vehicles which use only an internal combustion engine consume fossil fuels and emit gases such as carbon oxides, hydrocarbons, and nitrogen oxides [1]. In order to overcome the environmental and energy crisis issues that conventional vehicles contribute to, hybrid electric vehicles (HEVs) have been developed and applied over the past few years. HEV technologies provide a fuel economy improvement and enable HEVs to exhaust less emissions compared to the conventional internal combustion engine vehicles (ICEVs), but HEVs cannot completely resolve the abovementioned issues. Thus, HEVs are only a temporary step in the development from ICEVs to pure electric vehicles (PEVs). It is significant and imperative to develop PEVs for the following main reasons.

The most important reason is that presently environmental issues are becoming increasingly serious. Exhaust gas emissions from vehicles have become the main source of air pollution, especially in densely populated areas. According to the China Vehicle Environmental Management Annual Report (CVEMAR) in 2018, vehicle emissions contribute to 52.1% of the sources of fine particulate matter (PM2.5) air pollution in Shenzhen, China, followed by 45% in Beijing [2]. Air pollution happens in many parts of the world at dangerously high levels and poses a major environmental risk to human health. There are almost 6.5 million premature deaths every year in the world duo to poor air quality and around 3 million people die from exposure to outdoor air pollution. Vehicle emissions are one of the three leading factors to cause the outdoor air pollution [3]. On the other hand, global warming, which is caused by greenhouse gas (GHG) emissions dominated by CO_2 (90%), is affecting people's life and health with the transportation sector being one of the largest contributors to GHG emissions. According to the data from the International Energy Agency (IEA), global CO_2 emissions reached 32.3 gigatonnes (Gt) of CO_2 in 2015, while transportation accounted for 24% of the total emissions and three-quarters was contributed by the road sector [4]. Global warming not only increases human mortality due to heat stress, disease, and natural disasters, but also can shift the location of viable agriculture, harm ecosystems and animal habitats, and change the timing and magnitude of water supply [5]. Global warming has sounded an alarm to human beings. It was reported the temperature in the Arctic Circle reached 32 °C in the summer of 2018 and deaths caused by the extreme hot weather happened worldwide such as in Europe, Japan and Canada. Perhaps, some researchers argue that the production of electricity for charging battery electric vehicles (BEVs) or generation of hydrogen for fuel cell electric vehicles (FCEVs) can produce a great deal of GHG emissions which are not even less than those from ICEVs based on an equivalent assessment, but this is based on the hypothesis on the use of fossil fuels such as coal and oil for electricity generation. In fact, based on a Well-to-Wheel (WTW) analysis, the GHG emissions to produce electricity or hydrogen are strongly dependent on the primary energy sources [6]. If the electricity is generated by nuclear power, hydro power or renewable energy sources such as biomass, solar, and wind energy, the WTW GHG emissions for BEVs are much less than those for ICEVs. With solar electrolysis hydrogen, the GHG emissions of FCEVs can be reduced about 99.2% compared to the gasoline ICEVs. It is worth mentioning that the main countries in the world including United States, China, and European Union all have plans to increase the ratio of renewables in their electricity generation, which will significantly enhance the beneficial environmental effects of PEVs [7,8]. Thus, the result of the argument will become clear and PEVs can completely outperform ICEVs in the reduction of the GHG emissions with the development of technologies and policies. Another major contributing factor of developing PEVs is that the energy crisis caused by the depletion of the fossil resources is becoming an urgent issue. The IEA reported that the world oil demand stood at nearly 97.7 million barrels per day on average in 2017, while the remaining technically recoverable crude oil resources only can sustain use for approximately 60 years. The world energy balance shows that transportation is by far the predominant oil consuming sector taking up 56% of the world oil consumption [3]. Therefore, it is imperative for human beings to take effective measures in advance in order to avoid the social and economic chaos when the day of energy exhaustion comes. In addition, the energy efficiency of the PEVs is much higher than that of the conventional ICEVs. Taking the component efficiencies such as the batteries and electric motor, recharging efficiency and regenerative braking energy into account, the total energy efficiency of BEVs is approximately from 60% to 70%. As for FCEVs, the average conversion efficiency is between 35% and 55%, while the fuel efficiency of conventional ICEVs is merely 15–18% [9]. Furthermore, PEVs offer another potential advantage that they can be utilized as distributed energy storage systems to connect with a smart grid compared to ICEVs and common HEVs with a small battery. The power flow of this connection can be bidirectional. The excessive energy in the energy storage devices of PEVs could be fed back to the grid during the high peak demand period or for compensating renewable power generation variability. The surplus energy from the grid can be stored through charging the batteries or electrolyzing water to produce hydrogen. This vehicle-to-grid (V2G) option can provide ancillary services, load leveling, and help to improve the power quality and reliability of the grid and reduce the effects of renewable generation intermittency [10–14].

According to the data from the website of China Association and Automobile Manufacturers, global light duty vehicle sales totaled approximately 96.8 million in 2017 and it is estimated that the number will grow by 3.2% between 2018 and 2022. There were at least 217 million passenger vehicles and trucks of all kinds in China which also had the biggest automobile market with more than 29 million sales in 2017. As the number of vehicles in the world rises significantly, the problems mentioned above will become more serious. Determining how to deal with these problems has caught the public's attention and many governments and automobile companies are developing new technologies and products. In September 2017, China announced that manufacturing and selling of conventional ICEVs will be stopped in the near future, while some countries such as the Netherlands and Norway, Germany and India, as well as England and France have announced they will ban selling conventional ICEVs in 2025, 2030 and 2040, respectively. Therefore, developing EVs is the inevitable trend. Although EVs still have emissions in the process of production and manufacturing, they produce much less pollutants in the operation than ICEVs. Especially, PEVs are completely environmentally-friendly on the road. There are numerous literature surveys on the technologies of HEVs and some papers related to PEVs have generally focused on configuration design, modeling approaches, and/or energy management of a certain PEV. But, there is a lack of published papers presenting a comprehensive review for PEVs. This paper is the first study to comprehensively investigate the key technologies of PEVs.

The paper is organized as follows: In Section 2, the characteristics of energy sources for PEVs are presented and the models of the energy storage or generation systems are established. Section 3 classifies and depicts the existing PEV type in the present literature. In Section 4, Energy management strategies (EMSs) employed for PEVs are investigated. Prior to this, EMSs used for HEVs are firstly categorized and discussed for some EMSs can be applied in both HEVs and PEVs. Section 5 describes the charging technologies for PEVs with electric storage devices. In Section 6, the main challenges of PEVs becoming popular in the public market are addressed and the solutions to the problems are indicated, whilst the latest developments related to PEVs are presented. Finally, conclusions are given in Section 7.

2. Characteristics and models of energy sources for PEVs

There are various energy systems to store electrical energy (batteries, Supercapacitors, superconducting magnet), generate electrical energy (FCs, photovoltaic cells, wind turbines), and store mechanical energy (flywheels, pumped hydroelectric plant, hydraulic accumulators) [15]. However, some of them are not suitable as the onboard energy sources for PEVs because of the installation requirements, either technological level or super-high costs. The following energy sources can be used on PEVs.

2.1. Energy storage devices

2.1.1. Battery

A battery is the most widespread energy storage device in power system applications with the ability to convert the stored chemical energy into electrical energy. Today, there are three main types of batteries which are suitable for road transportation application: lead-acid batteries, nickel-based batteries, and lithium-based (Li-based) batteries. There are also three uncommon types of batteries in the market: sodium sulphur (NaS) batteries, metal-air batteries, and flow batteries.

Lead-acid batteries are the oldest rechargeable electrochemical devices for both household and commercial applications. The advantages of the lead-acid batteries are that they have low capital costs (60–200 $/kW h), high energy efficiencies (63%–90%), fast response and small self-discharge rates with around 2% of rated capacity per month (at 25 °C). Nevertheless, lead-acid batteries have low specific energy density (25–50 Wh/kg) and relatively low cycle life (500–1500 cycles). It also causes environmental problems in the production or disposal process of these batteries. These unfavorable factors limit the more widely commercial application of lead-acid batteries [15–17].

Nickel-based batteries consist of four types: nickel-iron, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and nickel-zinc (NiZn) batteries. The nickel-iron battery has higher stability, longer lifespan, and relatively lower cost when compared to other nickel-based batteries. But the nickel-iron battery also has the drawbacks such as low power density, high self-discharge rate, heavy weight, and high maintenance cost. The NiCd battery has quick charge performance, the durability of overcharge/discharge, and good adaptability of large temperature range. However, the NiCd battery has a memory effect in the charging and discharging process, and environmental problems due to its toxic materials, therefore it is almost obsolete in the application of digital electric devices. The NiMH battery has higher energy density and a higher discharging speed compared to other nickel-based batteries but it generates a great deal of heat during charging. The NiZn battery is environmentally-friendly and safe, but the present major issue is the short cycle life, which significantly limits the commercial application. It was reported in 2018 that the researchers at Dalian University of Technology had made the breakthrough in the cathode material of the NiZn batteries and the cycle life could be increased tenfold reaching early 10,000 cycles. As a whole, nickel-based batteries are generally superior to lead-acid batteries in terms of higher energy density and cycle life, while they also have a higher cost ranging from 100 to 300 $/kWh and lower energy efficiencies with less than 80% [1,16].

