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Recent Development in Green Fuel Vehicles and their Future Advancements

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Abstract - *In recent years there has been a major shift in the Automobile sector from the conventional internal combustion engine to more refined and environmentally more sustainable technologies to run our vehicles. Through this study, a comprehensive summary of past, recent and future development in the department of an environmentally clean transportation system is concluded. The study mainly focuses on green technologies that will be used to power our vehicles in the near future. A technological roadmap of development of different configuration of EV's including HEV, BEV and FCEV in the past year is concluded. The study of HEV is presented with details of generally used powertrain structure (series, parallel, combination and plug-in-HEV) along with details on BEV and major subsystems used in running pure electric vehicles such as types of power sources used, motors and power converters. Through this paper working of electric vehicle is discussed along with presentation on the different energy flow diagrams and finally, an overview of hydrogen-powered vehicles is presented with details of Fuel cell and future technologies. Finally, to conclude our study a discussion on global trends and various trades-offs that have to be made with electric vehicles for future trends and potentials areas of research for future use in EV is discussed.*

Key Words: Electric Vehicles [EV]; Hybrid Electric vehicles [HEV]; Fuel Cell Vehicles [FCV]; internal Combustion Engines [ICE]; ultra-capacitors; Battery Management System; Lithium-ion Battery; Battery Module; Supercapacitors; Energy Storage System [ESS]; Induction Motors [IM]; Permanent Magnet Motor [PMS]; Converters

1. INTRODUCTION

Increase in pollution and severe harm to the mother Earth has led us to look for alternative sources of energies that will help us to control and reduce harmful emissions from our Automobiles and other industries. In 2016, over 194 countries participated in Paris climate agreement enforcement and pledged to limit the average global temperature increase to less than 2-degree Celsius in this century [1]. According to the reports, more than 50% of the world's Green House Gases (GHGs) emissions comes from USA, China and India.

The transport sector astonishingly accounts for more than 80% of pollutants released from major cities in countries like USA, CHINA and INDIA etc. In our country usually the quantity of air pollutants, particulate matter, sulfur dioxide, nitrogen oxides (NO), ozone (O_3) and carbon monoxide (CO) are often above the National Ambient Air Quality Standards (NAAQS) [2]. During the 2014 assessment, World Health Organization (WHO) listed New Delhi among the top ten cities around the world having the worst PM!) pollution. Vehicular emission from ICE has been the major contributors to the rise in pollution and can constitute the following emission sources as shown in figure 1 [2].

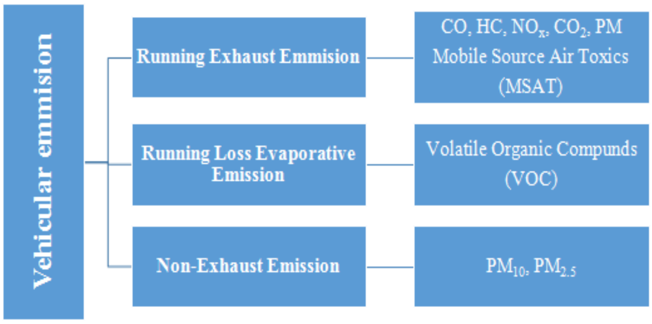


Figure 1: Types of vehicular emissions [2]

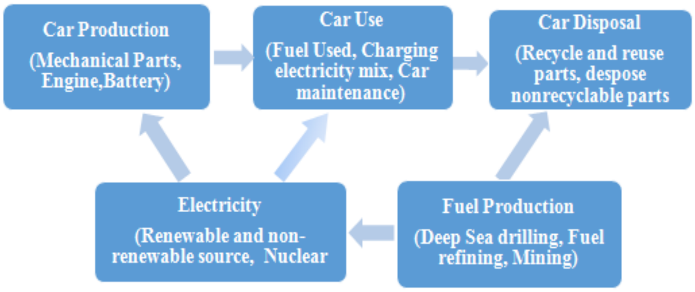


Figure 2: Sources of emission in life cycle of a car

The USA and China has already started wide spread adaptation of e-vehicles over fossil fuel powered vehicles to tackle the rising Green House Emissions in their country and as of 2019 they have highest stock of EV in the world however, India is still lagging behind its counterparts [1].

Electric vehicle transportation is potential resource to meet wide range of transportation policy goals and has boosted energy efficiency. EVs does not require any direct fuel for combustion and can fully depend on electricity. EVs will lead to great amount of energy to be secured, much better air quality, reduced noise or very less amount of noise, and have reduced the greenhouse gas emissions [3].

As of now INDIA has been lagging in the Electric vehicle department, but in coming years a lot of development will be there in terms of infrastructure and technologies to support and increase the penetration of EV's in Indian automobile industry. The Indian government has been trying to make this happen as soon as possible and plans to promote EV's. The Indian government aims at 100% e-mobility by year 2030. The foundation of India's journey to 100% e-mobility was laid in year 2017 when the first 100 e-vehicles unit were manufactured, and four charging stations were set-up [1].

But the usage of electric vehicles alone does not mean the reduction of air pollution. Electric vehicles will be effective in the reduction of pollution only if the major portion of electricity is obtained from renewable sources and the battery manufacturing plants are set-up far from the vehicle use region [2]. So not only the use of electric vehicles will reduce pollution, we need to develop new technologies to produce electricity such as nuclear power plants to deal with the increased requirement of power to run EV's. As of now, most of the electricity in India is generated by thermal power plants that use coal as their fuel. So, not only the development of new EV technologies, India must work on renewable sources of electricity generation too. So, a proper strategy has to be set up for the green future which is shown in figure 3.

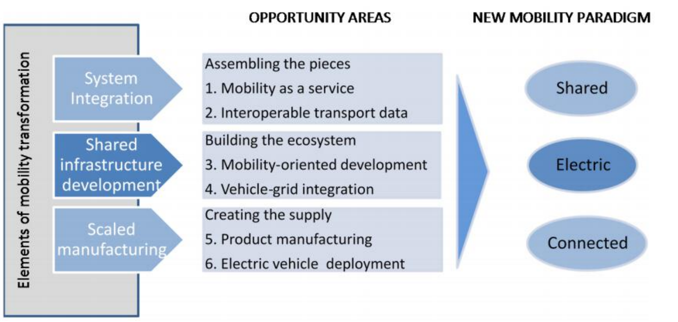


Figure 3: India's strategies to reduce vehicular emission and transform the whole mobility sector [2].

There has been a lot of research in the department of Green fuel vehicles and several review papers have focused on the general electric vehicles, electronic components, and energy management strategies. But there is a lack of published papers that present a comprehensive overview of EV's including powertrain configurations, power electronic components, energy management strategies, and new future technologies. This study fills this gap quite well by evaluating the practical vehicle applications and patents as well as published papers. The objective of this paper is to give a comprehensive overview of all-electric vehicles, evaluating the components used and the future of vehicles equipped with better BMS, IoT connectivity, and India's policies in favor of the development of EV's.

2. OVERVIEW ON ELECTRIC VEHICLES

Electric vehicles will be shaping our future for a better tomorrow. With less pollution, better air quality index, reduced noise pollution and efficient use of energy. Electric vehicles will be able to provide the growth to the stagnant automobile sector and increase the competitiveness in the industry. EV industry growth has attracted many investors and automobile companies towards electrified future. In the following section, the working principle and some light on the past present scenario of the electric vehicle are given.

2.1 Working Principle:

In simple words an electric vehicle works when electrical energy is used to power the motors from the controller which in turn receives the power from the rechargeable batteries. The battery pack stores energy in the form of electricity and supply power to the motors. The motor then uses the power (voltage) received from the battery pack to rotate and provide motion to the vehicle. The energy to be delivered to the motor is determined by the signal sent to the controller by potentiometer [4].

The article begins with a study on different EV configuration such as BEV, HEV, and FCBEV, then discussion on the engineering philosophy of EV development. Further, the advancement of Embedded systems used an overview of the EV market in INDIA is discussed.

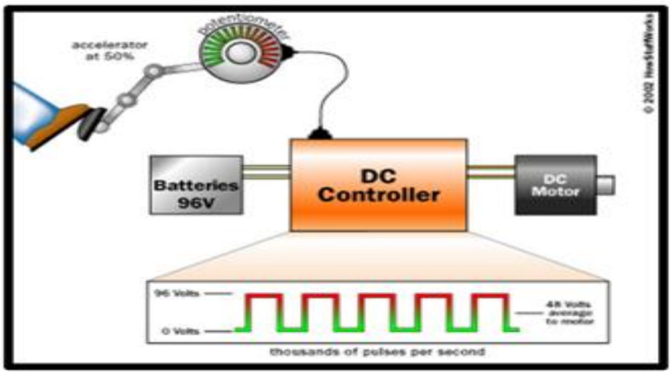


Figure 4: Working Principle of an Electric Vehicle [1]

2.2 Past Years Development

The first electric vehicle was developed in year 1834 and by the end of 19th century many auto-manufacturers in USA, Britain and France started making EVs. Figure 5 shows the World's first electric car. Due to the restrictions related to the batteries and therefore the rapid advancement in combustion engine (ICE) vehicles, EVs have almost vanished from the scene since 1930 [4]. The high cost, low top speed, and limited range of battery electric vehicles, compared to the combustion engine vehicles, led to a worldwide decline in their use; although electric vehicles have continued to be used in the form of electric trains and another niche uses [5].

