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A Review on Electric and Fuel Cell Vehicle Anatomy, Technology Evolution and Policy Drivers towards EVs and FCEVs Market Propagation

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Electric Vehicles
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Emission Norms
Battery
Powertrain topology

The transportation sector is the largest consumer of fossil fuels; making it a major producer of greenhouse gases. Due to declining fossil fuel reserves and increasingly stringent vehicle emission regulations globally, it is essential to shift to alternative energy sources. Economic and eco-friendly fuel-efficient hybrid, electric, and fuel cell vehicles are regarded as one of the best alternative solutions to cope with the government policies and to reduce the rise in global temperature caused by the automotive sector. Technological advancements in fuel cells, batteries, and chargers have further supported the development of electric vehicles. The major challenges of range and charging time in electric vehicles can be countered by range extension technology and developing all-electric hybrid vehicles. In this review, a comprehensive study of different type of vehicles and their architectures are presented. Insights on energy storage devices and converters of electric vehicles currently in use were also provided. Furthermore, various fuel cell advancements and the technical challenges faced during the commercialization of fuel cell vehicles were highlighted.

1. Introduction

The transportation sector, the largest energy consuming sector, derives most of its energy from fossil fuels. Fossil fuels contribute 55^% of transport energy requirements, as stated by the U.S Energy Information Administration.[1] A statistical source by U.S Environmental Protection Agency states that the automotive sector emitted 29% of global GHG emissions in 2019.[2] Among various modes of transportation, roadways contribute 70^% of sector GHG, and its energy demand was 73.4^% in 2014.[3] In reality, passenger cars with ICEs are the major contributors (61^%) to total road emissions[4] which are now being controlled by government regulatory norms. ICEs have been the most preferred energy conversion device for more than 100^^years. Figure^^1<figr1> shows global oil production and consumption rates between 2015 and 2021. It is evident that consumption is increasing every year.[5] There is a dip in world oil consumption and production during the second half of 2019 and in 2020, this drop is due to the widespread of COVID’19 and the subsequent lockdown measures taken by the governments to prevent the spread. Another major concern about fossil fuel usage is its high cost due to limited accessibility as these reserves are only available in limited countries. Excessive consumption of these resources by other countries creates an economic imbalance that is controlled by political dominance.[6]

Treating exhaust gases to meet government norms is expensive, which in turn increases vehicle costs. Therefore, substituting fossil fuels with renewable resources is required. Electrical energy can be derived from naturally occurring renewable resources. Hydrogen is an efficient and suitable resource for vehicles than other sources such as solar, tidal, wind, etc., as they are affected by environmental changes.[7] Of late, in view of reducing GHG, automotive sectors are switching to electrical based propulsion systems, powered by batteries, FCs, or a hybrid system. In some hybrid vehicles, ICEs are also used as they perform well in constant speed conditions like highway driving.[8] In addition to the environmental benefits from electrification or hybridization, these vehicles reduce operating costs compared to fossil fuel powered vehicles. The cost of operating EVs is 2 cents/mile, while it is 12 cents/mile for gasoline vehicles.[9] The higher operating cost of ICEs is because only 15^% of the total fuel power is used to propel the vehicle, while the remaining energy is lost as heat during combustion, as stated by the U.S. Department of Energy,[10] which contributes to global warming. On the other hand, EVs utilize 90^% of the total energy available, making them more efficient and a suitable alternative to ICEs.[11]

The major problem with EVs is the battery cost, which accounts for 45^% of the total vehicle cost. Different types of energy sources are applied to reduce the storage cost with improved efficiency, which results in different configurations of EVs.[12] The major classification of EVs comprises four types namely, BEV, FCEV, HEV, and FCHEV. HEVs are propelled by two or more energy sources. ICEs are the primary energy source. Secondary energy storage devices like the battery, ultracapacitor, or FC provide traction power to the EM. An additional feature available in EVs is that energy can be recovered while braking or downhill driving, which may also contribute towards increasing the range. It has been estimated that by 2050, on producing 20 million EVs/PHEVs or FCVs, CO_2 emissions can be reduced by 30^%.[13]

This review work elaborates the progressive energy sources available and topologies of EVs, HEVs, FCEVs, and FCHEVs. Also, a detailed analysis of existing technologies and insights on future development is provided.

2. The Need for EVs

Energy production from fossil fuels in ICEVs involves fuel and heat energy conversion to mechanical energy. This energy reaches the wheel through a gearbox and propeller shaft. In each step, there is loss due to energy conversion. WTW efficiency of ICEV is around 14 to 17^% which is very low compared to BEVs and FCEVs.[14] As a result of incomplete combustion, by-products are formed which have numerous ill effects on humans and the environment.

The effect of air pollution became apparent in Los Angeles during the 1940s. In 1952, A. J. Haagen Smit demonstrated that oxides of nitrogen and hydrocarbons react in the presence of sunlight to form smog.[15] Since automobiles are the major contributors of hydrocarbons, emission standards were first introduced in California and later to the entire nation.[16] Following this, European countries and Japan introduced vehicle emission norms. In subsequent years, norms became more stringent and the technology costs for treating exhaust emissions increased, along with the overall cost of vehicles. The oil crises in the 1970s stimulated the search for various alternative power generation technologies, which led to the development of battery and FC technologies.

The major goal of the European Union (EU) is to sustain cars that operate on fossil fuels until 2030 and eliminate them by 2050. To achieve a 60^% reduction in CO_2, 50^% of middle distance passenger and long distance freight journeys must shift to other modes of transport.[17] The key targets of the EU 2030 climate and energy framework are: (i) reduce GHG emission to 40^% with reference to 1990 levels, (ii) increase utilization of energy from renewable sources to 32%, and (iii) improve energy efficiency by 32.5^%.[18] The Indian government has also adopted European energy norms, with BS-VI being the recent target. In order to cope with global emission standards, the Indian government decided to upgrade its emission norms from BS-IV to BS-VI equivalent to EURO 6. The emission ratings are tabulated in Table^^1<tabr1>.

2.1. History of EVs/HEVs/FCHEVs/FCEVs

2.1.1. History of EVs

The first ever EV, a tricycle was built in 1881 by Gustave Trouve. It was powered by a 0.1 HP DC motor drawing its power from lead acid batteries, with a gross vehicle weight of 160^^kg. In 1883, two British professors built a similar EV that attained a maximum speed of 15^^km/h with a range of 15^^km.[20] In 1889, the first electric car was introduced in the US as a taxi by William Morris,[21] with a maximum speed and range of 32^^km/h and 40^^km respectively. In 1900, among 4200 vehicles sold in the US, 38^% vehicles were EVs and 22^% were ICEVs. These EVs lost their importance due to the mass production strategy for the Model T by Henry Ford, which sold at 1/3rd of the ICEVs cost. Also, since the battery technology was premature with slow speeds and low range, a complete decline of EVs took place in the 1930s.

EVs underwent a comeback after the oil crisis in the late 1970s. The Arab oil embargo in 1973 incentivized the use of alternative energy sources, creating a renewed interest in EVs. The major breakthrough in the 1980s and 1990s was the development of high power and high frequency semiconductor switches and microprocessors, which made EMs more efficient by using rational power converting designs. In 1990, the California Air Resource Board mandated that for every 35,000 vehicles there should be 2^% ZEVs by 1998 and then gradually increased it to 10^% by 2003. However, due to practical limitations, it was restricted to 4^% by 2003. The invention of more powerful and robust motors, DC to AC Inverter, and efficient battery management systems were then further contributors to the resurgence of EVs. Post-2015, the Paris agreement[22] has promoted the reduction of GHG emissions increasing interest in EVs.