Li-based batteries are becoming the most promising and popular storage devices because of their advantages such as high energy density, light weight, no memory effect and no environmental problems. There are four main types including Li-ion, Li-ion polymer, Li-iron sulphide, Li-iron phosphate. Among these batteries, the Li-iron phosphate battery is the most expensive but has much higher power density (2–4.5 kW/kg) and high cycle life of more than 2000 cycles. The Li-iron sulphide battery has a higher energy capacity with low weight, while its cycle life is only more than 1000 times. The Li-ion polymer has good reliability and ruggedness, but its conductivity is poor and the power density is comparatively lower. The Li-ion battery is the best choice for cost performance as it has high specific energy density (up to 250 Wh/kg), high power density (ranging from 0.5 to 2 kW/kg) and high energy efficiency (90–100%), low self-discharge, long lifetimes with moderate cost. However, it is noteworthy that the lifetime of the Li-ion battery can be reduced abruptly due to the effects of the high temperature and deep discharge whilst a protection circuit is required to ensure safe operation [1,16–18].

The uncommon batteries can be briefly described as follows. The NaS batteries have the features such as high energy density (150–300 Wh/L), good energy efficiency (89–92%), long cycle life (2500 cycles upon 90% depth of discharge), and high pulse power capability with prompt and precise responses. But an extra system is required for the NaS batteries in order to ensure the operating temperature. Their operating costs per year are a little high, which makes them suitable only for large-scale stationary applications [17,19]. Metal-air batteries make use of an electropositive metal such as zinc and aluminium in an electrochemical couple with oxygen from the air to generate electricity. These batteries are compact and have low costs but the limitations are low energy efficiencies (50%), short cycle life (a few hundred cycles), and limited operating temperature ranges [17]. The flow batteries, classified into redox flow batteries and hybrid flow batteries, have an inherent strength of very small self-discharge for the electrolytes are stored in the separately sealed tanks. However, they have the disadvantages such as high initial costs, complex system structure and low performance, which prevent them from commercial applications [19].

Because Li-ion batteries are being widely used in PEVs, the battery model is established here taking Li-ion batteries for instance. The conversion characteristics of Li-ion batteries can be described considering the internal resistance and the battery discharged power P_b can be expressed as [20,21]:

$$P_b = U_{oc} I_b - I_b^2 R_{int} \tag{1}$$

where R_{int}, U_{oc}, and I_b are the internal resistance, the open circuit voltage, and the battery current, respectively. Note that Eq. (1) is also valid in the charging mode, and the direction and sign of the battery power and current will be negative. Solving the quadratic Eq. (1), the current can be derived

$$I_b = \frac{U_{oc} - \sqrt{U_{oc}^2 - 4R_{int}P_b}}{2R_{int}} \tag{2}$$

The state of charge (SOC) of the battery, namely SOC_{bat}, shows the remaining amount of electric energy stored in the battery and can be defined as [22,23].

$$SOC_{bat} = SOC_0 - \frac{\int I_b dt}{C_n} \tag{3}$$

where SOC_0 is the initial battery SOC, and C_n is the battery rated energy storage capacity representing the maximum total electrical charge. In order to avoid over-discharge/charge and prolong the battery lifetime, the maximum and minimum of the SOC_{bat} are usually predefined as 0.9 and 0.2, respectively.

2.1.2. Supercapacitor

Supercapacitors (SCs), also named ultra-capacitors, have a similar structure as conventional capacitors but store energy by means of an electrolyte solution between two solid conductors. The capacitance of SCs is much larger than conventional capacitors, which also makes their energy storage capacities as high as 20 times that of conventional capacitors. There are three types of SCs: electric double-layer capacitors (EDLCs), pseudo-capacitors, and hybrid capacitors. Although their energy storage mechanisms and electrode materials are different, they have similar characteristics such as power density, life cycle, and energy efficiency. It should be mentioned that EDLCs have smaller specific energy density (5–7 Wh/kg) compared to the other two (10–15 Wh/kg). High life cycle (1×10^5 cycles for around 40 years) is the distinctive feature of SCs compared to other energy storage devices. Besides, SCs have high power density (1000–2000 kW/kg) and energy efficiency (~84–97%). Thus, they can be quickly charged and release a large amount of power without excessive energy losses. The major issues of SCs are the short duration and high self-discharge rate which are also the reason that SCs cannot be used alone as the energy source for vehicles. Another challenging problem for SCs is their high capital costs (more than 6000 $/kWh). Therefore, SCs are very suitable to be utilized as an auxiliary energy source for short-term energy storage applications [15,17,19,24].

A SC model can be described through an equivalent circuit, as its electric characteristics are more complex compared to a conventional capacitor. The classical equivalent circuit of the SC unit comprises of a capacitance (*C*), an equivalent series resistance (*ESR*, *R*) and an equivalent parallel resistance (*EPR*). The *ESR* represents the charging and discharging resistance, while the *EPR* represents the self-discharging losses in the circuit [25].

The effective discharging voltage of an *RC* circuit can be described as follows:

$$V_{SC}(t) = V_i \exp\left(-\frac{t}{RC}\right) \tag{4}$$

where V_{SC} is the SC voltage, V_i is the initial voltage before discharging, t is the time, and R, C are the resistance and capacitance values, respectively.

The amount of energy released from the SC bank is directly proportional to the capacitance and voltage changes throughout discharge. The relationship expression of the released energy can be presented as:

$$E_{SC} = \frac{1}{2} C\left(V_i^2 - V_f^2\right) \tag{5}$$

where E_{SC} is the released energy from the SC bank and V_f is the final voltage.

In practical applications, the amount of energy that the systems requires can be obtained through the connection of a number of SCs in series and parallel. The terminal voltage and the total capacitance depend on the number of capacitors connected in series and parallel, respectively. The total resistance R_{SC} and the total capacitance C_{SC} of the SC bank can be calculated as [25,26].

$$R_{SC} = n_s \frac{ESR}{n_p} \tag{6}$$

$$C_{SC} = n_p \frac{C}{n_s} \tag{7}$$

where n_s and n_p represent the number of capacitors connected in series and parallel, respectively.

2.1.3. Flywheel

Flywheels store energy in the angular momentum of a high-speed rotating mass (rotor) in a high vacuum environment which enables them to minimize the windage losses and protect the rotor assembly from external disturbances [15]. During the charging phase, the rotor is accelerated by an integrated motor/generator (M/G) in the motor operation mode to achieve a certain high speed. During the discharging phase, the rotor decelerates and transfers the kinetic energy rotor to electrical energy through the integrated M/G in the generator operation mode [17]. Based on the rotational speed, flywheels can be categorized into two groups: the low speed flywheels and high speed flywheels. The low speed flywheels, with steel material and less than 6×10^3 rpm, are typically used for short-term and medium/high load applications. The high speed flywheels, which utilize advanced composite materials and rotate up to ~10^5 rpm, are mainly applied in high power quality and ride-through power service in traction and the aerospace industry [27].

The major strengths of flywheels are low maintenance cost, long life cycle, high efficiency (90–95%), no depth of discharge effect, environmentally friendly, wide operating temperature range, and ability to survive in harsh conditions [28,29]. Nevertheless, the issues related to safety and the gyroscopic force management as well as the weaknesses including low energy density and high self-discharge losses restrain flywheels from vehicle applications. For high speed flywheels, the specific energy density is less than 100 Wh/kg, while the low speed flywheels can achieve only 5 Wh/kg. As a result of friction losses, the self-discharge can be up to 20% of the stored energy capacity per hour. Consequently, flywheels are not well suited for long-term storage applications [15,30,31].

The principle of storing energy for a flywheel is based on a rotating mass, and the stored energy is determined by the moment of inertia and the angular velocity. In a practical flywheel system, the angular velocity normally has an operation range in order to avoid too large voltage variations and limit the maximum torque of the M/G. The storage capacity of a practical flywheel can be obtained by the follow equation [32,33].

$$E_{FW} = \frac{1}{2}J\left(\omega_{max}^2 - \omega_{min}^2\right) \tag{8}$$

where E_{FW} is the stored energy in a flywheel, J is the moment of inertia, and ω_{max}, ω_{min} are the maximum and minimum angular velocity, respectively.

The produced power of a flywheel depends on the rate of the converted energy, which can be given as follows [32]:

$$P_{FW} = \frac{1}{2}J\frac{\omega_2^2 - \omega_1^2}{\Delta t} \tag{9}$$

where P_{FW} is the produced power of a flywheel, Δt is the time during the angular velocity variation, and ω_1, ω_2 are the angular velocities before and after the variation, respectively.