Figure 5: World's first electric car. [5]

During the start of the 21st century, with growing concern over the issues related to the hydrocarbon-fueled vehicles has led to an increased interest in electric and other alternative fuel vehicles. Increasing fuel prices, government regulation, and a general desire to scale back environmental damage have resulted in increased sales for fuel-efficient vehicles. Since 2010, there has been an increase in the combined sales of all-electric vehicles reaching over 5 million units delivered globally in September 2018, and the sales of light-duty all-electric vehicles and plug-in hybrids passed 8 million in December 2019 [5].

In the early times, the electric vehicles were powered by galvanic cells (batteries) and direct-drive reluctance motors. Then with further development first rechargeable batteries were used (Lead-acid batteries) with better induction motors but all EV's failed the race to newly developed IC engine vehicles in terms of efficiency, cost, and range.

2.3 Electric Vehicles at Present

The fist electric vehicle was introducing in the 18th century however the wide spread adaptation of EVs has been seen in the present decade only. Global EV sales have escalated from less than 10,000 in 2010 to 774,000 in 2016, surpassing two million cumulative sales. Electrification of vehicles is considered the main decarburization pathway for nearly all road-based transportation. Several countries on the account of worsening urban air quality have announced the intention to ban sales of internal combustion engine vehicles (ICEs) in the near future and replace the existing one with EVs [6].

3. ELECTRIC VEHICLE DRIVE-TRAIN

With recent development, vehicles can be classified into three main categories: internal combustion engine vehicles (ICEs), hybrid electric vehicles (HEVs) and all-electric vehicles (AEVs) as shown in figure 6 also. IC engine has been developed at the peak of their efficiency in the last several decades and now a sustainable source of energy requirement is been felt by all in the automobile industry. Now, further development is been made in the department of hybrid and electric vehicles.

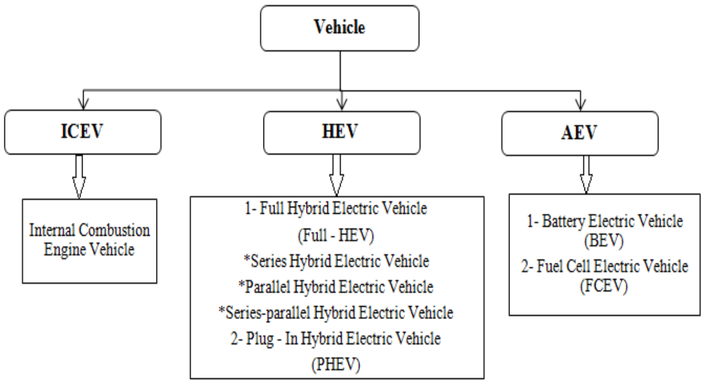


Figure 6: Classification of Vehicles [7]

From the above figure 6, we see that new technologies in vehicle propulsion are been developed other than internal combustion engines. Hybrid electric vehicles seem to be much practical in today's time due to the lack of infrastructure for the growth of AEV's. In HEV the ICE work in tune with the motors to provide better efficiency and less fuel consumption, the configuration of HEV's will be discussed in a further section. However, the HEV vehicles are also lagging behind in the Indian market due to their high cost and increased maintenance cost that normal ICE vehicles. So, the best alternative is to switch to AEV with the proper development of other sectors as well such as infrastructure for charging and production of electricity. The comparison of different characteristics of each drivetrain is given in table 1.

4. TYPES OF ELECTRIC POWER TRAIN

Through the past year's development, we have seen many applications of batteries and motor for automobile use. The structure of the drive-train is also different. So, in this section a brief discussion about the different types of power-train layout used for electric vehicles. Different types of power-train layout are hybrid-electric, All-electric and hydrogen fuel cell power-train.

4.1 HEV Power Train Configurations

In 1997, Toyota Prius was the first HEV to be introduced in the automobile market and since then more than 150 different models of HEV have been developed around the world. In hybrid electric vehicles (HEV) the conventional internal combustion engine (IC) is combined with an electric propulsion system that forms the combined hybrid vehicle drive train. The electric motors are provided to assist the conventional IC engines to provide either better fuel economy or better performance. So, the working of hybrid electric vehicle is mainly focused on the following key points:

- Maximize the fuel economy.
- Minimize vehicular emissions
- Minimize the system cost
- Better driving performance

Table -1: Characteristics of ICEVs, BEVs, HEVs, PHEVs and FCEVs [7]

Characteristics	ICEVs	BEVs	HEVs	PHEVs	FCEV
Propulsion System	ICE based	Electric motor based	Electric motor & ICE	Electric motor & ICE	Electric motor based
Energy storage	Fuel tank	Battery Ultra-capacitor Flywheel	Fuel tank Battery Ultra-capacitor Flywheel	Fuel tank Battery Ultra-capacitor Flywheel	Fuel cell Battery Ultra-capacitor
Energy source infrastructure	Refueling station	Electric charging facility	Electric power Refueling station	Electric charging station Refueling station	Hydrogen cylinder Hydrogen refiner & refueling station
Advantages	Fully commercialized Matured technology Better performance Simple operation Reliable	Zero emission Quite Smooth operation Energy efficient Independency from petroleum product Commercialized	Low emission Higher fuel economy Long driving range Reliable Commercialized Durability	High fuel efficient Lower emission Extended electric driving range V2G or G2V capability Quiet and smooth Operation	Ultra-low emission Competent driving range Highly efficient Independency from petroleum products Reliable Durable High cost
Drawbacks	Less efficient Harmful emission Poor fuel economy Comparatively bulky	Limited driving range Poor dynamic response High recharging time	Complex system Costly Bulky Increased component	High complexity Higher initial cost Battery technology Impact on grid	Slow dynamic response Not commercialized Sophisticated electronic controller
Major issues	Harmful emissions Fuel economy Dependency on petroleum products	Size & weight of battery pack Infrastructure for charging station	Size & weight of battery pack & ICE Integration of components	Charging station infrastructure Size & weight of battery pack & ICE Impact on grid	Cost of fuel cell Infrastructure for hydrogen conditioning, storage and refilling system

4.1.1. HEV's power-train configuration can be of four types [9]

a) Series Hybrid Electric Vehicles (SHEV):

In series hybrid electric vehicles there is no mechanical connection between ICE and wheels. SHEV involves internal combustion engine (ICE), generator, battery packs, rectifier, capacitors, converters and electric motors as shown in Figure 7. These configurations do not need supercapacitors (also known as ultracapacitors).

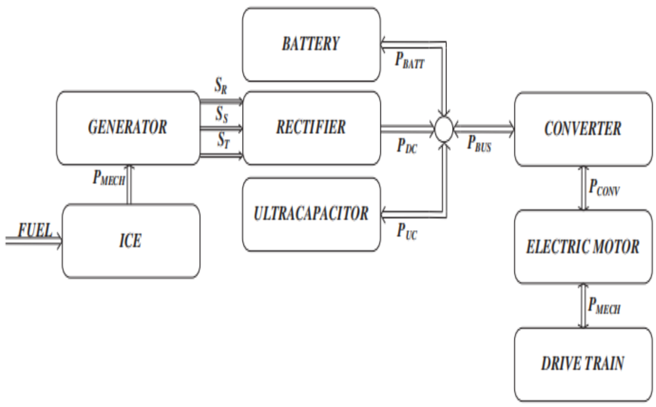


Figure 7: The Power Flow of SHEV Power Train [9]

In this type of configuration, the ICE is switched off when the battery is feeding power to the wheels and ICE only turns on when the batteries are low on charge. General working of a SHEV can be understood on the following way that when the power demand on the electric motor is less than the output of generator, the remaining power is used to charge ultracapacitor banks and the battery pack and if the power demand of the motor is higher than the output power of the generator than the additional power is supplied from the ultracapacitors [9]. So, the engine always works at it BEP.

b) Parallel Hybrid Electric Vehicles

In parallel hybrid electric vehicles, both IC engine power output and electrical power output are connected in parallel to drive the wheels as shown in figure 8. In this type of configuration, the IC engine is in always-on mode at almost constant power output at maximum efficiency point

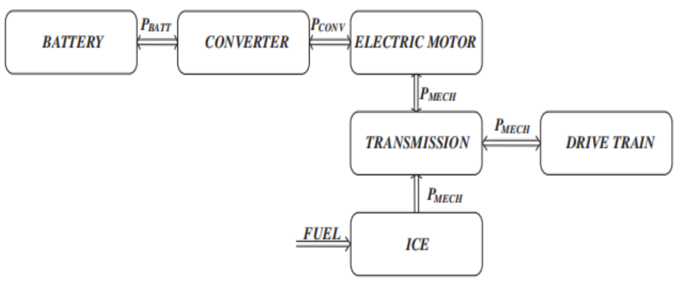


Figure 8: The Power Flow of PHEV Power Train [9]

The power flow can be understood as when the power required by the transmission is higher than the output power of ICE, the electric motor is turned on. In this arrangement the ICE and the electric motors both supply power to the transmission and in case the output power of the engine is more than that required by the transmission, the additional power is used for charging the batteries and the ultracapacitors [9]. This configuration leads to high maintenance and complex power management system algorithm. Yet this is the most commonly used hybrid vehicle powertrain.

c) Combination of Parallel and Series HEVs

This type of configuration is a combination of series and parallel hybrid system. As the name implies this configuration is neither fully parallel nor series hybrid system. Figure 9 shows the architecture of this drive. This configuration consists of a feature of both series and parallel hybrid systems. This type of drive is equipped in passenger vehicles or small automobiles.