2.1.2. History of HEVs

EVs lacked driving range[23] which was appeased by HEVS. HEVs combine ICE power and the zero emission nature of EVs. The first ever hybrid car was built by Porsche, which used an ICE to generate electricity that powered hub motors. In battery mode, it could cover a distance of 40 miles. In 1899, the Pieper vehicle was introduced by the Pieper establishment of Liege, with the first-gen parallel hybrid architecture and a small air-cooled SI engine. A series hybrid tricycle was derived from a pure EV built by Vendovelli and Priestly.[20] Its rear wheels were powered by individual EMs, and to extend the range, the vehicle had a 1.1^^kW generator coupled with a 3/4 HP SI engine as a trailer. Only in 1990 did the hybrid concept become more viable, when it was evident that EVs could not meet the expected energy saving target. Ford initiated a Hybrid Vehicle Challenge, which inspired universities to develop hybrid automobiles. Subsequently, several automobile manufacturers developed prototypes and achieved superior performances, on a par with ICEVs. Some notable hybrid vehicles are the Dodge Intrepid ESX 1, 2, and 3, Ford Prodigy, GM Precept, Renault Next, and Volkswagen Chico. The most significant development in HEVs was achieved by the Japanese in 1997 with the release of the Toyota Prius,[24] the most famous hybrid vehicle to date. Two years later, Honda released its Insight and Civic hybrids. These vehicles were the first to address the issue of personal fuel consumption as they had excellent fuel saving capacity.

2.1.3. History of FCVs

Many attempts were made to produce electricity from FCs using coal or carbon, but they were suppressed by the rapid development of the ICE. In 1932, Francis Bacon developed the first successful FC operating on hydrogen and oxygen using alkaline electrolyte and nickel electrodes. The first practical FC of 5^^kW was demonstrated by Bacon and company in 1959. In the same year, Harry Karl Ihrig developed his tractor powered by a 20 HP fuel cell.[25] In 1967, General Motors developed its Electrovan for carrying 6 passengers, but its usage was limited due to safety issues.[26] The Electrovan was powered by an alkaline FC manufactured by the Union Carbide Corporation, capable of producing a continuous power of 32^^kW and 160^^kW peak power for a shorter duration. The vehicle’s efficiency was above 50^% and 30^% at peak load conditions. The main drawback was that it required a 3^^h start-up time.

In the late 1980s, many companies took an interest in FC technology. Research programs were launched by Los Alamos National Laboratory and Texas A&M University to reduce the amount of platinum as a catalyst in PEMFCs. In the 1990s, Ballard Power Systems developed an FC engine of 120^^kW to operate a bus using PEMFC. Compressed hydrogen was stored in cylinders positioned underneath the bus.[27] PEMFC was the most favored FC system due to several advantages stated in Table^^2<tabr2>, describing the various FC types and their features. However, AFCs were also used by manufacturers.

Recently, automobile manufacturers are trying to develop indigenous FCVs. Few FCVs are available in the market but the most remarkable is the Toyota Mirai. To commercialize FCVs, infrastructural developments and an alternative route to efficiently producing hydrogen are required. Hydrogen production, distribution, and storage are the major challenges faced by automobile makers. Commercialization of FCVs is still a big leap forward and intense research is being carried out with support from various funding agencies. Comprehensive knowledge on hydrogen generation,[28–33] compressed hydrogen storage for FCEVs, [34–41] and filling and emptying characteristics[42–48] are required. Although FC technology has seen major advancements, its full potential has not been tapped yet to deliver enhanced performances at reduced cell cost and cost per kWh of energy produced.

2.2. Policy Drivers for EVs/HEVs/FCHEVs/FCEVs

The growth in electric mobility worldwide has also resulted from government policies. Multiple types of national and sub-national government policies are established globally that can be categorized using a policy instruments perspective, comprising regulatory mechanisms, market-based instruments, government information, industry-led measures, and public-private partnerships.[91]

Regulatory instruments include national or sub-national legal frameworks. Regulations can stimulate technological development, for example, Section^^915 of the U.S. Energy Policy Act 2005 that created a federal electric vehicle battery use research program, and the U.S. Energy Independence and Security Act 2007 establishing federal grants for encouraging EV technologies. They can also compel EV vehicle sales, for example, California’s Executive Order N-79-20 that requires all new passenger vehicles sold in the state must be zero emissions by 2035. China’s New Energy Vehicle mandate sets targets for new electric vehicle market share credits.[92] Regulations can also establish user benefits for EV drivers, for example, traffic laws that allow preferential parking, plus free use of bus lanes and tollways.[93]

Market-based instruments, including public subsidies, fiscal incentives, and infrastructure expenditure, are also used by governments to promote electric vehicle use.[92--98] For example, the UK government provides a plug-in car grant of up to £3000.[94] Import duty exemptions for EVs are provided in Brazil and Russia.[93] National governments also give subsidies or tax breaks for installing private vehicle charging or to help fund commercial charging infrastructure.[93]

Several academic studies have identified various policy factors that lead to successful EV uptake.[93,95--97] Government policy instruments, in particular financial incentives, are considered significant drivers, for example in Norway where different fiscal instruments are employed.[98] Other important factors are the degree of voluntary industry support for national EV innovation, particularly in Germany where major auto manufacturers have increased their electric vehicle production and collaboration between public and private sectors.[93]

3. Overview of Vehicle Technologies

Automotive research has led to the replacement of mechanical and hydraulic systems with sophisticated and efficient electrical systems. These electrical systems provide comfort, safety and are environmentally friendly. The phases of vehicle technology development can be classified into three, namely: ICEVs, HEVs, and AEVs. ICEVs are solely powered by gasoline/diesel fuels. AEVs depend only on electrical energy sources like a battery, FC, and ultracapacitors for propulsion. HEVs use both ICE and EM for propulsion which has advantages like increased range, fuel economy, and relatively lower emission characteristics. Fuel economy due to hybridization is expressed in miles per gallon (MPG) or it's equivalent (MPGe), where 33.7^^kWh electrical energy is equal to 1 gallon of gasoline.[99–101] Different vehicle technologies are discussed as follows.

3.1. Internal Combustion Engine Vehicles (ICEVs)

ICEVs convert chemical energy into kinetic energy by burning fossil fuel in a closed combustion chamber. Due to combustion, heat is released along with harmful pollutants as tailpipe emissions. The most common form of ICE is the reciprocating type. ICEVs are categorized into two based on the mode of ignition and fuel: SI engines use gasoline, ignited by introducing a spark, and CI engines use diesel, ignited by compressing the air to the self-ignition temperature of the fuel.[102,103] ICEVs are of two types: (1) ICEVs with no EM to assist during start-up and (2) micro HEV where there is a small EM to assist the start-up. These types of motors are generally called starter motors with a power rating of around 5^^kW and operating voltage ranging from 12--14^^V.[104,105] A notable feature of a starter motor is that during coasting or stopping, the engine can be shut down, which improves the fuel efficiency by 5 to 15^% in urban driving conditions.[105] A typical ICEV layout is shown in Figure^^2<figr2>.

Micro hybrid vehicles can only perform a start-stop action, which is achieved by EEM. EEM monitors parameters like brake pedal and accelerator pedal position, clutch, and transmission gear state to perform start-stop actions. As a result, idling emissions are reduced and fuel efficiency is improved.[106,107] Despite several advancements, conversion losses and tail pipe emissions are inevitable in ICEVs.