For an instantaneous angular velocity ω, the torque output T_{FW} can be calculated by the following equation.

$$T_{FW} = \frac{P_{FW}}{\omega} \tag{10}$$

2.1.4. Hydraulic accumulator

Hydraulic accumulators (HACCs) are used to store and subsequently release hydraulic energy through a variable displacement high pressure pump/motor (P/M). When the P/M operates as a pump, the hydraulic fluid is pumped into the accumulator from a tank and the gas (usually nitrogen) in the chamber of the accumulator is compressed. At the same time, the mechanical energy is converted to the hydraulic energy stored in the accumulator. When the external load requires energy, the hydraulic energy is released from the accumulator to drive the P/M operating as a motor [34,35]. Based on the membrane between the gas and the fluid side of the accumulator, the common accumulators are subdivided into three types: bladder type often found in industrial installations, membrane type often found in the automotive industry, and piston type often found in the off-shore and chemical industry [36].

HACCs have high power density (approximately 5 kW/kg), high energy conversion efficiency (93%–97%), and low costs. In addition, they have the ability to accept exceptionally high rates of charging and discharging, which facilitates effective regeneration and reuse of energy for vehicle applications especially in urban cities with frequent stop-and-start road conditions [37–39]. However, the relatively lower specific energy density prevents them from being used as an independent energy source [38,40]. Although HACCs and SCs have similar characteristics, the capital cost of SCs is much higher than that of HACCs. In addition, the charge leakage of SCs can result in environmental issues [38]. Thus, it seems to be a more competitive option in vehicle applications between HACCs and SCs.

When the HACCs discharge the stored hydraulic energy, the high-pressure fluid flows into the P/M operating as a motor to drive the vehicle. When the vehicle decelerates, the HACCs store the braking energy through the P/M operating as a pump. The relationship between the pressure and volume of the gas in the HACCs is as follows [35]:

$$p_1 {V_1}^n = p_2 V_2^n = p_0 V_0^n \tag{11}$$

where p_1, p_2, and p_0 denote the minimum, maximum, pre-charge pressure of the HACCs, while V_1, V_2, and V_0 are the corresponding gas volume in the HACCs; n represents the polytropic exponent and its value is 1 for the whole changing process of the gas compression and expansion is slow. The SOC of the HACCs, namely SOC_{acc}, is defined as the ratio of instantaneous fluid volume in the HACCs to the maximum fluid capacity [41].

$$SOC_{acc} = \frac{V_{max} - V}{V_{max} - V_{min}} \tag{12}$$

where V, V_{max}, and V_{min} denote the instantaneous, maximum, and minimum gas volume in the HACCs, respectively. The maximum and minimum of the SOC_{acc} are 0 and 1 which represent the HACCs as empty and full, respectively. The values of the SOC_{acc} vary between the maximum and minimum.

2.1.5. Hydrogen storage

Hydrogen energy is one of the most popular energies due to its storable, transportable, and clean nature [17]. The byproducts are basically water and heat whether the hydrogen gas is burned in an ICE to convert into mechanical energy or oxidized in a Fuel Cell (FC) to produce electricity without any pollution. The energy conversion efficiency of hydrogen in a FC can achieve more than 70%, while the efficiency of the hydrogen combustion in an ICE is only about 30% [42]. Hence the application of hydrogen energy in a FC to produce electricity directly is more promising.

Hydrogen can be generated through the electrolysis of water and the conversion efficiency is around 60% [17]. The method is very environmentally-friendly, but the costs are considerably high as it consumes plenty of electricity. Renewable energy sources (solar, wind, geothermal, etc.) can also supply clean and sustainable energy for the electrolysis of water, but the current costs are also a little high. Presently, most of the global hydrogen is produced by reforming natural gas using steam and catalyst because of its low cost and higher efficiency (85%), but the shortcoming of this method is that it has the additional product of CO_2 [43]. In addition, direct production of hydrogen through photocatalytic water splitting based on nanotechnology seems to be very promising. Nevertheless, the technology is still in the research stage [42].

As to the storage of hydrogen, the widely used solution is compressing hydrogen under high pressure (normally 7000 times atmospheric pressure) in the sealed hydrogen tanks. Another storing method is using a cryogenic system (at −253 °C) to liquefy hydrogen, but the liquefaction requires about 30% of the energy in the hydrogen. Furthermore, hydrogen is possible to be stored on the surfaces or within some absorbing materials by absorption, but the method has disadvantages such as the high temperature or pressure requirements, a long time to release the hydrogen, and the difficulty in material recycling [1,43,44].

2.2. Energy generation systems

2.2.1. Fuel cell systems

FC systems convert chemical energy into electricity through chemical reactions between hydrogen (or hydrocarbon such as methanol, natural gas) and oxygen (from air) with the help of catalysts. The conversion process is the FC splits hydrogen into electrons and protons, and the electrons are forced into a circuit to create an electric current when protons pass through the electrolytes. Generally, the process to generate electricity using FCs is quiet, highly reliable, pollution-free, and highly efficient. According to the choice of fuels and electrolytes, FCs can be categorized into six major groups: direct methanol fuel cells (DMFC), alkaline electrolyte fuel cells (AFC), molten carbonate fuel cells (MCFC), phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC), and proton exchange membrane fuel cells (PEMFC) [45]. The DMFC have high energy density, but they have low efficiency and emit CO_2. The MCFC and SOFC have a high operating temperature (600–1000 °C), and are normally used in electric utilities and distributed power generation. The DMFC, PEMFC, AFC, and PAFC are commonly used in transportation due to their normal or moderate operating temperature. Compared to other FCs, the PEMFC have the highest power density and the strengths such as long lifespan, low temperature operation, and fast response. Thus, the PEMFC are very attractive in transportation applications [1,18]. Although FCs have the shortcoming of a high capital cost at present, the cost is dropping thanks to the expanding market and the better economy of scale.

The PEMFC are the most promising in the FC sources to be applied in PEVs, and many empirical PEMFC models are derived by the Nernst equation. The ideal voltage generated by a single cell of a typical FC can be described as [46]:

$$E_{cell} = E_0 + \frac{RT}{2F}\ln\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}} \tag{13}$$

where E_0 is the cell open circuit voltage at standard pressure, R is the universal gas constant, F is Faraday's constant, T is the operating absolute temperature, P_{H2}, P_{O2}, and P_{H2O} are the partial pressures of hydrogen, oxygen, and gas water inside the cell, respectively.

However, the single cell output voltage is less than the ideal potential due to some factors which cause voltage losses including activation losses, internal current losses, resistive losses, and concentration losses. As a result, the output voltage of the FC stack can be expressed as [46,47]:

$$V_{FC} = N\left(E_0 + \frac{RT}{2F}\ln\left(P_{H_2}\left(P_{O_2}/P_{std}\right)^{1/2}\Big/P_{H_2O}\right) - V_L\right) \tag{14}$$

where N is the number of cells in the stack, P_{std} is the standard pressure, and V_L is the voltage losses.

2.2.2. Photovoltaic cell systems

Photovoltaic (PV) cells (or called solar cells) can convert sunlight directly into electricity. An individual PV cell has very small power output (only about 1 or 2 W). Generally, PV cells are connected together (in series and/or parallel chains) to form modules or panels, and PV modules can be grouped to form PV arrays for larger power needs [48]. Apart from PV modules, a PV system consists of a solar inverter to change the electric current from direct-current (DC) to alternating-current (AC), as well as mounting, cabling and other electrical accessories. During the operation, PV systems do not generate pollution and GHG emissions, whilst these systems have the advantages such as silent operation, long lifetime and low maintenance [49,50]. However, the main disadvantages of PV systems are high initial capital costs and unpredictable availability caused by weather conditions [51,52].

The main manufacturing materials for PV cells in market are from crystalline silicon and thin films. The crystalline silicon PV cells, namely the first-generation PV cells, are one of the most commonly used – accounting for around 90% of the worldwide production in recent years. This crystalline silicon PV cell includes Mono-crystalline silicon (mono-si) and multi-crystalline silicon (multi-si). The mono-si PV cells have an average efficiency of 14.0% which is relatively higher than the multi-si ones with an average of 13.2%, but the multi-si ones have simpler and cheaper manufacturing techniques [53]. The thin film based PV cells are the second-generation PV devices which are made from amorphous silicon or nonsilicon materials such as cadmium telluride (CdTe) and copper indium diselenide (CIS). Generally, the thin-firm PV cells have the advantages such as a relatively lower cost and lighter weight. The CdTe type is one of the fastest-growing thin-film PV cells and the highest power conversion efficiency can achieve 21% [54]. The third-generation PV cells are developing new materials such as solar inks using conventional printing press technologies, solar dyes, and conductive plastics to improve the energy efficiencies and decrease the capital costs of PV cells.

PV systems have widespread applications in practice such as supplying power to buildings, spacecraft, water heater, and road lights. They can also be built over parking lots to provide daytime charging for commuter vehicles [55]. However, it remains a challenge to directly apply PV systems in commercial EVs because of the limitation of space and low power generation. However, PV systems can be used to improve vehicle efficiency (10–20%) or to keep the vehicle in comfortable temperature range by running the air conditioner [56].