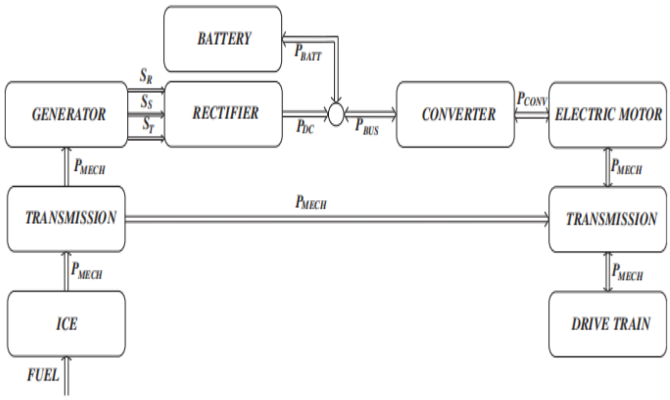


Figure 9: The Combination of Parallel and Series Hybrid Configurations [9]

This configuration of a combination of series and the parallel hybrid system works in conjunction with a power split device, a planetary gear that makes the power to be sent to wheels from the ICE. A planetary gearbox connecting the electric motor and the ICE is shown in Figure 10. With this configuration the speed of the engine can simply be adjusted by varying the speed of the generator.

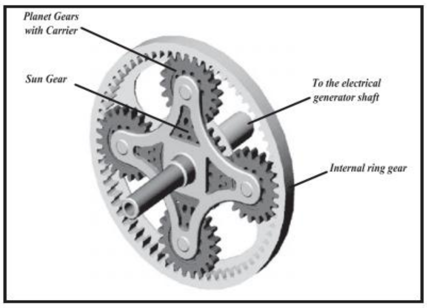


Figure 10: View of Planetary Gear System [9]

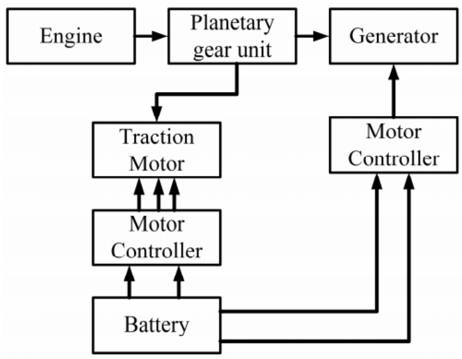


Figure 11: Drive train of SPHEV Using Planetary Gear

In figure 11. A planetary combination (PC) hybrid in Toyota Prius is shown. The figure shows the planetary gear unit coupled with ICE, alternator coupled to the sun gear and output torque is transmitted to the differential. The working of this power train is similar to that shown in figure 14.

d) Plug-in Hybrid Electric Vehicles (PHEV)

In plug-in hybrid electric vehicles, the capacity of the IC engine is much smaller than that of the electric propulsion system. In these vehicles, we have to charge the batteries every time as the IC engine is not capable of charging the batteries on the go and the main driving force is achieved by electric motors. These vehicles are a step towards all-electric vehicle (AEV), but there are some advantages of PHEV over AEV that are:

- Charging time is less.
- The car can be driven on ICE alone when the batteries die out.
- The vehicle range is more.
- Higher efficiency and less pollution
  PHEVs' has the ability to run solely on electric power only, which further reduces the carbon footprint smaller than the HEVs.
- The fuel cost associated with PHEV is also less.

A roadmap to the technological advancement in electric vehicles is shown in figure 12. At the beginning of the electric vehicle stage, a large engine is supported by a smaller battery and motor but as there were more advancement and need for clean vehicles the larger engines are being replaced by big batteries and motors.

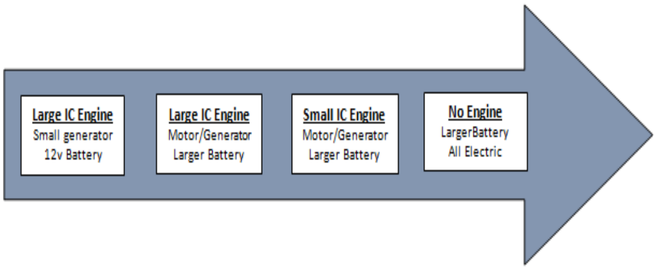


Figure 12: The Evolution Steps of the HEV Technologies [9]

4.2: Battery Electric Vehicles (BEV)

Battery electric vehicles are also known as All-electric vehicles (AEV) in which the vehicle propels by motors working on electricity. There is no IC engine assistance as in Hybrid Electric vehicles. BEV's have one or several high-energy batteries onboard which drive the traction motor with the help of embedded systems, which will be discussed in further sections. All BEV's have to rely solely on energy store in the batteries for propulsion, even with today's development in batteries technologies BEV's can only have an estimated range of 200-250km for smaller vehicles and 400-450km for heavy vehicles on a full charge. BEV's are simple in construction, operation, and easy to maintain. These vehicles are eco-friendly as they do not produce greenhouse gases (GHG) and produce less noise while running. All-electric drive train are very efficient and easier to maintain as compared to its ICE counterparts. The mentioned advantages coupled with limited driving range make them perfect vehicle for use in urban areas. [10]

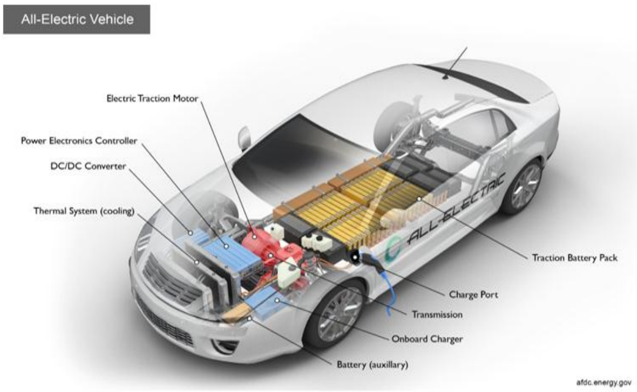


Figure 13: Layout of an All Electric Vehicle (AEV) [11]

Figure 13 shows the layout of a BEV and the major hardware components of the vehicle. The figure shows a front-wheel-drive BEV in which the motor drives the front wheels and the battery pack is placed at the center of the vehicle floor for better weight distribution. The weight of the BEV is higher than normal IC engine vehicles due to battery pack and a lot of research is going on to reducing the weight of the batteries and improve the handling of the vehicles. The weight of the vehicle severely affects the driving range that can be obtained from battery electric vehicles.

EVs as whole can be considered as a combination of different subsystems. The interaction between the systems is what required to make an EV work and for proper functioning multiple technologies can be employed [10]. From figure 14 an observation on the major components of EV's can be made but figure 14 show how the components interact with each other. Observing figure 14 a conclusion can be made that some parts interact significantly with other parts, whereas some parts interact less with other parts. But it is the combined works of all these parts/systems which make an EV operate.

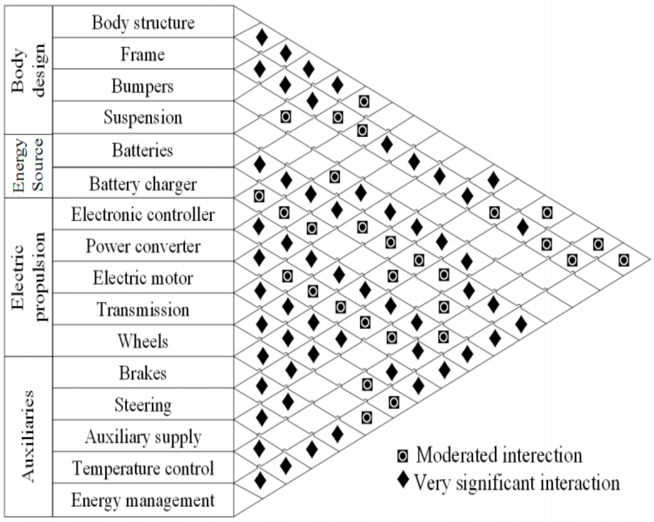


Figure 14: Major EV Subsystems and their Interactions [10]

4.2.1 EV Configurations:

It is concluded from figure 17 that how different subsystems interact. It is clear from figure 17 that some components of EVs are closely related while some have fewer interaction with other parts. In this section, a detailed explanation on how these systems interact with each other and make an EV work at its full potential is explained.