3.2. Hybrid Electric Vehicle (HEVs)

EVs have zero emissions and high energy efficiency which are superior to ICEVs. Yet, their range is limited due to poor battery capacities. To overcome this, HEVs use two power sources, one of which is electrical. HEVs can deliver power from both sources during specific operating conditions like peak load acceleration, gradient navigation, etc. The ICE in HEVs is mostly used for steady-state operation (cruising) while the EM is used for dynamic operation (urban driving). Based on a drive train configuration, HEVs are classified as series, parallel, series-parallel, complex, and plug-in hybrid.

Degree of hybridization is defined as the ratio of EM power to the total power,[108,109] given by the equation:<ffr1>

<ff1> $$HF = \frac{P_{EM}}{(P_{EM} + P_{ICE})}$$ <ZS>(5)

<?><?>Dear author, please check the numeration of the equation.<?><?>

Where, P_{EM} -- Power of EM and P_{ICE} -- Power of Internal Combustion Engine. Figure^^3<figr3>. shows the concept of hybridizing a vehicle -- Power flow while propelling and charging.

Traditional HEVs were built using series and parallel configurations. In a series configuration, the ICE's power is converted to electricity to charge batteries, and the batteries power the EM. In parallel configuration, both the ICE and EM can propel the vehicle simultaneously or separately as per load demand. Currently, series-parallel and complex powertrain configurations are being developed.[110,111]

3.2.1. Series Architecture

The architecture of a hybrid vehicle determines the energy flow routes and control ports between the components. In a series hybrid drive train, two power sources propel the vehicle. The series hybrid drive train has liquid fuel as a unidirectional energy source and the ICE, coupled to a generator, as a unidirectional energy converter. The bidirectional energy source and converter are the battery pack and EM.

The output of the generator is connected to the battery pack through a rectifier and the output of the EM through a DC/DC converter. The EM is controlled electrically by an MCU. The EM can act as a generator and is capable of operating in forward/reverse directions. Vehicle propulsion is entirely controlled by the EM, powered by a battery pack. Once the SOC of the battery pack reaches some minima (65--75^%), the ICE starts to charge the battery pack.[112] In an HEV, the ICE is an onboard battery charger operated at an optimum speed and torque that ensures high efficiency and low fuel consumption rate.[113,114] The following operation modes are available in series hybrids:

1._*Pure electric mode*: The entire power required for propulsion is supplied by the battery. During this operation, the ICE is turned off.

2._*Pure engine mode*: Propulsion power is provided by the ICE-generator, while the power to/from the battery pack is cut-off.

3._*Hybrid propulsion mode*: Both the ICE-generator and battery pack supply power for propulsion.

4._*Engine traction and battery charging*: The ICE-generator supplies power for propulsion and a part of this power is used for charging the battery (no power is drawn from the battery).

5._*Regenerative braking*: The EM acts as a generator, charging the battery pack. The ICE is turned off. This mode is possible only when braking / coasting (descending a slope or a hill).

6._*Stationary Charging*: During standstill, the ICE-generator supplies power to charge the battery pack.

7._*Hybrid charging mode*: Both the ICE generator and EM charges the battery pack.

Figure^^4<figr4>. shows the flow of power in different operating modes of a series hybrid powertrain.

3.2.2. Parallel Architecture

In a parallel hybrid drive train, both the ICE and EM are mechanically coupled to the vehicle wheels. This mechanical coupling blends the torque from two sources. Basically, it is an EM-assisted ICEV to achieve low fuel consumption and emissions.

Parallel hybrid vehicles can be driven with an ICE or EM or both. Many configurations are possible in parallel hybrid EVs. One commonly used strategy is to propel the vehicle with the EM at low speed and with the ICE at high speed.[115,116] It has fewer energy conversion stages compared to a series hybrid which is advantageous. Parallel hybrids require special planetary gear for switching power from one drive train to another. Possible modes of operation are:

1._*Pure engine mode:* The ICE provides the total power required for propulsion, while the electric driveline is inactive. This mode is used during cruising.

2._*Pure electric mode:* The EM provides the necessary power to propel the vehicle by drawing power from a battery pack. Used in urban driving conditions.

3._*Hybrid traction:* Power from both the powertrain is delivered to the wheels. This mode comes into play when the power required is more than that generated individually by an ICE or EM, i.^e. during high speed or acceleration conditions.

4._*Regenerative braking:* The electric powertrain is active and the EM acts as a generator and recharges the battery pack. This mode is possible only during braking/coasting.

5._*Battery charging from engine:* When the power demand and SOC are low, part of the power generated by the ICE is converted into electricity to charge the battery pack.

Figure^^5<figr5>. Shows the energy flow in different modes of operation. A parallel configuration is more efficient for highway driving and cruising, as it allows both the powertrains to operate simultaneously. Some of the parallel hybrid vehicles in the market are the Chevy Malibu Hybrid, Honda Insight, Ford Escape Hybrid, and Honda Civic Hybrid.

3.2.3. Series-Parallel Architecture

Although early HEVs used series or parallel configurations, it was later realized that using them together was more efficient and advantageous. This type of hybrid configuration is categorized under a parallel hybrid configuration, as it retains the parallel structure for component arrangement. The difference relies on the bidirectional functionality of the EM in a compound powertrain and the unidirectional functionality of the generator in a series-hybrid powertrain.[117] Based on the activity of the ICE and EM this topology is further classified as:

i._ICE heavy series-parallel HEV and

ii._EM heavy series-parallel HEV.

An additional EM in this architecture acts as a generator and a traction motor. The following are the operation modes of ICE heavy series-parallel topology.

1._*Pure Electric mode:* Only the EM drives the vehicle, the ICE powertrain is inactive. A battery pack supplies power for the EM.

2._*Hybrid mode:* Both the ICE and EM drive the vehicle, mostly during acceleration/peak load cruising/ high power demanding operations. During this mode, the generator is inactive, while power for the EM is supplied by the battery pack.

3._*Pure ICE mode:* During cruising the ICE is operated at the most fuel-efficient operation range, while other systems are inactive.

4._*Regenerative braking:* During braking, deceleration, and downhill driving, the kinetic energy of the vehicle is converted into electric energy by the EM which acts as a generator and charges the battery pack.

5._*Battery charging:* Part of the power produced by the ICE is used to charge the battery while driving if the SOC of the battery is below a fixed value. During idling the ICE engine's total power is utilized to charge the battery.

Different operating modes of ICE heavy series-parallel HEV are shown in Figure^^6<figr6>. The only difference in the mode of operation of Electric heavy series-parallel HEV is that during cruising both the ICE and EM propels the vehicle and the power for the EM is supplied by the generator.

3.2.4. Complex Architecture

A complex hybrid configuration is used in vehicles where both the front and rear axles are driven separately. This configuration results in a relatively lighter, efficient, and less noisy powertrain compared to conventional all-wheel drive vehicles. Several modes of operation are possible due to the bidirectional power flow:

1._*Start-up mode:* Both the EMs propel the front and rear axles. The ICE is turned off. Power for the EMs is supplied by the battery pack.

2._*Pure Electric mode:* Only the front axle EM is powered, while the ICE is turned off. This mode is suitable for light load operation.