The PV model can be described via an equivalent circuit, and the output current of a PV module can be presented as follows [57–59]:

$$I = I_{pv} - I_0\left[\exp\frac{q(V+R_sI)}{N_sKTa} - 1\right] - \frac{V+R_sI}{R_p} \tag{15}$$

where I_{pv} and I_0 represent the PV current and saturation current of the module; q refers to the electron charge; V denotes the voltage across the diode; R_s and R_p are the equivalent series resistance and parallel resistance of the module; N_s, K, T and a indicate the number of cells, the Boltzmann constant, the module temperature and the ideality factor of the diode, respectively.

In Eq. (15), the PV current I_{pv} has the following relationship with the solar radiation and the temperature.

$$I_{pv} = \left[I_{pv,n} + K_I(T - T_n)\right]\frac{G}{G_n} \tag{16}$$

where $I_{pv,n}$ is the current generated by the PV module at the nominal condition of solar radiation at 1000 W/m^2 and temperature at 25 °C; K_I indicates the short circuit current temperature coefficient (A/°C); T and T_n denote the actual and nominal temperatures (K); G and G_n are the actual and nominal solar radiations (W/m^2).

The saturation current I_0, which is strongly dependent on the temperature, can be expressed by:

$$I_0 = \frac{I_{sc,n} + K_I(T - T_n)}{\exp\frac{q[V_{oc,n}+K_V(T-T_n)]}{aN_sKT} - 1} \tag{17}$$

where $I_{sc,n}$ and $V_{oc,n}$ are the short circuit current (A) and the open circuit voltage (V) at the nominal conditions, while K_I and K_V are the current and voltage coefficients, respectively.

2.2.3. Regenerative braking systems

Regenerative braking systems can provide energy for vehicles through recovering and storing the kinetic energy of the vehicle decelerating stage in the energy storage devices. If there are no regenerative braking systems on the vehicle, the kinetic energy of the vehicle in the decelerating stage is converted into heat by the mechanical braking. Presently, there are four methods to realize the functions of regenerative braking systems. The first common method is using an electric M/G and batteries or a SC. In the vehicle deceleration, the M/G operates as a generator to convert the kinetic energy into electricity and stores it in the batteries or the SC. When the vehicle accelerates, the M/G operates as an electric motor and releases the energy. Another extensively used method is using a hydraulic P/M and HACCs. In the braking mode, the P/M pumps the hydraulic fluid from a low-pressure reservoir to the HACCs, which converts the kinetic energy into the hydraulic energy. If the vehicle requires energy, the stored hydraulic energy can be released by the P/M operating as a hydraulic motor to drive the load as an auxiliary power. Thirdly, the kinetic energy of a vehicle can be stored in a flywheel as rotating energy. Furthermore, the braking energy can also be stored as potential energy through springs [60,61]. Compared to other methods, the hydraulic and flywheel regenerative systems have the higher energy efficiency. Moreover, the hydraulic regenerative systems have faster charging and discharging ability, higher power density, and a large capacity to recover the maximum possible regenerative braking energy. In contrast, the battery regenerative systems are not suitable to be charged and discharged frequently in order to avoid overheating, reduction of the lifetime or even destruction. The main drawback of the SC regenerative systems is the high costs, while the spring regenerative systems have very low energy efficiency [23,62,63].

3. Existing types of PEVs

3.1. Single-source PEVs

The single-source PEVs only have a single energy source to propel the vehicles. BEVs, invented in 1828, are the earliest single-source PEV as illustrated in Fig. 1(a). But the limited driving range and long charging time for batteries of BEVs limited their extensive application in the market during a period, while the conventional ICEVs were comparatively more popular because of the advancement in dynamic performances and low costs of fuels. BEVs have regained the attention from manufacturers and consumers during recent years due to the serious environmental problems and energy crisis resulting from ICEVs. The advantages of BEVs are zero emissions, high efficiency and less noise. In addition, the electric motor can operate as a generator in the vehicle deceleration, which enables BEVs to recover the regenerative braking energy [64,65]. However, it should be noted that frequent charging and discharging can cause the overheating of the batteries and shorten their lifetime.

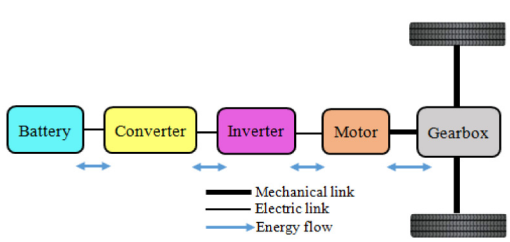
Another single-source PEV type is FCEVs as shown in Fig. 1(b) whose powertrain consists of a FC stack (with a hydrogen tank), a power converter, an inverter and an electric motor. The FC stack is the core component to supply the power for FCEVs and the PEMFC are the most promising for vehicle applications because of the low operating temperature, high power density, and the option of conventional air operation [66]. The FCEVs use electrical energy converted directly from hydrogen and oxygen, while their chemical product is pure water. Thus, FCEVs have the features such as high efficiencies, recycling and sustainable energy supply, and quiet operation. Additionally, the liquid hydrogen is conveniently portable similar to the fuel tank of conventional ICEVs. However, when compared to BEVs, FCEVs are not able to recover the braking energy as the power flow of the powertrain is not bidirectional [65].

3.2. Dual-source PEVs

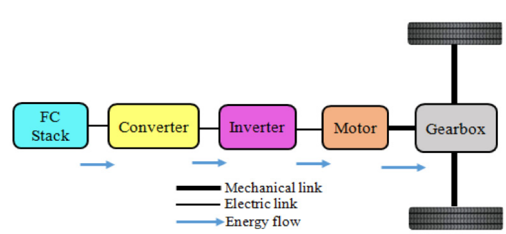
The dual-source PEVs combine two energy sources in the vehicle propulsion system, and can overcome the shortcomings of utilizing a single energy source. There are several combinations of dual sources in the literature including battery and SC, battery and flywheel, battery and HACC, battery and FC, and FC and SC. For the battery-SC PEVs as depicted in Fig. 2(a), the battery acts as the main energy source to supply traction energy, while the SC as the auxiliary energy source can provide the power requirement to fulfill the dynamic performance of the vehicle and recover the regenerative energy [67,68]. Similarly, in the hybrid energy storage system of the battery and flywheel illustrated in Fig. 2(b), the battery is used as the main energy source to meet the power needs and the flywheel as the auxiliary energy storage device to store the regenerative energy in transients. The flywheel stores the braking energy during the deceleration and discharges energy during the vehicle acceleration. Hence, the battery lifetime can be extended and the vehicle performance as well as the efficiency can be improved [69]. Different from the SC and the flywheel, the HACC as the auxiliary energy source can directly convert the kinetic energy into fluid power during vehicle deceleration and release the energy when the vehicle needs. The battery and HACC powertrain can be designed as parallel and series configurations which are presented in Fig. 2(c) and fig2(c1), respectively. The series configuration enables the battery to charge the HACC, which can fulfill the potential of the HACC and ensure the dynamic performance of the vehicle. Nevertheless, more energy conversion in the series configuration can result in extra energy losses and decrease the whole system efficiency [70]. In the powertain of integrating the battery and FC as depicted in Fig. 2(d), the FC generally supplies the constant power, while the battery is used to supplement the deficit or absorb the surplus of the FC power. In addition, the battery can also store the braking energy during the deceleration [71,72]. The configuration of PEVs combining the FC and SC is illustrated in Fig. 2(e). The FC acts as the main energy source and provides the main traction power, while the SC supplies the auxiliary power during the acceleration and captures the regenerative energy during the deceleration [73,74].

3.3. Multi-source PEVs

The multi-source PEVs consist of at least three energy sources in the vehicle powertrain. Integrating multiple energy sources can completely fulfill their respective potential and facilitate a better dynamic performance. The multi-source combination increases the energy storage capability and is able to make full use of its respective advantages to improve the system efficiency, durability, and component lifespans. In addition, the optimized design among all the energy sources provides an opportunity to minimize the costs and avoid the oversized or overweight components.



(a) Powertrain of BEVs



(b) Powertrain of FCEVs

Fig. 1. Powertrain configurations of the single-source PEVs. (a) Powertrain of BEVs (b) Powertrain of FCEVs.