An electric vehicle is quite flexible in power transmission, unlike its ICE counterparts. In a BEV the power is transmitted through flexible electrical wires rather than rigid mechanical links in ICE or HEV. BEVs have only one moving part i.e. motor and can be controlled by different control algorithm and techniques.

All EV's are equipped with 3 major subsystems that are an energy source, electric propulsion, and the auxiliary.

The Energy source subsystem consists of:

a) The energy storage devices (battery, fuel cell, ultra-capacitor)
b) EMU (Energy management unit)
c) Energy charge unit

The Electric propulsion subsystem comprises of:

a) Electric motors
b) Power converter
c) Controller
d) Transmission
e) Driving wheels

The auxiliary subsystem consists of:

a) Power steering unit
b) Temperature control unit
c) Auxiliary power supply

In figure 15, the mechanical links are represented by the black lines, electric link between components are represented with Green lines and the control information communications are represented with blue lines. The motor speed is based on input from the accelerator pedal which interacts with the electronic controller a part of an embedded system; hence named as throttle-by-wire. The energy management unit along with electronic controller works together, to regulate regenerative braking and its energy recovery. It also works with the energy-refueling unit to control refueling and to monitor the usability of the energy source. The auxiliary power supply provides the required power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units.[12]

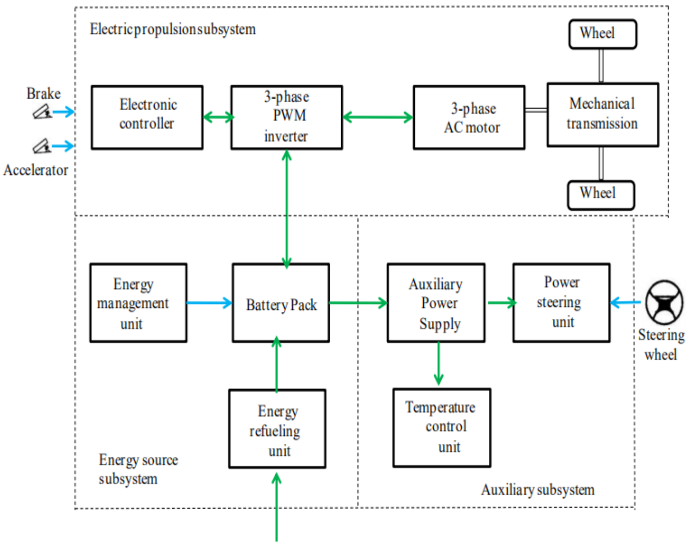


Figure 15: Modern configuration of Electric Vehicles [12]

The components mentioned in figure 18 are further discussed in the following section along with their specification and why they are best fit for modern EVs is also discussed.

4.2.2 Electric Vehicle design:

Modern EVs can be configured in many possible ways with variation in placement of different components of the propulsion system and the power sources. From figure 16, the different drive train configuration of EV's can be understood. The placement of electric motors can on the front wheels/axel or on the rear wheels/axle. Each configuration has its own characteristics and benefits. Motors are placed on front wheels in small or passenger vehicles so that they do not have a problem climbing steep hills and rear placement of motor is usually done on sports cars which require high accelerations of the line.

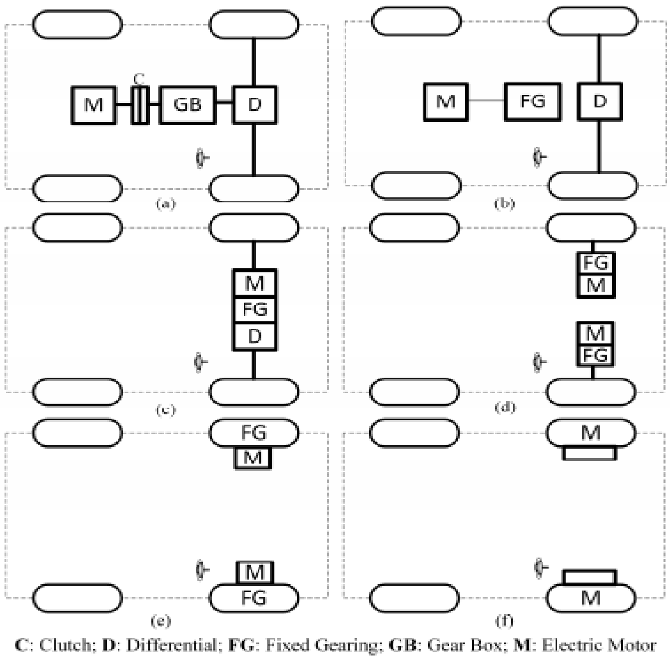


Figure 16: Different configuration of front-wheel drive (FWD) EV. (a) FWD vehicle which has motor powering the front-wheels (b) No clutch configuration (c) A single unit comprising of motor, gears and differential powering the front wheels (d) 2 motors are placed at separate front-wheels to obtain differential action (e) A modification of fig 19(d) configuration with fixed gearing placed within the wheels (f) A low-speed motor placed on the wheel rim to remove the mechanical gear system [10]

In the followings figure the bottom layout of different Vehicle is given. Through the figure, it can be observed that Motors can be placed on front-axel, rear or on both. The layout is designed with keeping many factors in mind such as weight of the car, cost and mileage range. Figure 17 Shows a rear-wheel drive configuration in which the battery and motor are placed at the rear-axel.

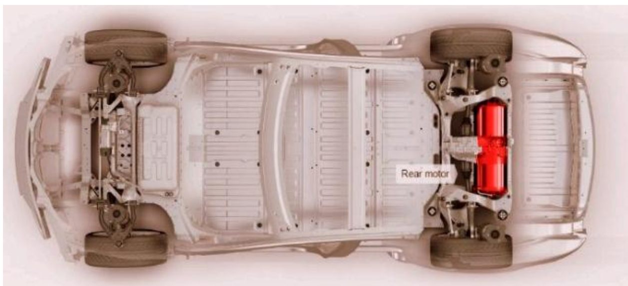


Figure 17: Tesla Model S, Rear Wheel Drive Configuration [10]

When there is a need for more traction and power, all-wheel drive (AWD) configuration is also used in electric vehicles by placing motors on the front and rear wheels/axels. All-Wheel drive systems lead to increases in cost, weight, and complex power management strategies. These vehicles are equipped with torque vectoring systems to provide better performance and handling. Figure 18 shows a layout of AWD vehicle with electric motors placed on each front and rear axle.

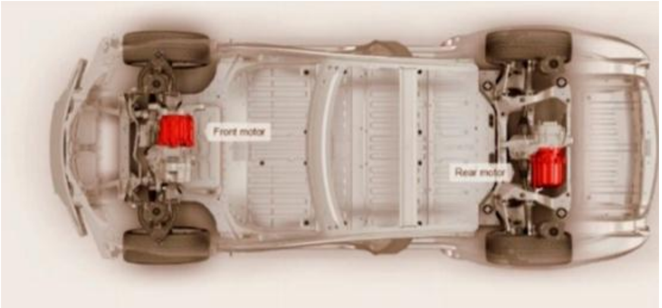


Figure 18: All-Wheel Drive Configuration [10]

5. MAJOR SUB-SYSTEM USED IN ELECTRIC VEHICLES

The working principle of the electric vehicles was discussed in earlier sections. Through this section, an explanation of the details of major sub-system used in electric vehicles is discussed with their working and interaction with other components. These sub-systems make an EV work and can be categorized in Energy Sources, Motors, Inverter and Converters, Embedded Systems and Charging Modules. Below the details of each such sub-system of EV mentioned above is given.

5.1. Energy Sources for EV's

EV's require electrical energy for propulsion. This energy requirement is fulfilled by different energy storage devices onboard of the vehicle. Each energy storage device is selected on the basis of some predefined criteria's and among them high energy density and high-power density being the most important ones. High specific power is required to give the motors great push thus increase acceleration and high energy density is required for long driving range. There are several other characteristics that have to be sort after to make a reliable power source such as fast charging, large cycle count, and long service. A lot of research goes into finding the right energy storage system (ESS) with desirable characteristics. Modern EV's are a combination of 2 or more. Energy-storage system are the devices which stores the electric-charge required to make the motor run and can be categorized as discussed below:

5.1.1 Battery

Batteries are fundamentally an energy storage device which provides energy for the population of electric vehicles. Batteries are composed of two electrodes dipped in an electrolyte, the electrolyte acts as a medium for exchange of ions between electrodes to produce electric charge. Batteries have been used in vehicles since the early days, earlier the batteries were known as auxiliary batteries which provided energy to start the engine or for vehicle internal electronics.