3._*Hybrid mode:* Both the electric and ICE drive trains are active. The ICE and rear axle EM propels the rear axle together, while the second EM propels the front axle. This mode kicks in during heavy load conditions such as wide-open throttle acceleration.

4._*ICE traction and Battery charging:* The ICE power is split to propel the rear axle and to generate electricity through the EM. Generated electric power is used to charge the battery pack. This mode is suitable for cruising, where the ICE is operated in most fuel-efficient conditions.

5._*Regenerative braking:* During braking, deceleration, and downhill driving, kinetic energy is converted into electric energy by the EM that acts as a generator. In this mode both the EMs act as a generator and charge the battery pack simultaneously.

6._*Axle balancing:* Unique for dual drive axle systems. The driving torque is interchangeable between front and rear axles is driven by EM, by which axle balancing is achieved.

Different modes of operation are shown in Figure^^7<figr7/ol>. All these operational modes are common for the front wheel and rear wheel electric complex hybrids.

3.2.5. Plug-In Architecture

Plug-in HEVs have provisions for charging the battery with grid electricity. The plug-in hybrid was introduced with the main aim of extending the range of EVs.[118–123] Plug-in hybrids also use both ICE and EM for propulsion, but the primary source of power is grid electricity. An ICE acts as onboard charging. Figure^^8<figr8>. shows the series PHEV configuration

PHEVs have reduced the dependency on recharging facilities. Hence, the battery size is reduced compared to BEVs. Concurrently, due to deep discharge-recharge cycle operations, PHEVs need a larger battery size that operates in constant SOC. The distance a PHEV can travel is denoted as PHEV ‘X’, where X is the distance that can be travelled in pure electric mode. For example, PHEV50 denotes that a particular vehicle can travel 50^^km in pure electric mode.

3.3. All Electric Vehicles (AEVs)

AEVs exclusively use electrical power for propulsion. At present, there are six configurations available, of which three are widely used. AEVs are classified based on the energy source as BEVs, FCEVs, and FCHEVs. BEVs and FCEVs have similar topological configurations. The FCHEV uses both battery and FC as energy sources. The following section briefly describes the different AEVs.

3.3.1. Battery Electric Vehicle (BEVs)

EVs which operate solely on battery power are known as BEVs. Since BEVs rely on battery power, their range depends on the battery pack capacity. The typical range of a BEV is between 100--250^^km in a single charge and some higher-end models have a range of 300--500^^km.[124] BEVs are potentially ZEV, but the mode of electricity production determines the WTW emission. The efficiency of BEVs can be as high as 75^%.[125]

Key concerns of BEVs are the total range covered by the vehicle and the extended time taken for recharging the batteries. Battery pack capacity limits the BEVs usage to urban driving alone with advantages of simple construction and high torque at low speeds.

Figure^^9<figr9>. shows the schematic of a BEV. The powertrain is classified into two segments: mechanical and electrical modules. The mechanical module consists of a driving wheel, differential, and transmission system, while the electrical module consists of an electrical motor, power management controller, charger converters, converters for regenerative braking, and energy storage systems. The main function of the controller is to regulate the power flow to and from the battery pack as demanded by the driver's action.

An EV powertrain system is differentiated between a converted and dedicated system. In a converted system, the EM and battery replace the ICE and fuel tank, while the rest of the components remain unaltered. Based on the nature of the transmission system, a clutch or torque converter is required.

In a dedicated system, the vehicle chassis is designed appropriately to meet the requirements of BEVs. The powertrain is integrated within the vehicle body. A further dedicated system is classified based on the number of motors, battery pack, and arrangement of components as follows:

1._*Rear-wheel drive out-wheel motor:* Contains an EM, fixed gearing, and a differential. Fixed gearing is used since the EM is capable of operating at a constant power even at higher speeds.

2._*Front-wheel drive out-wheel motor:* The EM, fixed gearing, and differential is integrated into a single assembly in the front axle. This configuration is similar to the front-engine front-wheel drive.

3._*Dual out-wheel motors front-wheel drive:* The mechanical differential is removed and two separate EMs are used with fixed gearing.

4._*In-wheel motor drive:* The main advantage of this configuration is that the mechanical components are eliminated from the drive train. EMs are fitted inside all the wheels, with or without fixed gears. An inner rotor motor is used, which enables higher motor speed and individual wheel control. There is a possibility to use an outer rotor motor too, that directly controls the wheel torque, thereby maneuvering the vehicle speed. This configuration can be used as front-wheel or rear-wheel drive alone, where only two EMs are used in the drive axle instead of four EMs.

3.3.2. Fuel Cell Electric Vehicle (FCEVs)

FCEVs overcome the short-range and prolonged recharge problems posed by BEVs. In an FCEV, FC stacks are used to power the vehicle, which uses hydrogen to generate electricity. The generated electricity is either used by the EM to provide traction or can be stored in the onboard storage device. Hydrogen is stored in compressed form, as it facilitates fast refilling. This makes it a reliable technology in the near future.[126]

Major advantages of FCEVs are their driving range and zero emissions. The efficiency of FC is higher than other energy-generating devices and can be further increased by utilizing the waste heat from the cells, leading to an overall efficiency of 85^%. The lifetime of an FC is higher compared to ICE as there are no moving parts and high corrosion resistance.[127] The ideal characteristics of FC are suitable for low-speed vehicles, where there is no sudden change in power demand from the EM. Nowadays, modified FCs are used to power high-speed vehicles too.

Figure^^10<figr10>. shows the schematic of an FCEV. DC voltage generated is supplied to the power conditioning unit to obtain the required output current and voltage. There can be negligible losses in the power condition unit, as the efficiency of the power condition unit is around 90^%.[128,129] FC systems are supplemented with a battery pack or ultracapacitors as they cannot handle sudden changes in load, and onboard power storage is necessary to store excess power and the power generated by regenerative braking.[130–134] Major hindrance in commercializing FCEVs is its cost per kW, which is more than 200^^USD,[135] and the hydrogen is stored at 700 bar pressure which in case of accident or leakage is hazards to the occupants, this demands for a robust composite tank which in turn limits the shape of tank to cylindrical. [126] Another possible storage system that may be used in the future is solid-state storage, where hydrogen is stored in a metal hydride form, where the hydrogen is adsorbed over a metal surface by application of external energy and can desorb on applying external energy. [126,136]

3.3.3. Fuel Cell Hybrid Electric Vehicles (FCHEVs)

FCHEV is the modified form of FCEV, where energy storage devices like a battery or ultracapacitor are used to power the vehicle. The battery pack size is usually larger than in FCEV. FC acts as the primary energy source, which powers the EM and also charges the battery pack or ultracapacitors. Most commercialized FC vehicles are actually FCHEV as their battery pack contributes equal power to that of an FC stack. A typical schematic of an FCHEV is shown in Figure^^11<figr11>.

3.4. Key Components of EVs

3.4.1. Fuel Cell

In FCEV and FCHEV, FCs are the primary power source. In some HEVs, FCs act as a secondary power source (on-board chargers) that improves the range of the vehicle. These HEVs are also termed Range Extended Vehicles. An FC is an electrochemical energy-producing device, which produces DC and water as a by-product when reactants are supplied. It is a single-step process with no intermediary energy conversion losses.[137] FCs have the advantage of being both batteries and ICEs as they can operate without any interruption as long as the reactants are supplied. Most potential applications for FC are in the transportation sector. FCs, compared to existing propulsion devices are highly efficient, pollution-free, and directly addresses fossil fuel demand. Car manufacturers like GM, Honda, and Toyota are developing indigenous FC technologies, while others outsource them from Ballard, Horizon FC Technology, and UTC FCs. One of the earlier prototypes is the AFC powered vehicle by Kordesh. The main drawback of the car is the cylinder positioning on the rooftop, which created a major concern in terms of safety.[138] Scooters and bicycles were also demonstrated by several companies using hydrogen to run the vehicle and metal hydrides to store them, or using DMFC and methanol as alternatives.