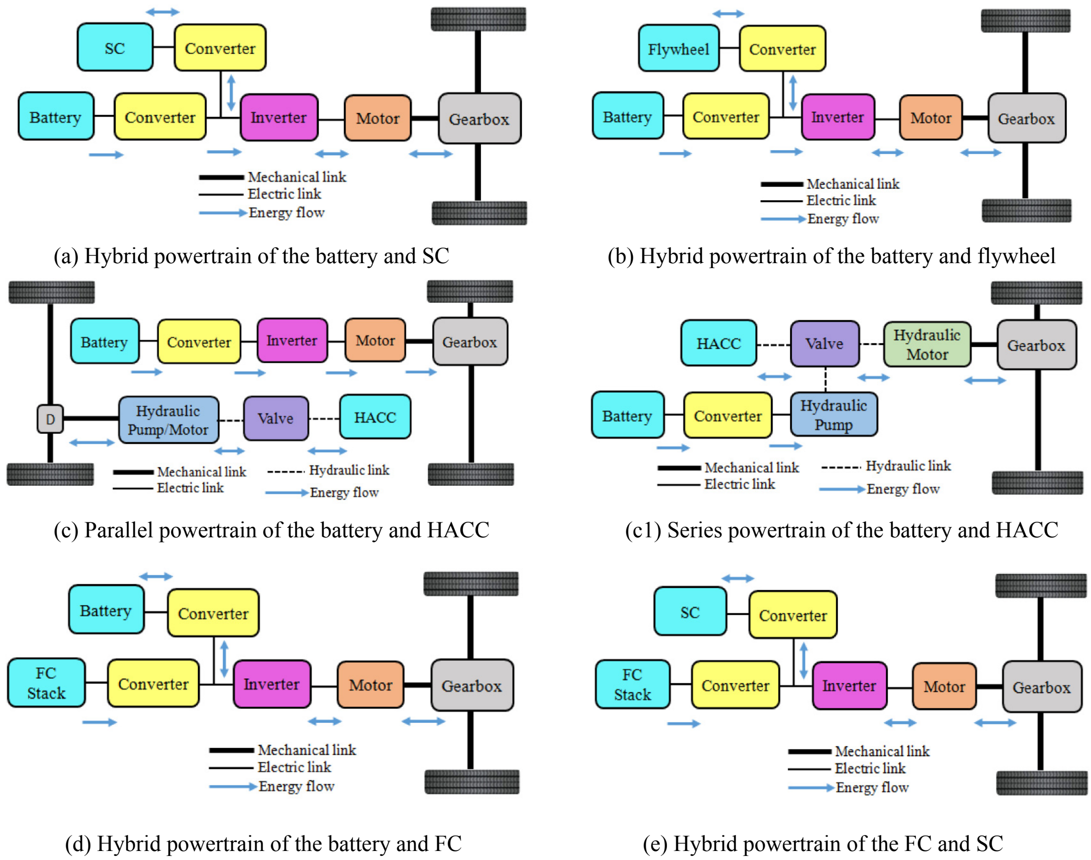


Fig. 2. Powertrain configurations of the dual-source PEVs, (a) Hybrid powertrain of the battery and SC (b) Hybrid powertrain of the battery and flywheel, (c) Parallel powertrain of the battery and HACC (c1) Series powertrain of the battery and HACC, (d) Hybrid powertrain of the battery and FC (e) Hybrid powertrain of the FC and SC.

Consequently, combining multiple energy sources offers a cost-effective solution to the practical application of PEVs. The multi-source powertrain configurations existing in the literature are illustrated in Fig. 3 [75–80]. In these configurations, the FC stack is generally utilized as the main energy source to supply traction energy, while the SC is employed as the auxiliary energy source to

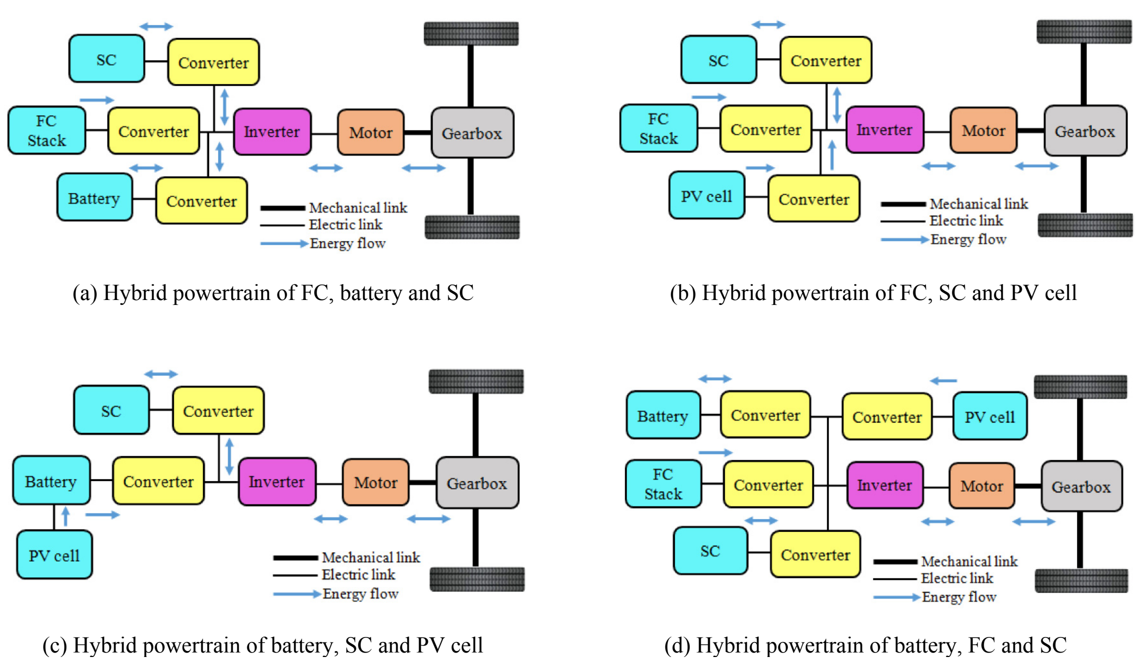


Fig. 3. Powertrain configurations of the multi-source PEVs, (a) Hybrid powertrain of FC, battery and SC (b) Hybrid powertrain of FC, SC and PV cell, (c) Hybrid powertrain of battery, SC and PV cell (d) Hybrid powertrain of battery, FC and SC.

store the regenerative energy in the deceleration and braking process. The battery can be used as the main energy source as illustrated in Fig. 3(c) and it can be also used as the auxiliary energy source to store the surplus regenerative energy. It should be noted that the PV cell is employed as the auxiliary energy source to generate electricity and realize energy saving.

3.4. Environmental impacts of PEVs

The environmental impacts of PEVs can be evaluated by Life Cycle Analysis (LCA) which can explicitly quantify resource use and environmental releases throughout the entire life cycle of a product. One typical application of LCA is WTW analysis which provides an overall picture of energy consumption and the emissions from the point of initial energy source extraction (well) to the point of utilization (wheels). In order to make the comparison among different powertrains more intuitive, the uniform standards of evaluations need to be expressed. Although kilometers are not the best functional unit for LCA, the functional unit is the most commonly used in the literature. As a result, the energy consumption can be evaluated in terms of 'litres of gasoline equivalent/100 km (l_gas_eq/100 km)'. In addition, CO_2 emissions are the most commonly measured output used to assess the environmental impacts and other emissions such as water vapour are not considered in this evaluation. Hence, the emissions are evaluated by 'grams of CO_2 equivalent/km (g_CO_2_eq/km)' [81,82].

The single-source PEVs are the most widely used vehicle type in the commercial applications and other PEVs are developed based on the single-source ones. Thus, we only discuss and compare the environmental impacts of BEVs and FCEVs in this study. Furthermore, Li-ion batteries are a very suitable choice for BEVs because of the high specific energy density, lack of memory effect, and slow self-discharge rates, while PEMFCs have the highest potential among the FCs for vehicle applications. Consequently, Li-ion battery based BEVs and hydrogen based FCEVs are considered for the WTW evaluation in this paper.

Although Li-ion battery BEVs and hydrogen-based FCEVs do not have local emissions, the material acquisition, production, delivery and even final disposal of the energy sources supplying energy after conversions for the vehicles mentioned above have energy consumption and associated emissions. Natural gas is commonly used to produce hydrogen because of its low cost. In order to compare intuitively, the BEVs use the electricity converted from natural gas. In addition, renewable energy sources such as solar and wind energy can be used for the hydrogen and electricity production too. The comparison of Li-ion battery-BEVs and hydrogen-FCEVs, which are supplied energy by natural gas and solar/wind energy as the initial energy sources respectively, together with conventional ICEVs is illustrated in Table 1 [82]. As seen from the results, both the WTW fuel consumption and emissions of the FCEVs powered by pure hydrogen are higher than that of the BEVs whether it is supplied energy natural gas or solar/wind energy. This is due to the fact that BEVs use the converted electricity directly but the hydrogen production experiences energy conversions more times and has a high carbon footprint. However, both the BEVs and FCEVs have considerably less WTW fuel consumption and emissions compared to ICEVs. It is noticeable that using renewable sources enables the BEVs and FCEVs to have extremely low WTW emissions and offers the most benefits to the natural environment. In particular, the BEVs using the electricity converted from solar/wind energy have zero emissions. Moreover, it should be noted that the WTW fuel consumption of the FCEVs based on solar/wind energy is almost thrice as much as the BEVs. This is attributed to the low efficiencies of the FC and the electrolysis process using solar/wind generated electricity to produce hydrogen. Nevertheless in other respects, the FCEVs have technical advantages such as a longer driving range per recharge, a shorter refueling/recharge time, and availability of recycling waste heat for heating in winter, compared to the BEVs.

Table 1
Comparison of Li-ion battery-BEVs and H_2-FCEVs supplied energy by different initial energy sources [82].