But with the development of high energy capacity traction batteries, we are able to power the entire vehicle movement in conjunction with electric motors. The first battery to be developed was **Lead-Acid battery** by Gaston Plante in 1859. After 40 years of research, Nickle-Cadmium battery was developed in 1899 by Waldemar Jungner. Ni-Cd batteries made significant improvement in terms of storage capacity but were backed down due to its disadvantages including a voltage suppression issue that occurred as the battery ages, known as the memory effect.

After the Lead-acid and Ni-Cd battery, the research continues throughout the 20th century to find the best suitable battery for EV. It was in 1985 when the first Lithium-ion battery was developed and powers most of the EV's today. Later ZEBRA batteries and Nickel-Metal Hydride batteries were developed. Researchers are still in search of new and better battery composition to attain the desired performance goals. Some of the prominent batteries types once used or are in current development state are lead-acid, Ni-Cd, Ni-Zn, Zn/air, Ni-MH, Na/S, Li-polymer and Li-ion batteries. In this section, only the LI-ion battery will be discussed and compared to other alternative batteries available. As most of the EV's today run on Li-ion battery it is very important to understand the chemistry of the battery, cost and lithium deposits in the world. Through the means of the figure 19 it can also be seen that most modern EV's uses Li-ion batteries of different capacity and power.

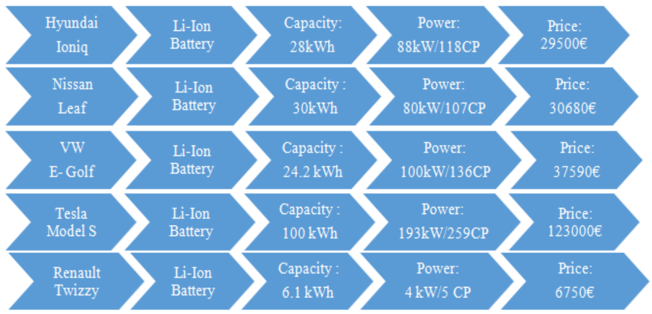


Figure 19: Comparative evaluation of different electric vehicles in market [13]

5.1.2 Lithium-Ion Battery Composition and Construction

In Li-ion batteries, the charge carriers are the lithium ions. In lithium-ion battery family, there are many different cell chemistries available and more are to be developed in future. The negative electrode of Li-ion batteries is principally composed of carbon (e.g. Graphite) or lithium titanite ($Li_4Ti_5O_{12}$) and some other novel materials are under development such as Li metal and Li (Si) [14]. The electrodes are immersed into an electrolyte medium which are typically composed of a mixture of lithium salts (e.g. LiPF6) and an organic solvent (e.g. diethyl carbonate) to allow for charge transfer [14].

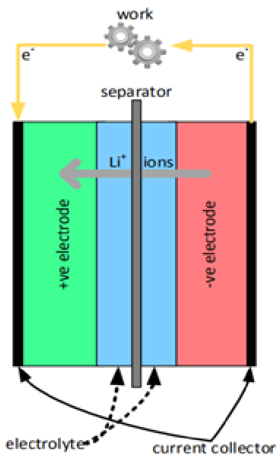


Figure 20: Construction of Li-ion Battery Cell [15]

The arrangement of Li-ion battery is shown pictorially in figure 20 which illustrates the ion flow in the battery when operating as an energy source (i.e. aa a galvanic device)—when the batteries are used to supply electric current than the electrons travels from negative electrode to the positive one and simultaneously the Li+ ions travel to the positive electrode through the electrolyte so that electro neutrality is maintained. During the charge mode i.e. when batteries act as electrolytic device or accept charge the flow of electrons and Li+ ions are reversed [14]. Through figure 21 a comparison of Li-ion batteries with other types of batteries is given on a plot of energy density VS weight. It simply shows that why the Li-ion batteries are the top priority of EV manufacture as the primary energy-storage device in modern electric vehicles.

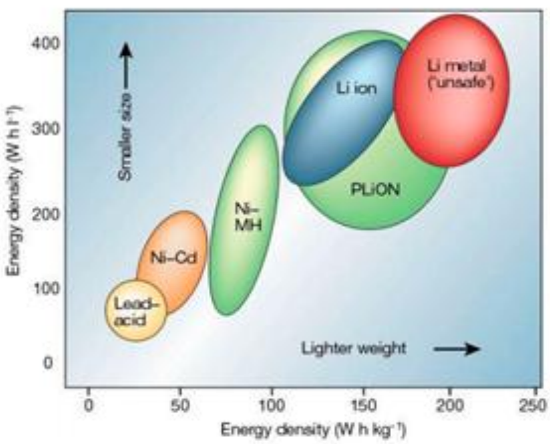


Figure 21: Range plot of EVs equipped with different composition of batteries [14]

The Li-ion battery family as of now consists of many practically applicable compositions which are Lithium Titanium Oxide (LTO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Manganese Oxide (LMO）, Lithium Cobalt oxide ($LiCoO_2$), and Lithium Iron Phosphate (LFP) [15].

Batteries for the EV are usually selected on the basis of specific parameters. Parameters on which batteries are compared are battery specific energy, specific power, energy density, weight and size. A comparison of different batteries on the basis of different parameters is shown in table 2.

5.1.3 Conclusion on Selection of Batteries:

Referring to table 2, it can be concluded that $Na\text{-}NiCl_2$ batteries have a better energy consumption rate (12.6 kWh/100km) as compared to other batteries. $Na\text{-}NiCl_2$ batteries are also important due to it's advantages such as low cost, high number of lifecycles and better functioning under harsh conditions. One major drawback of this technology is that these batteries tend to heat-up, which causes the battery electrolyte to solidify when the vehicle is not in use. So, in this case additional costing of cooling and heat management system is required which maintains the temperature and prevents failure.

According to studies, Li-S batteries are the one with highest energy consumption (17.2 kWh/100km) and are most suitable for high energy storage systems. Mi-MH batteries have intermittent properties and are considered outdated as well. In the recent development Li-Ion batteries have acquired the position of the most popularly used batteries for EV application due to its continuously declining cost, moderate energy consumption (14.7 kWh/100km), advance manufacturing technique, increased life cycle, light weight and high energy storage as well as driving range make them most suitable for EV application today.

Table 2: Comparing Lead-acid, Ni-MH, ZEBRA and Li-ion.

Battery type	Specific Energy (Wh/Kg)	Energy Density (W/Kg)	Mass of battery for EV to run a 100Km with 20 Wh/100km	Specific power (W/Kg)
Lead-acid	35-40	80-90	500-600 kg	285
Ni-MH	50-60	100-140	300-400 kg	200
ZEBRA ($Na\text{-}NiCl_2$)	100	160	200 kg	170
Li-ion	150-200	250-400	100-140 kg	260

5.1.4. Construction of Battery

The Battery packs used in electric vehicles consists of numerous battery cells connected in series. For example, in

Tesla model S has 7104 Li-ion cells which make a total of 85KWh battery pack. The cells used to make the battery module can be in different form and shape. The different form of battery cell used in EV is depicted in figure 22 and the cooling arrangement is shown in figure 23.

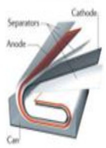
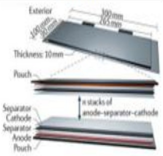
Shape	Cylindrical	Prismatic	Pouch
Diagram			
Electrode Arrangement	Wound	Wound	Stacked
Mechanical Strength	++	+	–
Heat Management	–	+	+
Specific Energy	+	+	++
Energy Density	+	++	+

Figure 22: Cell designs and Relative Strengths and Weaknesses [13]

All battery modules in EV consist of the battery module, battery management system and the cooling system. The Li-ion batteries used in EV today tend to overheat with use and are prone to failure which may lead to fires. The battery module provides protection to the batteries, manage batteries efficiently and safely. A cooling system is needed to make sure that the batteries operate at an optimum temperature range and provide consistent power output without the fear of fire breakouts due to high-temperature.