3.4.2. Battery

A battery is an electrochemical storage device that stores electrical energy. A battery is composed of multiple electrochemical cells stacked together.[139,140] Basic components of a battery are positive and negative electrodes immersed in an electrolyte and the two electrodes are physically separated by a permeable electrically insulating layer. An ideal battery releases energy to the external circuit only on demand, but in real-time, there is always a slow discharge of electrons from the terminal even in open circuit conditions due to a diffusion effect known as self-discharging. This makes batteries unsuitable for long-term energy storage. Table^^3<tabr3> gives the important parametric values of some batteries.

3.4.3. Ultracapacitors

Capacitors are energy storage devices that store electrical energy by the separation of equal numbers of positive and negative electrostatic charges. Conventional capacitors, also known as electrolytic capacitors, have a power density in the range of 1012^^W/m^3 and an energy density in the range of ~50^^Wh/m^3.[144] Supercapacitors and Ultracapacitors are modified forms of conventional capacitors, where the energy density has been increased by sacrificing the power density to function as a battery. The energy and power densities of super and ultracapacitors are in the range of 10^6^^W/m^3 and 10^4^^Wh/m^3 respectively. Though the energy density is much lower than batteries, they have higher specific power densities, faster discharge rate in the order of 110s, and a longer lifetime in the range of ~10^5.[145]

Ultracapacitors store energy in a polarized liquid layer at the interface between an ionically conducting electrolyte and an electrically conductive electrode this is known as an electrochemical double layer. At the interface of the electrolyte and the electrode, positive charges are accumulated, which attracts negative charges known as counterions, which neutralizes the double layer. As the double layer gets thicker the capacitance increases. This double layer concept helps in realizing the supercapacitor/ultracapacitor performance.[146,147] By increasing the surface area of the interface, the storage capacity can be increased. The primary reason for preferring ultracapacitors is that they can quickly discharge and recharge high voltages. They are also good at absorbing the energy from regenerative braking. A drawback of ultracapacitors is that the storage is limited between 2 and 5 volts, so a series connection of 500 cells is required to meet the requirement of an EV.[148] Table^^4<tabr4> gives the important parametric values of the ultracapacitor and supercapacitor.

3.4.4. Ultrahigh-Speed Flywheels

Flywheels store kinetic energy in mechanical form within a wheel-like disk made of composite materials. Flywheels are extensively used in ICEs to deliver smooth power but the limit of energy stored is low for the acceleration of a vehicle. Flywheels can be used as a primary power source in EVs, replacing batteries or used in tandem with batteries.[150] Flywheel technology has two approaches namely mechanical output and electrical output. The efficiency in mechanical output (70^%) is double that of electrical output. The rotational speed of the flywheel is also increased in the range within 30,000 and 60,000^^rpm from the conventional 1000^^rpm employed in ICE.[143,151] Increasing the rotational speed increases the energy storage capacity but is limited by the tensile strength of the constituent material. Maximum benefits can be yielded if the ratio between tensile strength and specific density is increased. Table^^5<tabr5>. gives possible materials for Ultrahigh-speed Flywheels.[117]

To reduce aerodynamic losses, the flywheel rotating at high speed is placed inside a high vacuum chamber and the frictional losses are reduced by the use of a friction-less magnetic bearing. This increases the mechanical output up to 97^% and cycle efficiency to 85^%.[142,144,150] Existing systems specific energy and power densities are in the range of 10--150^^Wh/kg and 2--10^^kW/kg respectively. They are considered as potential candidates as they have high specific energy and specific power and long lifespans while are energy-efficient, maintenance-free, low cost, and environmentally friendly.[145,151] Potential application areas are

EVs/HEVs, spacecraft energy storage, motorsports, and energy storage in grid and wind turbines.[152] However, safety and gyroscopic force management issues raise doubts over their applicability in EVs.

3.4.5. Electric Motor

The EM is the main component of the electric powertrain,[153–158] which utilizes the electric energy from the battery and propels the vehicle. During regenerative braking, the EM acts as a generator and converts kinetic energy to electric energy to recharge the battery. Requirements from the EM are high torque, high power, and wide range of speeds, robustness, and reliability, low cost, and small size. Different EMs that suit the requirements of EVs are as follows:

1._*DC motor:* Stator is made of PM. Rotors are provided with brushes to facilitate the power supply between stator and rotor. A DC motor can provide high torque at low speeds. However, due to bulkiness and heat generation, they are no longer used in EVs.[159]

2._*PM Brushless DC Motor:* The rotor is made up of PM. Though a DC motor, the stator is supplied with AC through an inverter. Power is supplied from a battery. Since copper loss is neglected in the rotor, it is more efficient than induction motors. Constant power region is quite short due to restrained field and the torque decreases with increasing speed as back EMF is generated in the stator. As heat is generated in the stator, heat dissipation is more effective than in a brushed DC motor. It is possible to enhance speed and efficiency by additional field winding.[117] Efficiency of a PM BLDC can be increased along with speed by controlling the power controller’s conduction angle. This leads to a four-fold increase in the base speed of the motor. PM BLDCs can be used in vehicles that require a maximum power of 60^^kW.[160]

3._*PM Synchronous Motor:* They can be operated without any gearing system at a wide range of speeds, making them relatively more efficient and compact. Due to their compact build, they can be used for in-wheel configuration providing maximum torque even at very low speeds. Nevertheless, it manifests large iron loss during higher speeds.

4._*Switched Reluctance Motor:* SRM is unipolar inverter-generated current driven and the stator and rotor have salient poles, so they are known as doubly salient motors. They are reliable, simple, and robust in construction with minimal hazards, low cost, high operating speed, higher constant power range, and high power density. The control strategy is complicated due to fringe effect of slots and poles and pole-tip saturation.[159,161,162] Drawbacks of SRM are their large size, noisy operation due to variable torque operation, and heaviness. Due to rare earth materials used in PM machines, SRM has attracted wide attention in recent times. Advancement in SRM control strategies has led to a new configuration, which has a dual stator providing low inertial loss and noise, higher torque, and power density with increased speed ranges.[163–165]

5._*Induction Motor:* Induction motors are widely used in EVs. Requirement of EVs can be induced by vector control. With field-oriented control, IM can be used as a separately excited DC motor. Speed range can be increased fourfold through field orientation control. Three-phase motors with copper rotors are mostly employed in EVs.

3.4.6. Bidirectional AC-DC Converter

In an EV, the battery charger converts the grid AC to DC voltage by a two-stage power conversion system. The first stage involves an AC-DC converter and the second stage is a DC-DC converter described in the next section. Briefly, a DC-DC converter provides galvanic isolation with battery charging controls.[166] The controls of both converters are synchronized with a single master controller. A bi-directional converter is a combination of a converter and an inverter. It is used to maintain (i) good AC shaping which prevents harmonic pollution and (ii) to regulate DC voltage that can provide a high-quality DC.[167] This bidirectional AC-DC converter must be highly efficient in order to prevent the problems of poor power quality such as high THD, low power factor, AC voltage distortion, ripple in DC, and DC voltage pulsations. Several AC-DC converter topologies can be used in EV battery chargers. Compared with a traditional design, that has a transformer at the AC grid side, the transformer-less topology is preferred due to its improved efficiency, less complexity in control, and low total weight.[168] The topology chosen depends on requirements such as efficiency, size, volume, weight, etc.[169] The converter can be a single-phase or three-phase converter as shown in Figure^^12<figr12>a, b.[170] A three-phase converter handles more power than a single-phase converter.