Vehicle types with energy sources	Fuel consumption (l_gas_eq/100 km)	Emissions (g_CO_2_eq/km)
Li-ion battery-BEVs based on natural gas	3.02	58.83
Hydrogen-FCEVs based on natural gas	4.00	74.21
Li-ion battery-BEVs based on solar/wind energy	1.54	0.00
Hydrogen-FCEVs based on solar/wind energy	4.44	2.99
Petrol-ICEVs	6.00	144.00
Diesel-ICEVs	4.70	133.00

4. Energy management strategies

Energy management strategies (EMSs) play a crucial role in the energy systems with multiple energy sources because they control the power flow in the powertrains and can determine the vehicle performance, efficiency as well as the life expectancy of the components [83]. There are a large number of published papers to present EMSs employed in HEVs, while the research publications related to EMSs used in PEVs are still very limited. However, some EMSs for HEVs also can be applied in PEVs. Thus, the EMSs used in HEVs are briefly introduced before elaborating the EMSs in PEVs.

4.1. EMSs in HEVs

The EMSs of HEVs can be broadly divided into two main categories as shown in Fig. 4: ruled-based strategies and optimization-based strategies.

4.1.1. Rule-based strategies

Rule-based (RB) strategies are the most common supervisory control strategies for HEVs and the rules are often based on heuristics, intuition, human expertise and even mathematical models [84]. These strategies can be further subdivided into deterministic and fuzzy RB methods. The deterministic RB methods consisting of thermostat (on/off), power follower, modified power follower, and state machine-based strategies are based on the analysis of power flow with precise rules. The fuzzy RB methods including conventional, adaptive, and predictive control strategies utilize fuzzy logic theory to deal with approximate reasoning and are more suitable to be applied in advanced or complex powertrains [85].

The RB strategies are real-time strategies with advantages such as simplicity, good reliability, less computation, and natural adaptability to online applications. However, developing RB

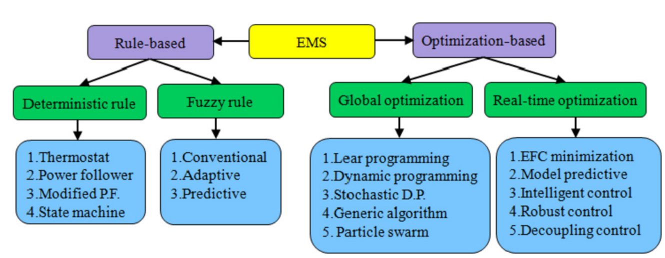


Fig. 4. Classification of EMSs employed in HEV.

strategies is time-consuming due to the difficulty of defining the accurate rules and the requirement of repeated parameter tuning and calibration for improving the vehicle performance. Particularly, the rules need to be redefined in the different vehicle configurations and new driving conditions. Moreover, the RB strategies do not involve in any minimization or optimization and cannot facilitate the best fuel economy [85,86].

4.1.2. Optimization-based strategies

Optimization-based strategies are used to minimize the fuel consumption or emissions through calculating the optimal reference torques and gear ratios [82]. According to a minimizing cost function representing the fuel consumption or emissions over time or instantaneously, there are global optimization and real-time optimization solutions. The global optimization solution aims at minimizing the cumulative energy loss throughout an entire driving cycle which has to be a priori knowledge. Thus, the global optimal solution cannot be applied in real-time energy management, but they are useful as a control benchmark for comparisons with other strategies [87]. Global optimization strategies can be categorized into linear programming, dynamic programming (D.P.), stochastic D.P., genetic algorithm (GA), and particle swarm optimization (PSO). The real-time optimization solution reduces global optimization problems into a succession of local optimization problems, which eliminates the requirement of obtaining the future driving information [85]. Hence, the real-time optimization solution can be used for online implementation and applications. The real-time optimization strategies can be sorted into equivalent fuel consumption (EFC) minimization, model predictive control (MPC), intelligent control, robust control, and decoupling control strategies [87,88].

4.2. EMSs in PEVs

Whether RB strategies or optimization-based strategies employed in HEVs can be found in the EMSs of PEVs. Presently the fuzzy logic control (FLC) strategies are the most common applications. Li et al. [89] studied a FC/battery PEV and presented a fuzzy logic controller according to the load power demand and the battery SOC. Gao et al. [90] and Ferreira et al. [91] also employed the EMS based on fuzzy logic supervisory for the FC/battery/SC hybrid powered vehicles. The designed strategy enabled every single power source to operate in the high-efficiency operation region without sacrificing the vehicle performance and reliability. The test results demonstrated the effectiveness of the proposed strategy. Ahmadi et al. [92] presented an optimized FLC-based EMS for a FC/battery/SC PEV. The power splitting method was constructed and implemented based on FLC, whist the control parameters were optimized by the GA. The simulation results demonstrated the improvements in fuel economy, vehicle performance, and battery charge-sustaining capability based on the proposed EMS. Moreover, Trovão et al. [93] proposed a multi-level EMS based on an integrated rule-based meta-heuristic approach which was used to split the power demand between the batteries and SCs for a battery/SC PEV. The approach made a better use of the sources and reduced installed power capacity. Yan et al. [94] proposed a RB EMS based on wavelet transform (WT) for a battery/SC bus. In the power splitting, the high frequency and low component power were assigned to the SC and the battery, respectively according to WT theory. The hardware-in-loop experimental results validated the reasonableness of the strategy. Song et al. [95] proposed a multi-mode EMS based on driving condition recognition technology for a FC/battery PEV. This strategy could automatically switch to the GA-optimized thermostat strategy under specific driving conditions. The better economic performance was obtained after simulation compared to the single-mode thermostat strategy. In addition, some optimization-based strategies also appeared in the EMSs of PEVs. Capasso et al. [96] described an offline EMS based on nonlinear programming for a battery/SC PEV in order to minimize the battery current variance. Then an online strategy based on the calculus of variations theory was proposed for comparisons with the abovementioned strategy. The simulation results over an ECE (Economic Commission for Europe) 15 driving cycle showed the good performance of both strategies and the effectiveness in reducing the battery charging/discharging peak current values. Kim et al. [97] developed a sub-class optimal EMS based on stochastic D.P. for a FC/battery PEV. The optimization of the control strategy took the parameter design of different component sizes into account, thus the control was near optimal. However, the study results demonstrated that combined optimization could effectively reduce the hydrogen consumption. Rodatz et al. [98] developed a real-time EFC minimization strategy to control the power distribution of a FC/SC powered vehicle. Both simulation and experiment were conducted and the results demonstrated the approach could optimize the hydrogen consumption while maintaining drivability. Zheng et al. [99] studied an optimal control based on the minimum principle for a FC/battery powered vehicle. In the EMS, a costate as the equivalent parameter between fuel usage and electric usage was proposed and the constraint on the battery SOC was introduced as a penalty function. The simulation validated the optimal trajectories of the fuel consumption. A neural network as one kind of intelligent controls was developed and used by Moreno et al. [100] for the energy management of a battery/SC combined vehicle. The simulation results displayed the effectiveness of the method in decreasing the variability of the battery current and reducing the energy consumption. It should be mentioned that the primary energy source of the battery could be replaced with other energy sources like a FC stack according to the investigation in this paper. Li et al. [101] presented a sequential quadratic programming based on EFC minimum strategy for a FC/SC/battery PEV. The experimental test results demonstrated that the hydrogen consumption had an obvious decrease and the FC degradation could be mitigated compared to the RB and the hybrid operating mode control strategies. Wieczorek et al. [102] proposed a new optimization-based EMS using gamma functions aiming at minimizing the energy consumption for a battery/SC vehicle. This strategy could derive many possibilities just by tuning function coefficients without defining a long set of rules and it could be widely used in practical applications because of its simplicity, computational efficiency, and relatively easy calibration. Especially, Koubaa et al. [103] proposed a meta-heuristic based EMS for a FC/SC powered PEV. The architecture of the EMS integrated a RB strategic layer and an optimization layer based on PSO algorithm or GA. The results displayed that the RB PSO integrated approach could achieve the optimal hydrogen consumption and maintain durability of the FC system with a low computational effort. Song et al. [104] proposed two new EMSs based on FLC and MPC for a battery/SC powered bus. The proposed control strategies were compared with the EMSs based on the existing RB control (RBC) and filtration based control. The results showed that the EMSs based on FLC and RBC were better than the other two EMSs when they were compared under their respective best performance.

Interestingly, some EMSs combining different control techniques were presented to manage the energy distribution for the PEV applications in the existing literature. Zandi et al. [105] proposed an energy management method based on the flatness control technique (FCT) and FLC. The FCT was employed to control the energy flow between the FC and the energy storage system with the battery and SC, while the FLC was used to manage the energy division between the battery and the SC. The experiment results verified the validity of the proposed strategy. Amin et al. [106] investigated an EMS based on MPC and hysteresis control for the hybrid sources comprising FC/battery/SC. The MPC was used to keep the DC bus voltage steady no matter how the load varied and to define the reference current of each converter, while the hysteresis control was utilized to track the aforementioned reference current. The simulation and experiment results validated the effectiveness of the strategy in regulating the DC bus voltage. Kraa et al. [107] proposed an EMS based on proportional-integral (PI) control and nonlinear sliding mode control (SMC) for a FC/SC hybrid system. The classical PI control was adopted to control DC bus voltage and determine the FC's reference current, while the SMC was used to control the currents of the FC and SC. The simulation results validated the success of the strategy with stable and robust performance. Hajizadeh et al. [108] proposed an online EMS for a hybrid FC/battery system. The method adopted a hierarchical hybrid controller with three layers. This first layer based on a supervisory controller was developed by Stateflow toolbox to manage the operating modes. The second layer with an advanced fuzzy controller was used for the energy splitting between the FC and battery. The third layer including local controllers was utilized to track the set points of each subsystem in order to reach the best performance. Simulation results illustrated that the operation efficiency was improved and the battery SOC was maintained at a reasonable level.