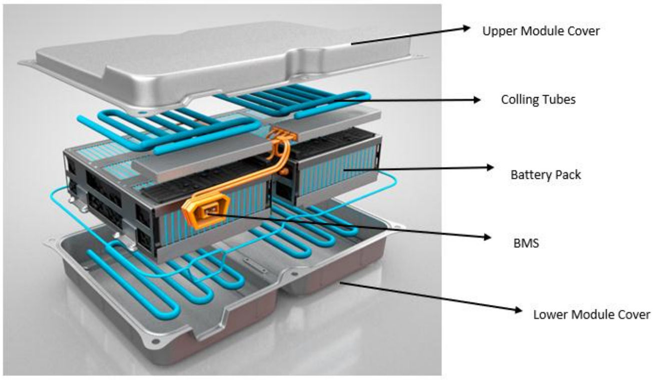


Figure 23: Arrangement of battery cells in the battery module. Special cooling tube are used to dissipate heat generated by the batteries [16]

Figure 24 shows the layout of the battery with the arrangement of the cooling tubes, cooling pads and upper-lower module cover. The design of battery modules placed in the vehicle has undergone significant development in the last 2-3 decades. Battery-module consists of many singular battery-cells to provide the required power output and takes a lot of space so, a proper layout is to be made to ensure better weight-distribution and thermal management in the electric vehicles. Through the figure 24 it can be observed that the how the battery module is designed and arranged on the vehicle chassis. The figure 24 shows the chassis design of the upcoming Jaguar I-Pace. [33]

Figure 24: Chassis Design of the Electric-Vehicle [33]

5.1.5 Super Capacitors

The next category of the Energy Storage System (ESS) is Supercapacitors also referred to as Ultracapacitors (Electrochemical Capacitors). These electronic devices behave like a high-capacity capacitor with a capacitance value much higher than other capacitors. They have lower voltage limits that bridge the gap between electronic capacitors and rechargeable batteries. It can store about 10 to 100 times more energy per unit volume or mass than electrolytic capacitors. These electronic devices can accept and deliver charge at a much faster rate as compared to batteries and can tolerate many more charge and discharge cycles than rechargeable batteries.

Supercapacitors have gained a lot of application in the EV industry requiring many rapid charge/discharges cycle, rather than long term compact energy storage. Ultracapacitors comprises of two electrodes separated by an ion-enriched dielectric liquid. When a potential is applied across the UCS, the negative ions are attracted by the positive electrode and the negative electrode gathers the positive ions. In this way the charge gets stored on the electrodes and provide a considerably high-power density.

During the process there is no chemical reaction involved at the electrode, this way they tend to have long cycle life but also makes them low in energy density [9]. Super-capacitors have low internal resistance which makes it highly efficient, but also causes high output current when charged at extremely low SOC. The basic construction of an ultracapacitor is shown in figure 25.

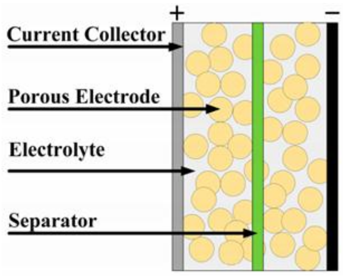


Figure 25: Construction of an Ultracapacitor [9]

While designing the power train of an EV the engineers have to take consideration of vehicle performance and energy storage requirements. From the above statement, we can apply that, a battery-based ESS has several challenges providing the impetus to look for additional solutions. While using battery-based ESS's high power density is required to meet the peak power demand. Although batteries with higher power densities are available, they are highly-priced as compared to the lower power density counterparts. So, to get high power density from the batteries we need to increase their size. However, this also causes an increase in cost. In addition to these issues, applications that require instantaneous power input and output typically find batteries suffering from frequent charge and discharge operations, which have an adverse effect on battery life.

In order to solve the problems listed above researchers have come up with an idea to combine a high-power density, but a lower energy density capacitor to the existing battery energy storage system to improve the efficiency. UC's are good options to compensate for the high peak of usage during short periods of time when the battery power is not sufficient. The combination of the battery-SC is known as a hybrid energy storage system (HESS). The basic idea of a HESS is to combine ultracapacitors (UCS) and batteries to achieve better overall performance [22]. Table no. 4 shows the typical characteristic of ultracapacitor cells compared to that of Li-ion battery.

Table 3: Comparison of Characteristics of UC and Li-ion Battery [22]

Chemistry	Nominal Cell Voltage (Volt)	Energy Density (Wh/kg)	Power Density (kWh/Kg)	Cycle Life (times)
UC	2.5/2.7	2-30	4-10	Over 1,000,000
Li-ion	3.6	250-400	150-180	Below 50,000

With the research and development in the field of energy storage systems (ESS), there are categories of ultracapacitor developed on the basis of chemical and physical composition of the energy storage mechanisms, active electrode material, cell characteristics, and their performance potentials (energy density, power density, etc.).

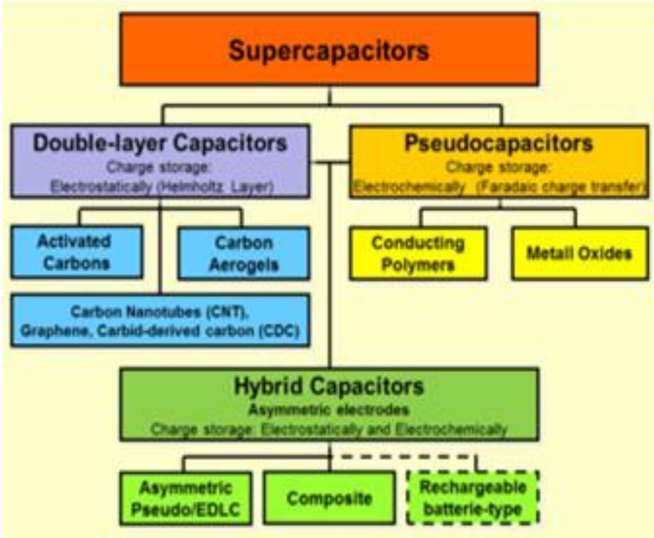


Figure 26: The Hierarchical Classification of Supercapacitors and Capacitors [19]

Through figure 26, it can be observed that modern age super-capacitors are divided into three major categories that will be discussed in detail below. These super-capacitors are divided into different categories on the basis of their cell structure and chemical formulation.

i. Double-Layer Capacitors (Carbon/Carbon) [21]

Most of the electrochemical capacitors currently available in the market are termed as electric double-layer capacitors (EDLC). The charge separation in a microscopically thin layer formed between a solid, conducting surface and liquid electrolyte results in energy storage in double-layer capacitors. The dominant electrode material is microporous, activated carbon [12,13]. The double-layer is formed in the microspores of the high surface area carbon material. Either an aqueous or organic electrolyte can be used.

ii. Pseudo-Capacitors [19]

These type of electrochemical capacitors uses metal oxides or conducting polymer electrodes with a high amount of electrochemical pseudo capacitance additional to the double-layer capacitance. Pseudo capacitance is a result of Faradaic electron charge-transfer with redox reaction, intercalation or electron sorption.

iii. Hybrid Capacitors [19]

Hybrid capacitors are usually a mixture of electrodes with differing characteristics, one exhibiting mostly electrostatic capacitance and other one electrochemical capacitance. Hybrid capacitors available are Lithium-ion capacitors

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5.1.6 Regenerative Braking

After so many years of research and development, it has been recognized that combining ultra-capacitors with batteries would drastically reduce the stress on the batteries in electric vehicles application in which the batteries are subjected to high current pulses in both charge and discharge.

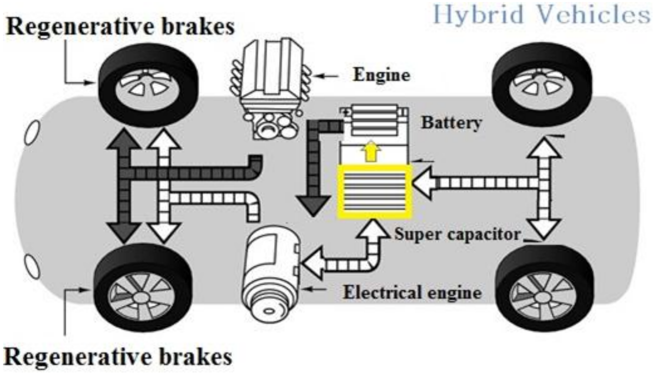

Figure 27: Arrangement of Supercapacitor in EVs [23]

From the arrangement shown in the figure 27, it is clear that the ultracapacitors have become an integral part of the EV powertrain. Many countries with less of lithium deposits have invested heavily in the development of UCs for their electric vehicles (E.g.: INDIA). The properties of UCs of getting charged and discharged quickly have significantly increased the life of the Li-ion batteries. The **figure 34** also shows the regenerative braking process in which the energy can be obtained by the backflow of current from the motor while braking and can be stored into the capacitors. The regeneration process would not have been possible without the supercapacitors property of getting recharged in 5-10 seconds.