3.4.7. Bidirectional DC-DC Converter

In order to charge and discharge the batteries, a bidirectional DC-DC converter is used. The BDC ensures that the high voltage and low voltage parts are electrically isolated from one another thereby ensuring safety. [171] BDC has received much attention in recent years due to its wide applications, particularly in renewable energy systems, UPS, and EVs.[172] It is a key device that interfaces the storage devices between the source and load in a renewable energy system for continuous power flow. They step up or step down the voltage level with the ability to allow power flow in either forward or reverse direction.[173] In HEVs and EVs, BDCs charge the low voltage battery during normal modes of operation (Buck mode). During emergency periods, when the battery is drained/discharged, BDC supports or charges the high voltage battery pack (boost mode). In a typical battery charge/discharge system, BDC operates as a four-switch buck-boost converter when the V_{out} is near to the battery operating voltage. If V_{out} is less than the battery operating voltage, it can operate in buck mode. A higher efficiency is achieved when BDC is operated at a four-switch buck-boost converter as it employs lower voltage rating power devices and lower operating current.[174] A detailed overview of the BDCs in HEVs, EVs, and FCVs is described in. [174] Different topologies of BDCs are shown in figure^^13<figr13>.

4. Overview of EVs in the Market

4.1. Nissan Leaf

The Nissan Leaf is a BEV with a driving range of 100^^miles/charge. Time taken to completely charge the battery pack is 8^^hours and Nissan claims that 31^^miles of range can be obtained with 10^^min charging.[175] The estimated electricity cost of charging the vehicle for a year is $561. A Nissan Leaf can accelerate from 0 to 60^^mph in 10^^seconds and has a top speed of 93^^mph. The vehicle is propelled by a 110 HP Interior EM powered by a Lithium-ion battery pack that can deliver 90^^kW power and 24^^kWh of energy.

The battery pack consists of 48 modules with 4 cells in each module. The battery pack is air-cooled and can be heated when necessary to facilitate smooth operation in freezing temperatures. A 12^^V Lead acid battery is provided for powering the basic systems like headlights, wipers, sound systems, etc. An auxiliary battery is trickle charged from the solar panel on the rear spoiler. The battery pack’s life is estimated to be 8^^years or 100,000^^miles. Charging ports are positioned in the front of the vehicle with two receptacles.[176] One receptacle is a SAE J1772 connector that can charge the battery by using 120/220 AC voltage and the other receptacle for providing fast charging uses a 480^^V, 125^^A DC source.[177] Nissan Leaf's price range starts from 27,000^^USD. [178]

4.2. Mitsubishi Innovative Electric Vehicle

MiEV is a BEV, launched on World Environmental Day, 2009.[179] The vehicle has a driving range of 62 miles in fully charged condition. The vehicle is propelled by a single PM synchronous motor with a rated power of 47^^kW. It is rear-wheel drive with a single-speed reduction gear transmission. It can attain a top speed of 80^^mph. The entire vehicle is powered by a 16^^kWh LIB pack which consists of 22 modules having 4 cells each. Estimated recharge time using a 220^^V power supply is about 7^^h. Fuel efficiency of MiEV, rated by US EPA in urban driving, is 126^^MPGe and in highway driving it is 99 MPGe with a combined efficiency of 112^^MPGe.[177] Estimated fuel saving cost over 5^^years is about $2,750.[180] MiEV price range starts from 27,998^^USD [181]

4.3. Tesla Roadster

The Roadster is the first vehicle by the Tesla motor company, launched in the year 2008. It is BEV powered by a 248.1 HP 3-phase 4-pole AC induction motor with a maximum torque of 370^^Nm.[182] It is rear-wheel drive with a transverse motor mounting, capable of accelerating from 0 to 60 mph in 4^^s with a top speed of 124.9^^mph. The EM powered by 53^^kWh LIB provides an overall driving range of 231.2^^miles. The battery pack consists of 11 modules with a total of 6831 cells providing an output voltage of 375^^V.

The EPA estimates a combined efficiency of 120^^MPGe. Recharge time required for completely recharging the battery pack from empty state with a 240^^V, 70^^A supply is less than 4^^hours. Earlier rear-wheel drive is converted to all-wheel drive with an estimated range of 620^^miles.[183] The price range of the Tesla Roadster starts from 200,000 USD.

4.4. Ford Focus Electric

Ford's first full EV was the Focus Electric introduced in 2009. The car has an overall driving range of 100 miles and can attain a top speed of 84^^mph. A 143 HP AC synchronous motor with a 245^^Nm torque is used for propulsion.[184] It uses a liquid-cooled Lithium-ion Battery pack rated 23^^kWh, 318^^V with 430 cells arranged in 86 series and 5 parallel configurations. In its 2017 version, the battery pack capacity was increased to 33.5^^kWh.

Time taken for charging the battery pack completely is between 3--4^^h when connected to a 240^^V supply by a J1772 connector. The EPA estimates a fuel economy of 118 MPGe, 96 MPGe, and 107^^MPGe in urban, highway, and combined driving conditions respectively. The total fuel cost-saving over 5^^years is around $2,750.[185]

4.5. Toyota Prius

The Toyota Prius is the first commercial mass-market HEV, introduced worldwide in 2001. The first-generation car's powertrain consists of 2 EM and a 1.5^^L 4-cylinder SI engine developing 70^^HP. Among the two EMs, one is used to start the engine and charge the battery pack, while the other acts as the traction motor, delivering 45^^HP. In the second generation, the ICE's power was increased to 76 HP and the EM's power to 68 HP. The fuel efficiency and energy captured during the regenerative braking were improved. Later, in its third generation, the power of the ICE was increased to 98^^HP with an engine capacity of 1.8^^L and the EM rated power was 80^^P.

The battery pack contains a nickel-metal hybrid battery rated 6.5 Ah 21^^kW capable of producing a nominal voltage of 201.6^^V. The battery is charged by the generator during regenerative braking and by using partial power produced by the ICE. During low speeds, the EM propels the vehicle exclusively and during highway driving, the ICE propels it with maximum fuel efficiency. Fuel economy, as rated by the EPA, in city, highway, and combined conditions are 54^^MPGe, 50^^MPGe, and 52^^MPGe respectively. Total fuel cost saved in 5^^years is approximately $2,750.[186] The price range of the Toyota Prius starts from 24,525^^USD [187]

4.6. Toyota Mirai

The Toyota Mirai is the first and most popular FCHEV introduced in 2014 with a total number of 10,250 cars produced during December 2019. Figure^^14<figr14>. shows the powertrain of the Mirai. The vehicle uses an indigenous PEMFC stack for power generation. It has a total of 370 cells capable of developing a maximum power of 114^^kW with a rated power density of 3.1^^kW/L. Fuel is supplied from two, multilayer composites tanks of 122.4^^L storage capacity, with a holding and maximum pressure of 700^^bar and 875^^bar respectively.