It is worthwhile to note that some EMSs which have not been found in the HEV applications are proposed and employed in the PEVs. Rezzak et al. [109] presented an energy management technique using conventional PI controller for a FC/SC hybrid vehicle. The simulation results over both urban and extraurban cycles validated the proposed strategy. Gualous et al. [110] proposed a strategy based on a polynomial controller for the energy management on a battery/SC PEV. The strategy was used to control the currents of two converters and compared with a classical PI control. The experimental tests showed the polynomial control had a higher accuracy and robustness than the PI control. Zhang et al. [111] proposed a wavelet-transform-based EMS for a FC/battery/SC powered vehicle. The strategy was able to identify the high frequency transient and real-time power demand of the vehicle, thus the power flow with different frequency contents can be allocated to the corresponding energy sources according to their respective characteristics. Simulation and experimental results validated that the system efficiency and life expectancy can be significantly increased. Jiang et al. [112] studied an adaptive control strategy for a FC/battery vehicle. This strategy could regulate the FC output current according to the battery SOC, and distribute the power flow of the energy sources appropriately. Odeim et al. [113] presented three EMSs for a FC/Battery/SC hybrid system on transit bus applications. Two offline optimization algorithms, namely, D.P. and Pontryagin's minimum principle (PMP), were firstly carried out. The two strategies only took the hydrogen consumption into account and the results were used as a benchmark. Then, an online EMS based on multi-objective GA considering the hydrogen consumption, the dynamics of the FC system and the battery power burden was proposed. As a result, the online strategy could achieve a significant improvement in the system durability with a slightly more hydrogen consumption. Thounthong et al. [114] proposed an original EMS using three control loops for a FC/Battery/SC vehicle system. The study considered the intrinsic characteristics of the three sources and defined the voltage control loops as: DC bus voltage regulated by the SC, the SC voltage regulated by the battery, and the battery voltage regulated by the FC. Experiment results validated that the strategy could distribute the power of the energy sources in an optimal way and increase the lifetime of the power components. Xiong et al. [115] presented a real-time power management strategy based on reinforcement learning algorithm for a Li-ion battery/SC powered PEV and this algorithm was systematically compared with RB and D.P. algorithm. The simulation results verified that the proposed algorithm outperformed others and the strategy could extend the lifespan of the battery pack and improve the system efficiency. Peng et al. [116] proposed a compound control method to manage energy for a battery/SC drive system. In the compound control framework, there was an active disturbance rejection controller, two current controllers, and two operational modes switch controllers. These controllers were employed to control the load following of the SC, the battery current and the charge current of the SC, and the operating modes of the controllers, respectively. With the help of the control strategy, the battery could provide the steady smooth current and the SC could supply the sharply changing current to reject the disturbance. The performance of the electric system was validated by the experimental results. Ettihir et al. [117] compared a Hysteresis EMS and an adaptive EMS based on PMP for a FC/battery hybrid powered PEV. The hysteresis EMS based on a hysteresis algorithm was designed to maintain the battery SOC level and meet the power demand. The adaptive PMP EMS was developed based on considering the real-time optimal operating points of the FCs. The comparison results showed that the adaptive PMP EMS could reduce more hydrogen consumption than the hysteresis EMS. Wang et al. [118] developed a WT-based EMS for a battery/SC powered system. The WT-based EMS with different decomposition levels was compared based on MATLAB/Simulink simulation and the results showed that the EMS with 3 decomposition levels was the best. The feasibility of the developed EMS was validated by further simulation under three typical driving cycles on a hardware-in-the loop test bench. Carignano et al. [119] proposed a novel energy-based estimation EMS for a FC/SC PEV. The strategy aimed at meeting the power demand, recovering maximum braking energy, and maintaining the maximum efficiency of the FCs. The hydrogen consumption was improved through simulation and experimentation compared to the EFC minimization strategy. Bendjedia et al. [120] presented an EMS based on frequency splitting for a FC/battery PEV. In the system, the filtered current representing the low-frequency harmonics was provided by the FC stack, while the battery played a role of a fast dynamic component. Tahri et al. [121] developed a new EMS based on Lyapunov controllers for a FC/SC PEV. The control strategy was designed according to the Lyapunov stability tools to achieve a good power splitting between the two sources considering the slow dynamics of the FCs and the bounded SOC of the SC. Ettihir et al. [122] proposed an adaptive optimal power splitting EMS for a FC/battery hybrid system. In this strategy, an adaptive recursive least square method was used to identify models online and an optimization algorithm based on PMP was employed to minimizing the hydrogen consumption. Geng et al. [123] proposed an on-off power following control strategy and a power following control strategy based on fuzzy algorithm for a BEV with the FCs as the range extender. The simulation results showed that the developed on-off power following control strategy could achieve the high efficiency and the hydrogen consumption improvement, while the power following control strategy using fuzzy algorithm could obtain the better results. Kaya et al. [124] developed two EMSs for a FCEV with the battery and the SC as the energy storage devices. One strategy was the hydrogen fuel saving control strategy which aimed at reducing the fuel consumption of the FC stack. The other was the life cycle saving control strategy which aimed at extending the lifespan of the battery and the SC. The simulation results validated the effectiveness of the proposed control strategies.

5. Charging technologies

Generally, most PEVs have electric storage devices, and charging technologies are important on the way to commercializing the PEVs so that the range anxiety of the customers can be alleviated. There are two charging methods including inductive charging and conductive charging. The feature of the inductive charging mainly lies in the power transfer without a contacting medium. A charging station produces an electromagnetic field through an induction coil, while the electronic device with a corresponding induction coil receives the energy from the magnetic field and converts it back into electric current to charge the battery. This charging method has the advantages such as robustness, safety, power compatibility and durability, but the efficiency will drop as the distance between the device and the charging board increases. As for conductive charging, it requires a metal-to-metal connection between the power supply and the vehicle. A charging board is used as the power transmitter to deliver the power which is received by a charging device with a built-in receiver. In this method, a conductor is needed to connect the charging board and the charging device, whilst the safety issues and circuit interface configurations need to be considered [125].

The infrastructures supplying electric energy for the recharging of PEVs are charging stations. These stations can be categorized into three types, namely residential, public and ultra-fast charging stations. The residential charging stations, installed at household areas, enable PEVs to be charged during night when the energy tariff is low and the peak hour demand can be avoided. The public charging stations are placed at everyday activity places such as public buildings, shopping centers, and company parking lots. These stations are generally provided by electric utility companies and integrated with payment systems. The ultra-fast charging stations are typically located at highway and express way rest areas. These stations have control and protection functions, and can provide higher voltages and currents from the main power grid to quickly charge the PEVs [126].

PEV charging draws a large current from the grid, which increases the loading burden to electrical utility systems. Especially, charging during peak hours needs consumers to pay a premium rate for the tariff. Moreover, charging stations are being increasingly installed with the development of PEVs and the growth of energy demand. To alleviate the pressure, renewable resources such as solar and wind energy can be utilized to charge the PEVs [127]. Presently, solar PV systems are more common to be used in the charging stations. There are two PV charging approaches, namely PV-grid and PV-standalone. The PV-grid charging has the advantages that PEVs can be continuously charged through the grid supply when PV generated power is insufficient and the surplus PV power can be injected to the grid. On the other hand, PV-standalone charging is more convenient and beneficial in remote areas where utility supply is not available or too costly [127,128]. The PV-grid charging systems are usually designed at parking lots in the cities to charge PEVs during working hours. An energy storage unit (ESU), in the form of a battery bank, is generally used to act as an energy buffer due to the uncertainties of the solar radiation, though the grid can play the same role. According to the relevant evaluation, the optimal ESU size can reduce the grid dependency by 25% [129–132]. Another renewable resource, wind energy, has also been reported in the literature to generate electric energy for charging PEVs. Fathabadi [132] proposed a grid-connected wind powered charging station and presented a novel maximum power point tracking (MPPT) technique to maximize the energy conversion. This author also presented a grid-connected solar/wind powered charging station which combines wind and solar energy together. In order to avoid the impacts on the stability of the grid, some researchers utilized batteries combining wind turbines and PV modules to design the standalone charging stations, which can also increase the stability of supplying electric energy [133,134]. In addition, other renewable resources such as concentrated solar power, geothermal, tidal, wave and hydro can also produce electricity to charge PEVs. Equivalent CO_2 emissions of converting abovementioned renewables to BEVs and FCEVs are analyzed, and wind powered BEVs performs best with the least impacts on the environment. It is estimated that around 32.5–32.7% of American CO_2 emissions can be reduced and 15,000 deaths per year due to vehicle-related air pollution can be eliminated in 2020 if all onroad vehicles in the United States (based on the data in 2007) are converted to BEVs powered by the wind energy [5].