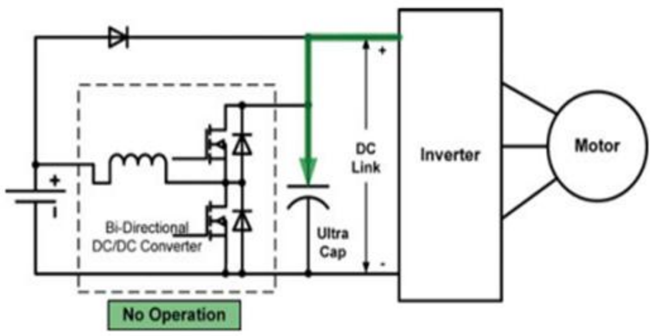

Figure 28: Flow of Current during Regenerative Process [21]

Due to recent research and development, we have been able to collect the energy produced while braking. This is called regenerative braking. Super or Ultra-capacitors play a very important role in regenerative-braking as they charge very quickly and also releases the charge a faster rate than typical batteries.

UCs can have a very large no. of charge and discharge cycles as compared to batteries so they are most suitable to charge through the small amount of energy produces while braking and supply this energy to the motors when battery power is not sufficient, like while heavy acceleration or in traffic.

5.2 Traction Motors

The next important parts in all-electric vehicles are the motors, because if the efficiency and the performance of motors are not satisfactory then the development in energy sources is of no use. The motor converts the electrical energy received from the power source into tractive motion which makes the vehicle move; same as that when fuel is burnt in the IC engine the engine converts thermal energy to mechanical motion. Motors also act as a generator during the regenerative braking process and send energy back to the energy source [10]. The selection of Tractive motor drive for an EV mainly considers the efficiency, reliability and cost of motors.

From a commercial point of view, the electric motors adopted or under serious consideration for electric vehicles includes the DC Motor, Induction Motor (IM), the Permanent Magnet (PM), Synchronous Motor, and the Switched Reluctance Motor(SRM). These five major types of tractive motors are considered best for EV application. Figure 29 and 30 show the different classification of DC and AC tractive motors for EV and HEV application.

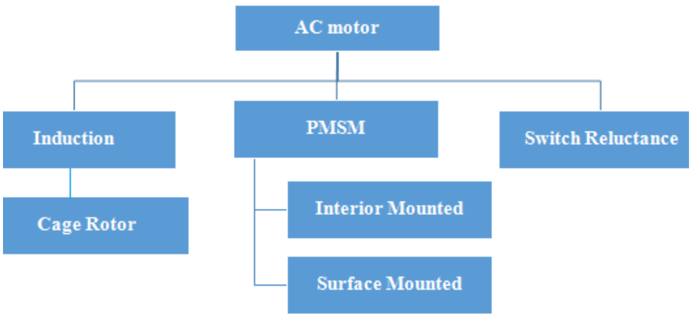

Figure 29: Classification of DC Motors [25]

In this section, the major five types of tractive motors will be discussed and compared on their characteristics and the most suitable for EV & HEV application is determined. All tractive motors can be classified into 2 types either AC or DC. Both the motors differ from each other in terms of working principle and construction.

However, AC motor drive has some clear advantages over DC motor drive such as higher efficiency, higher power density, effective regenerative braking, robustness, reliability and less need of maintenance

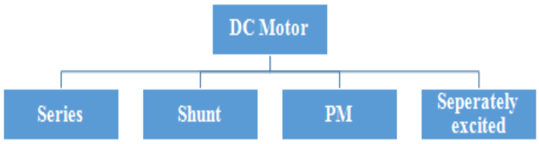

Figure 30: Classification of AC Motors [25]

In figure 31 the cross-sections of different electric motors for use in traction motors is shown.

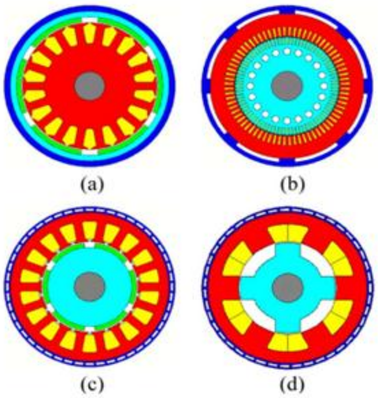

Figure 31: Cross section view of main traction motors used in EV a) DC motor. (b) IM (c) PM brushless motor. (d) SRM [25]

Through further discussion, explanation about different traction motors used in EVs today is concluded giving the advantages and disadvantages of each motor and deciding the most suitable for EVs today. Also, some highlights on their performance are given.

5.2.1 DC Motors

A DC motor is a class of rotary electrical motors that converts direct current electrical energy into the tractive effort. The most common type relies on the forces produced by the magnetic field. DC motors have been prominent in EV propulsion systems because of their torque-speed characteristics, simple design and their speed control is simple.

On the contrary, dc motor drives have a bulky construction, low efficiency, low reliability, and higher need of maintenance, mainly due to the presence of the mechanical commutator (brush and rings) [25]. After the growth of vector control for AC motors (synchronous and induction), the DC motors' attraction in traction applications diminished [24]. Nowadays DC motors are used for low power applications.

5.2.2 Induction Motors

An induction motor or asynchronous motor is an AC motor which produces electromagnetic induction from the magnetic flux of the stator winding to get the required current within the rotor to produce the tractive torque [27].

An Induction motor is of two types: wound type and squirrel-cage type. These are famously known as "Tesla motor". For EV traction motor application Squirrel-cage AC motors are quite desirable due to their reliability, robustness, less maintenance and the ability to work in a hostile environment. IM has become much mature in terms of technology than other AC motors in recent years. In induction motors, torque and field control can be decoupled using vector control methods and speed range can be extended using flux weakening in the constant power region.

The typical characteristics of an induction motor are shown in Figure 32.

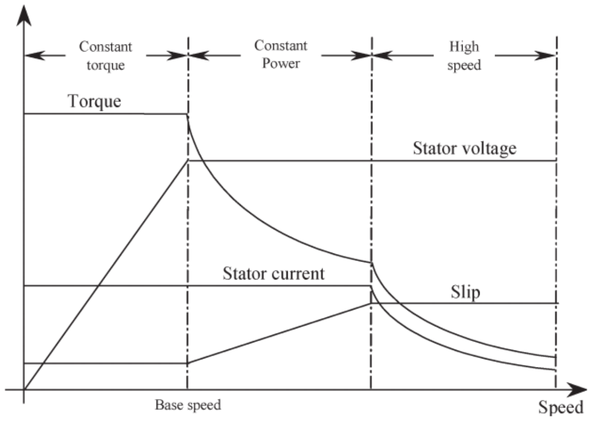

Figure 32: Characteristics of induction motor [24]

Induction motors also have some shortcomings which continue our search for more reliable and efficient traction motors for EV application. These drawbacks are mainly high loss, low efficiency, low power factor, and low inverter-usage factor, which become more significant for the high speed, large power motor. [25]

5.2.3 Permanent Magnet Synchronous (PMS) Motor

The Permanent magnet synchronous (PMS) motor is also known as brushless AC motor (BLAC). These motors are the most serious competitor to the induction motor in traction application in EVs. Many car manufacturers have already used these motors in their EVs as shown in the table below. These motors have several advantages: higher power density, higher efficiency and the more effective distribution of heat into the environment [24]. However, these motors have a narrow constant power region and to widen the speed range without over sizing the motor, conduction angle of power convertor is used in traction application of the motor. Figure 39 shows the characteristics of the BLAC motor with & without conduction angle control. With the use of conduction angle control speed range of BLAC can be extended to three or four times the base speed.

The conduction angle control is done by multiphase pole-changing IM drive. However, the shortcoming of the motor is that they tend to demagnetize due to the heart or armature reaction so a lot of attention has to be paid while designing the cooling and motor control system

5.2.4. Switched Reluctance Motor (SRM)

SRM motors have been developed as a good traction motor for EV application in last years. The development of SR motors has some advantages over other type of traction motors that are: simple & rigid construction, fault tolerance, simple control and excellent torque-speed characteristics.

However, there are some disadvantages too such as high noise, high torque ripple, special convertor topology and electromagnetic interference.

5.2.5 Brushless DC motor (BLDC)

This type of motor is conceptually the result of reversing the stator and the rotor of permanent magnet DC motor. BLDC are fed by rectangular waves in contrast to BLAC motors which are fed by sinusoidal waves. In these motors the stator are made up of permanent magnets (PM) and the rotors have brushes Their main advantages are the deletion of the brushes, their compactness, high efficiency and high energy density. However, the disadvantage overshadows the advantages due to which this motor has lost its application in the EV industry. The major drawbacks to this motor are its bulky structure, low efficiency, high heat generation because of the brushes. The heat produced is difficult to remove as it is generated in the center of the rotor and there is associated loss in efficiency with increasing temperature.