The vehicle uses a 151 HP PM AC synchronous motor mounted in the front axle with a maximum torque of 334.88^^Nm. Its battery pack is made of Nickel Metal Hydride with a rated V_{out} of 224.8^^V. The battery pack is used as and when the EM demands during high acceleration, hill climbing, etc. Power distribution is administered by the power control unit, which continuously analyses the driver’s acceleration pedal position, load on the EM, etc. The maximum driving range of the vehicle is 312 miles with a maximum speed of 200^^km/h and it can accelerate from 0 to 60 mph in 9^^s. Fuel economy, estimated by the EPA, is 67 MPGe for both highway and urban driving conditions. Mirai’s price range starts from 49,000 USD. [189] Table^^6<tabr6> shows a comparison of various other commercially available EVs.

5. Challenges Encountered by FC Based EVs in Commercialization

As a new vehicle technology, the major challenges in satisfying market needs are cost, safety, and reliability. In addition, other influencing factors like materials used, manufacturing process and cost, supply chains, and user mentality towards new products also play a major role in commercialization. The commercialization phase is split into three segments, namely the manufacturing process, fuel processing and storage, and user acceptance, as shown in Figure^^15<figr15>. There are a few reports, where a commercially available stack is studied and the cost split-up for every component and sub-system are detailed. The pie chart is shown in Figure^^16<figr16> labels various components and sub-system's cost contributions.[191] Since the voltage of an FC is minimal, the required voltage is achieved by cell scale-up and stacking. Each cell is connected both mechanically and electrically. Any failure of a component leads to the failure of the entire stack system. This makes repairs expensive as the entire stack has to be disassembled and reassembled. Thus, at least 50^% of assembly charges, conditioning, and balance of system add to the repair cost.[192,193] If there are multiple repairs and servicing during the efficient lifetime of the stack, the repair and maintenance costs may exceed 60^% of the system cost. This requires advancements in terms of reliability, repair, and maintenance in an FC.

Scaling-up and stacking FC generates auxiliary concerns like non-uniform distribution of reactants inside the cells that greatly impact its performance.[194] Hence, designing a flow channel based on the theory of low distribution can mitigate the non-uniform distribution in a stack. Another major barrier in commercializing is the hydrogen infrastructure which is split between hydrogen generation, storage, and distribution.[195] The preferred mode of storing hydrogen is in compressed form as the volumetric efficiency is around 94^% and it does not require any external energy as in a cryogenic or metal hydride form of storage.[34] The major difficulty encountered by the manufacturers is storing hydrogen at a pressure range of 350^^bar and 700^^bar.[36] Infrastructure needed for the distribution of hydrogen is also undeveloped. Currently, vehicle manufacturers are focused on power density and cost to make FCEVs a reality.

5.1. The Road Towards Commercialization of FC Based EVs

In spite of many technological advancements in PEMFCs, they are hardly used in automobile industries to power vehicles. One of the greatest challenges is the high cost of Pt electrocatalyst. This led to the development of several electrocatalytic materials with lower Pt concentrations and higher performance.[195--202] Moreover, electrocatalyst materials that replace Pt have also been explored by scientists worldwide.[203,204] However, recently Pollet et^^al. stated that the cost of Pt used in FC is much cheaper compared to that used in catalytic converters which account for 40^% of total global production per year.[56] As it is clear that FC has higher thermal efficiency compared to ICE, the fuel cost for the FC stack will be much less and in the long run, the entire stack cost will also be reduced. When coupled with co-generation, the efficiency can be as high as 90^%. Wang et^^al. suggested three models for connecting components of the stack and control system, as reliability and durability are major factors in commercializing FCs.[192] At present, FCEVs have a durability of 3500^^hours at various speeds, while FC buses have surpassed the 2016 durability target of 18,000^^hours to reach 23,000^^hours.[205]

Apart from technological developments, the US DOE plans to curtail the price of an 80^^kW FC stack system to the US $30--$40, which can reduce the vehicle cost by a large margin. Furthermore, efforts to reduce the cost of hydrogen production to <$2/kg, are being taken by adopting the PEM electrolysis method.[206] Furthermore, to develop the infrastructure for hydrogen distribution, 109 multinational transportation companies from 20 countries have formed the Hydrogen Council to accelerate infrastructure development.[207] The primary concern is the exorbitant cost of setting up a variable pressure nozzle hydrogen fuel station (US$750,000). However, this can be alleviated with the development of a modular approach for fueling stations.[208--210] With the above-stated initiatives, nearly 2 million FCEVs are expected to be on the road globally by 2030.

6. Conclusion

This paper has given an overview of different types of vehicles, their components, and their topology. It is evident that with relentless changes in emission norms, conventional ICE-powered vehicles are losing their value and there is a shift in the market towards HEVs, FCEVs, and FCHEVs as they are eco-friendly. Though BEV is a ZEV, it is not popular due to the short-range, cost, and prolonged recharging issues. On the other hand, HEVs, FCEVs, and FCHEVs have superior fuel economy and vehicle performance. Dynamic loading and Fuel cell cost are the major factors that hinder the successful commercialization of FCEV and FCHEV. Hence, future developments should be directed towards the improvement of the dynamic performance of the FC stack. Also, infrastructural developments are needed to safely generate, store and transport hydrogen.

Abbreviations

AEV	All Electric Vehicles
BEV	Battery Electric Vehicle
BS	Bharat Stage
CI	Compression Ignition
DC	Direct Current
EEM	Electronic Engine Management System
EM	Electric Motor
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
GDL	Gas Diffusion Layer

GHG Greenhouse Gases

GVW Gross Vehicle Weight

HEV Hybrid Electric Vehicle

HP Horse Power

ICE Internal Combustion Engine

ICEV Internal Combustion Engine Vehicle

ISG Integrated Starter Generator

LHV Lower Heating Value

MCU Motor Control Unit

OCV Open circuit voltage

ORR Oxygen Reduction Rate

PEMFC Proton Exchange Membrane Fuel cells

PHEV Plug-in Hybrid Electric Vehicle

SI Spark Ignition

SOC State of Charge

WTW Well to wheel

ZEV Zero Emission Vehicles

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Table^^1 Comparison of pollutant level limits in BS III, IV, and VI.[19]<W=3>

Vehicle Category	BS	CO (g/km)		HC (g/km)		NO_X (g/km)		PM (g/km)	
		SI	CI	SI	CI	SI	CI	SI	CI
Passenger (GVW≤2500)	III	2.30	0.64	0.20	0.06	0.15	0.50	--	0.05
	IV	1.00	0.50	0.10	0.05	0.08	0.25	--	0.025
Passenger (GVW≤3500)	VI	1.00	0.50	0.10	0.09	0.06	0.08	0.0045	0.0045

Table^^2 <?IMA size-30?>Comparison of parameters of different fuel cell types.<W=4>