6. Challenges and developments

6.1. Challenges and problem solving

PEVs are the final developing goal of the automotive industry, but there are still some challenges we have to face in the process of development. Firstly, PEVs have short driving ranges and those employing a single energy source cannot achieve a good dynamic performance [135]. Integrating at least two different energy sources into one powertain of PEVs can fulfill their respective advantages to meet the specific requirements and optimize the dynamic performance of the whole system, whilst the driving ranges can be extended [19]. However, to eliminate the range concerned problem, corresponding infrastructures need to be built for charging or refueling PEVs. This is also another challenge that charging points and hydrogen refueling stations are less dense at present, and a substantial number of them need to be set up on open roads [135]. According to the recent reports, China as the largest new energy vehicle market has 2.57 million new energy vehicles in 2018, 85.7% of which are PEVs, while there are only 0.3 million public charging points. Based on the total proportion of vehicle to charging points being 9:1, charging points are far from meeting the charging requirement. Furthermore, there were merely 328 hydrogen filling stations all over the world by the end of 2017, while China only has 31 hydrogen filling stations including 19 under construction. Whether building charging points or hydrogen refueling stations, they both need a massive financial investment. Fortunately, the main countries of developing new energy vehicles not only give considerable subsidies to customers but also carry out policies and plans to boost the developments of the infrastructures. China National Grid has announced they will invest more than 100 billion Yuan for building the charging points and to completely cover the whole country by 2020. In addition, China plans to complete the construction of 300 and 1000 hydrogen refueling stations in 2025 and 2030, respectively. The third challenge is that the cost of these PEVs is still high [47]. The cost mainly depends on the energy storage technologies and it is difficult to evaluate as it is influenced by several factors such as the storage type, the application requirements, the size and so on. However, the capital cost of the energy storage can be calculated in the ways such as cost per kW, per kWh and per kWh per cycle. The last one is more suitable to evaluate the systems with frequent charging/discharging applications. The capital costs of the common energy storage technologies are listed in Table 2 [17]. In terms of capital cost per kW, FCs have the highest cost which is followed by batteries. Table 2 also shows that batteries have relatively lower cost per kWh, while SCs have the lowest cost per kWh per cycle. The higher PEV cost might partly be compensated by accompanying measures including monetary and nonmonetary incentives [136]. Currently, the price of the PEVs is almost even with the conventional vehicles after deducting the government's subsidies. Additionally and certainly, the actual cost

Table 2
Capital cost of different energy storage technologies [17].

Technology	SCs	FWs	FCs	Batteries		
				Li-ion	NaS	Flow Batteries
Cost $/kW	100 −300	250 −350	1000 −6000	1200 −4000	1000 −3000	200-2500
Cost $/kWh	300-50,000	1000 −5000	–	600-2500	300 −500	200-1000
Cost $/kWh-per cycle	2–20	3–25	6000 −20,000	15–100	8–20	–

will be decreasing continuously as the relevant technologies develop. Also, the increasing production and considerable investment will offer significant cost reductions. Another challenge is the disposal of the electric devices in PEVs as the main energy storage devices including batteries and FC stacks may contain hazardous substances. For instance, batteries widely used for PEVs generally contain dangerous heavy metals such as lead, cobalt, nickel, and lithium. Thus, inappropriate disposal such as direct dumping in the trash or outside the landfill will pose threats to the environment and public health due to metal toxicity [137,138]. Similarly, the stack materials of FCs can cause environmental pollution and harmful effects on human health [139]. The solution to this problem mainly lies in the development of advanced technologies for recycling spent energy storage devices and finding good ways to recover the precious metals and other materials. Meanwhile, policies and regulations should be made by governments to establish collection systems, financially support recycling of spent electric components in PEVs, and punish improper disposal of them [140,141]. Moreover, the reliability of PEVs is also a challenge at the present state of technologies. The critical components such as batteries, power converter, electric motor, hydrogen storage devices, and FC stacks play an important role in the reliability assessment of PEVs. To improve the reliability, it is significant to develop new materials or material modifications for batteries, hydrogen storage, and FC membranes. Another approach is devoted to the robust system design [142,143]. Take the application of the PEMFC for PEVs as an example, the effective design of shock and vibration protection systems can increase the reliability of the FC stack and avoid numerous issues including clamping torque loosening, gas leakage, and structural damage or breakage in the harsh road conditions [144]. The optimal design of the clamping force and the thickness difference between the membrane electrode assembly and the gasket can also make the stack stay in the high level reliability [145]. It is noteworthy that software and information systems of PEVs have a strong connection with the reliability too. The process variations and software errors of the control units affect the reliability significantly [146]. The thermal and energy management system design of meeting the reliability requirements and the development of advanced technologies to detect the dynamic degradation of the key components in PEVs will be valuable for the reliability improvements [147,148]. The last but not the least challenge is that the main components of PEVs still have not been standardized and modularized [17]. This results in the complexity design of the components in the vehicle system, while modularization can help to promote the flexibility of the system and facilitate the maintenance. The solution to this problem lies in the relevant policies that the government and enterprises release.

6.2. Latest developments

In order to enhance energy security and pursue better air quality, less noise and reduction of GHG emissions, the main developing and developed countries all adopt actual measures to promote the development of the PEVs. In 2017, the number of the global electric passenger cars in BEV type reached almost 2 million which increased around 60% compared to 2016. Remarkably, more than 40% of global BEV passenger cars are in China, followed by the European Union and the United States with each taking up about a quarter of the global total. China also has the world's largest electric car market where nearly 580,000 electric cars were sold in 2017 with a growth of 72% based on last year. Apart from electric passenger cars, there were about 250,000 electric light commercial vehicles (LCVs) on the road in 2017.99% of electric LCVs are BEVs and they are often utilized in a company or government fleet. It is worth noting that nearly 900 million electric two-wheelers are in circulation at present in Southeast Asia Nations, China and India. Up to 2017, China had much more electric two-wheelers than others and also has about 50 million electric three-wheelers. In addition, medium andheavy-duty electric vehicles such as city buses and trucks are attractive too when they are used for commercial and municipal services with regular routes and schedules in urban environments. According to the relevant data, there were 370,000 electric buses in China by the end of 2017 and only 2100 electric buses are currently on the road in Europe, Japan and the United States. The use of electric trucks is still limited at present and a small number of electric heavy freight truck models were developed for pilot projects until 2017 [149]. In November 2017, a heavy pure electric truck model “Semi” with a gross weight of more than 36 tonnes and the maximum driving range of 500 miles was announced by Tesla. As another type of electric vehicle, FCEVs are not developing as fast as BEVs which are more mature and less costly. However, FCEVs have the advantage of a longer driving range. There were slightly more than 7200 FCEVs all around the world in the year of 2017. The United States accounted for almost half of the global FCEV fleet with more than 3500 FCEV cars which was followed by Japan and Europe with 2300 and1,200 units, respectively. Furthermore, there were 250 FCEV buses on the road worldwide in 2017. Other PEVs with more than two energy sources are still in the process of design and testing, while their practical applications have not been found in the literature.

The developments of PEVs are largely driven by the government policies. Direct purchase subsidies and tax breaks are frequently employed as the financial incentives, while some measures such as road priority and access to restricted traffic zones are non-financial incentives [150,151]. These incentives enable PEVs to be more attractive to customers, investors to reduce the investment risks, and manufacturers to be encouraged for expanding production. The main countries all round the world have set objectives for PEV deployments in the near future such as 2025 and 2030. It should be noted that the combination of the high energy efficiency of electric motors and low-carbon electricity potentially allows PEVs to significantly cut down CO_2 emissions. In 2017, 29.4 million tonnes of CO_2 emissions were avoided worldwide and PEVs emit no tailpipe emissions with air pollutants [149]. As the number of the PEVs increases continuously under the support of relevant policies, the positive impacts of PEVs on natural environments will become more noticeable.

7. Conclusions

The environmental issues such as air pollution and global warming have brought serious impacts on living and production for human beings. The energy crisis is also becoming an important and pressing problem. Based on these reasons, PEVs with high efficiencies will be the ultimate goal of developing vehicles, while HEVs are just an interim step in the process of PEVs replacing ICEVs. This paper has presented an overview of PEVs with a focus on energy sources, PEV types and EMSs. The characteristics and typical models of energy sources are illustrated. Among these energy sources, Li-ion batteries and hydrogen energy are becoming more popular and promising. The current PEV types are depicted and the environmental impacts of the typical single-source PEVs are evaluated based on the WTW method. After the EMSs employed in HEVs are classified and briefly introduced, the present EMSs used in PEVs are stated. Then, the charging technologies for PEVs are investigated. The analysis and development trend indicate that renewable resources are very promising to generate electricity for charging PEVs. Finally, the main challenges faced by PEVs for practical applications are discussed and general problem-solving methods are provided, whilst the latest developments with regard to PEVs are presented. Under the pressure from objective environmental factors and the subjective incentives from governments, PEVs will be developing rapidly in the next decades.

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