Electrolyte	Fuel	Catalyst	Oxidant	Efficiency (%)	App

Fuel cell Types		Charge carrier				Operating Temperature (°C)	Without heat recovery	With cogeneration	
PEMFC	Solid Polymer Electrolyte Membrane	H^+	99.999^% H_2	Pt	Air/O_2	50--100	40--50	90	· Tr · St gen · Au unit veh
DMFC	Solid Polymer Electrolyte Membrane	H^+	CH_3OH	Pt	Air/O_2	60--200	17--35	60	· Us repl batt port proc
AFC	Liquid solution of 85^% KOH Liquid solution of 30 to 50% KOH	$OH^{<M->}$	H_2	Pt	Air/O_2	100--250 <120	34--38	--	· St Por sou
AEMFC	Alkaline Anion Exchange Membrane	OH^-	CH_3OH C_2H_5OH N_2H_4	Pt/Non-Pt	Air/O_2	50 -80	60--64	--	· Ou app · St pow
PAFC	Phosphoric acid	H^+	H_2	Pt	Air/O_2	175--200	40 – 50	80--87	· Au sect stat pow with
MCFC	$LiAlO_2$	$CO_3^=$	H_2, CO, CH_4 and other	Ni	Air/O_2	650--700	50--60	75--80	· St dist pow

			hydrocarbons						· Na · Ut
SOFC	YSZ	$O^{=}$	H_2, CO, CH_4 and other hydrocarbons	Perovskites	Air/O_2	800--1000	50--60	70--75	· St and pow · Ut
ITSOFC	YSZ	$O^{=}$	H_2, CO, CH_4 and other hydrocarbons	Perovskites	Air/O_2	500--800	50--60	70	· St and pow · Ut
TSOFC	YSZ	$O^{=}$	H_2, CO, CH_4 and other hydrocarbons	Perovskites	Air/O_2	800--1000	50--60	70	· St and pow · Ut

Table^^3 Comparison of various batteries.[139--143]

Energy Storage Device	Cycle Life	Specific Power (W/kg)	Specific Energy (Wh/kg)
Lead Acid	500--800	150--400	35--50
Li-ion	400--1200	300--1500	150--250
Ni-MH	500--1000	250--1000	30--80
Ni-Cd	800	80--150	50--60
Ni-Fe	1500--2000	80--150	50--60
Ni-Zn	300	170--260	55--75
Al-Air		160	200--300
Fe-Air	500	90	80--120

Zn-Air	600	30--80	100--220
Zn-Br	65--70	90--110	70--85
Vanadium--redox		110	20--30
Na-S	800	230	150--240
Na-NiCl	1200	130--160	90--120
Li-FeS	1000	150--250	100--130
Organic Li-ion	1000	200--300	80--130

Table^^4 Ultracapacitor and Supercapacitor comparison.[149]

Energy Storage Device	Cycle Life	Specific Power (W/kg)	Specific Energy (Wh/kg)
Ultracapacitor	1000000	400	200
Supercapacitor	20000--50000	80-150	40-80

Table^^5 Possible materials that can be used for manufacturing Ultrahigh-speed Flywheels.

Composite material	Tensile Strength, σ (MPa)	Specific Energy, ρ (kg/m^3)	Ratio σ/ρ
E-glass	1379	1900	0.72
S-glass	2069	1900	1.08
S2-glass	1470	1920	0.76
Graphite epoxy	1586	1500	1.06
Kevlar epoxy	1930	1400	1.38
T1000 Carbon fiber	1650	1510	1.09

Table^^6 Summary of fuel economy of different types of vehicles.[190]<W=3>

Vehicle	Type	Energy Source	Combined Fuel Economy (MPGe)	Total Range (miles)	Annual Fuel Cost (USD)	Cost saving in 5^^years (USD)
Toyota Camry	HEV	ICE and Battery	52	686	600	3000
Toyota Corolla	HEV	ICE and Battery	52	593	600	3000
Toyota Highlander	HEV	ICE and Battery	35	598	950	1250
Ford Fusion	HEV	ICE and Battery	42	588	750	2250
Ford Escape	HEV	ICE and Battery	41	--	--	--
Tesla Model 3 Standard Range Plus	BEV	Battery	141	250	450	3750
Tesla Model Y AWD	BEV	Battery	121	315	550	3250
Hyundai Ioniq Electric	BEV	Battery	136	124	500	3500
Hyundai Kona Electric	BEV	Battery	120	258	550	3250
Chevrolet Bolt EV	BEV	Battery	119	238	550	3250
Volkswagen e-Golf	BEV	Battery	119	125	550	3250
Kia Soul Electric	BEV	Battery	114	243	600	3000
Kia Niro Electric	BEV	Battery	112	239	600	3000
Tesla Model X	BEV	Battery	101	258	650	2750
Audi e-tron Sportback	BEV	Battery	77	218	850	1750
Jaguar I Pace	BEV	Battery	76	234	850	1750
Porsche Taycan Turbo	BEV	Battery	69	201	950	1250
Hyundai Ioniq Blue	HEV	ICE and Battery	58	690	550	3250
Honda Insight	HEV	ICE and Battery	52	551	600	3000
Kia Niro FE	HEV	ICE and Battery	50	595	650	2750

Honda Accord Hybrid	HEV	ICE and Battery	48	614	650	2750
Chevrolet Malibu Hybrid	HEV	ICE and Battery	46	598	700	2500
Lexus ES 300^^h	HEV	ICE and Battery	44	581	750	2250
Toyota Avalon Hybrid	HEV	ICE and Battery	44	581	750	2250
Lexus UX 250^^h	HEV	ICE and Battery	42	445	750	2250
Toyota RAV4 Hybrid AWD	HEV	ICE and Battery	40	580	800	2000
Honda CR<C->V AWD	HEV	ICE and Battery	38	532	850	1750
Nissan Rogue Hybrid	HEV	ICE and Battery	34	493	950	1250
Ford Explorer	HEV	ICE and Battery	28	540	1150	250
Audi A6 Quattro	HEV	ICE and Battery	27	521	1550	1750
Honda FCX Clarity	FCEV	Hydrogen	68	360	--	--
Hyundai Nexo	FCEV	Hydrogen	57	354	--	--

Figure^^1 World Oil production and Consumption between 2015 and 2021.

Figure^^2 Architecture of ICE vehicles.

Figure^^3 Conceptual Power flow illustration in a HEVs.

Figure^^4 Series Hybrid Topology operating modes as follows: (a) Pure electric mode; (b) Pure engine mode; (c) Hybrid propulsion mode; (d) Engine traction and battery charging; (e) Regenerative braking; (f) Stationary charging; (g) Hybrid charging mode.

Figure^^5 Parallel Hybrid Topology operating modes as follows: (a) Pure engine mode; (b) Pure electric mode; (c) Hybrid propulsion mode; (d) Regenerative braking; (e) Battery charging from engine.

Figure^^6 Series-Parallel Hybrid topology operating modes as follows: (a) Pure electric mode; (b) Hybrid propulsion mode; (c) Pure ICE mode; (d) Regenerative braking; (e) Battery charging from engine.

Figure^^7 Complex hybrid topology operating modes as follows: (a) Start-up mode; (b) Pure Electric mode; (c) Hybrid mode; (d) ICE Traction and Battery Charging; (e) Regenerative Braking.

Figure^^8 Series Plug-in Hybrid Electric Vehicle Powertrain Topology.

Figure^^9 Schematic of Battery Electric Vehicle Powertrain Topology.

Figure^^10 Schematic of Fuel Cell Vehicle Powertrain Topology.

Figure^^11 Schematic of Fuel Cell Hybrid Electric Vehicle Powertrain Topology.

Figure^^12 (a) Single-Phase Bidirectional AC/DC Converter for Renewable Energy System, (b) Three-phase bidirectional AC-DC converter topology.

Figure^^13 Bidirectional DC/DC converter topologies.

Figure^^14 Shows the Powertrain of Toyota Mirai 2019.[188]

Figure^^15 Commercialization phases.

Figure^^16 (a) Cost split-up of Fuel cell components, (b) Cost split-up of Fuel cell sub-systems.