Table 4: Comparison of all Motors [10]

Motor Type	Advantage	Disadvantage	Vehicles Used In
Brushed DC Motor	• Maximum Torque at low speed	• Bulky structure • Low efficiency • Heat generation at brushes	Fiat Panda Elettra (Series DC Motor), Conceptor G-Van (Separately excited DC Motor)
Permanent Magnet Brushless DC Motor (BLDC)	• No rotor copper loss • More efficiency than induction motors • Lighter and smaller • Better heat dissipation • More specific power • More torque density	• Short Constant Power • Decreased torque with increase in speed • High cost because of PM	Toyota Prius (2005)
Permanent Magnet Synchronous Motor (PMSM)	• Operable in different speed ranges without using gear systems • Efficient and compact • Suitable for in-wheel applications • High torque even at very low speed	• Huge iron loss at high speeds during in-wheel operation	Toyota Prius, Nissan Leaf, Soul EV
Induction Motor (IM)	• The most mature commutator less motor drive system • Can be operated like a separately excited DC motor by employing field orientation control		Tesla Model S, Tesla Model X, Toyota RA V4, GM EV1
Switched Reluctance Motor (SRM) **Synchronous Reluctance Motor**	• Simple and robust construction • Low cost and High speed • Less chance to hazard • Long constant power range • High power density • Robust and Fault tolerant • Small and Efficient	• Very noisy • Low efficiency • Larger and heavier than PM machines • Complex design and control • Problems in controllability and manufacturing • Low power factor	Chloride Lucas

5.3 Power Convertors in EV's

In electric vehicles the energy storage system/devices (ESS) as discussed above, stores and supply electricity for the functioning of the electric vehicles. The system usually consists of battery and ultracapacitors (UC) only and both these electric devices stores energy as a DC charge. All-electric vehicles have to be charged before use and this charge is obtained by EV chargers which supply AC current to the vehicle's ESS. So, to store the charge in DC device AC charge has to be converted to DC charge and this is done by the converter (AC/DC).

When the ESS is fully or partially charge and power has to supplied to motors for propulsion from the batteries. Modern motors are AC charge type as discussed in the last section, so the charge from batteries i.e. DC has to be converted to AC again which is done by **Invertors (DC/AC).** Figure 33 shows the typical placement of different power convertors in EV with the energy flow direction.

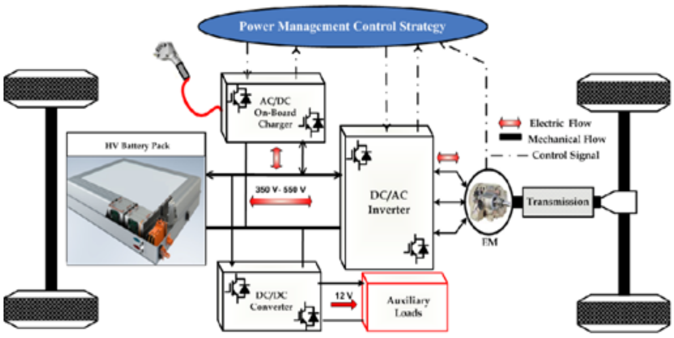

Figure 33: Power Conversion in Electric Vehicles [28]

As seen in the above figure all the arrangement of converters DC/AC or AC/DC is required to recharge the energy storage of EVs and then use it to propel the vehicles. In the above figure, it shows an AC/DC converter at the charging point which converts AC charge from power-grid to store DC charge in batteries. Then a DC/DC converter is shown for auxiliary loads which include the power required for electronics inside the vehicle like heater/AC or lightning inside the vehicle. Different auxiliary devices work at different DC voltages but battery supplies a rated DC voltage at all charge, so a DC/DC converter can be used to interface the elements in the electric powertrain by boosting or chopping the voltage levels [28]. Finally, a DC/AC inverter is shown in the figure which converts the DC charge from the battery to AC charge for the working of the motors. These converters are linked to a DC link to work as bi-directional converter while recharging the batteries or UC during the regeneration process. A simplified arrangement of convertor and invertors in EVs is shown in figure 33.

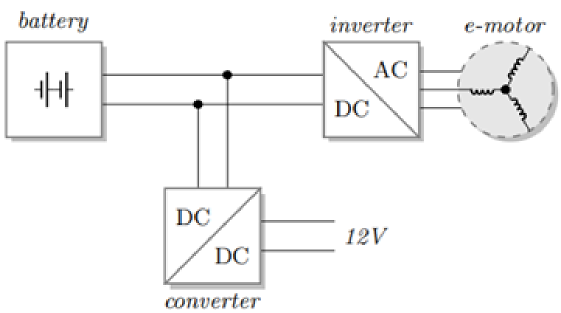

Figure 33a: Illustration of a Basic Electric Power Train of a Full Electric Vehicle [29]

6. HYDROGEN POWERED VEHICLES

The use of hydrogen as a mean to power our vehicles has attained the attention of many researchers and auto manufacturers as clean & more efficient energy source for our vehicles. The development of Hydrogen-powered vehicles is still in its infancy and no major applications of the Fuel cell technology have been made but, this fact only justifies the limitation of current times for the use of hydrogen in our vehicles. However, Hydrogen fuel cell technology has a very upscale potential to be used as fuel in our vehicles in the very near future [33]. The major interest of the use of hydrogen in vehicles is due to higher efficiency than IC engine, high part-load capacity, no tailpipe emission (only water vapors), quite running, higher driving range (over 500km) and faster refueling. In the year 2002, the Bush Administration along with industry-government cooperation announced the "Freedom CAR" initiative, to develop a fuel cell vehicle. [32]

Through this initiative, the use of Hydrogen to power our vehicles was started either as direct injectable fuel to IC engines or as a fuel cell to power motors in EVs replacing batteries. A comparison between all category of green vehicles is done in table. 6.

Table 5: Comparison between HEV, EV and Fuel Cell Vehicles [31]

Hybrid	**Substantial (100-200%)**	**Some zero-Emission range possible**	**Near term (2-7 y)**	**Substantial**	**Grade climbing ability or towing capacity may be reduced**
Fuel Cell	Very High (150-300%)	Low to zero tailpipe and total	Mid term (7-12 y)	Very high (>20%)	Potential petroleum independence
Battery-Electric	Very High (300%)	Zero tailpipe	Near term (2-7 y)	Very high (>20%)	Energy storage, range concerns, low petroleum use
Vehicle system	Fuel Economy Improvement Potential	Criteria Emissions	Years to mass Market introduction	Current Incremental Cost	Other Issues

As part of electric vehicle research, this section will be dedicated to the hydrogen fuel cell technology to replace the battery in BEV. The Fuel cells the most crucial part of hydrogen-electric vehicles. Hydrogen used in fuel-cells act as a energy carrier that can be produced from low-carbon source and has high specific energy as compared to most batteries. The first mass-produced fuel-cell electric vehicles (FCEVs), which use polymer electrolyte membrane (PEM) fuel cells, were introduced in 2013–2014 by Hyundai, Toyota and Daimler [31].

6.1. Fuel Cells

Fuel cells are the powerhouse for future electric vehicles. Fuel cells generate electricity by electrochemical reaction. A fuel cell consists of a negative electrode (ANODE), a positive electrode (Cathode) and the electrolyte between them.

The Hydrogen is stored in an onboard tank and supplied to the anode where it gets oxidized. The ions created to travel through the electrolyte to the cathode and combine with the other reactant introduced [34]. The creation of ions as the product of oxidization of hydrogen at anode produces electricity.

Hydrogen is preferred as fuel for FCs due to its high energy content and does not produce pollution (produces only water on combustion) and is abundantly available in nature in the form of different compounds such as hydrocarbons.

The chemical reaction inside a Fuel-cell is stated below: [34]

$$2H_2 + O_2 = 2\ H_20$$

The figure 34 shows the working principle of a fuel cell in which fuel and oxygen are taken in, the exhaust of oxidized hydrogen (H2O) and electricity produced as the product of the chemical reaction is shown. Figure 35 shows the construction of fuel cell.

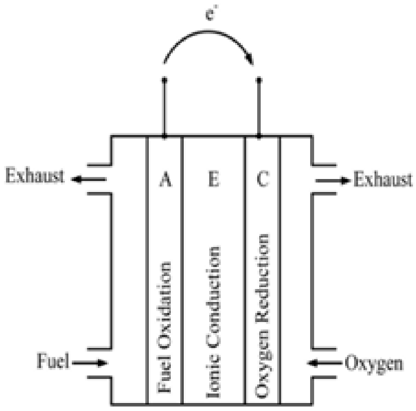

Figure 34: Working Principle of Fuel Cell [10]

Fuel cell application in EV has many advantages from producing electricity efficiently from fuel, noiseless operation, faster refueling, minimal emissions, durability and the ability to provide high density current output. A major drawback of this technology is its high price and as hydrogen has lower energy density compared to petroleum derived fuel. Therefore, larger fuel tanks are required for FCEVs to store large quantities of hydrogen fuel. So, additional cost goes into making larger tanks and also to make them capable enough to contain large amount of hydrogen fuel without the risk of any explosion in case of an accident.

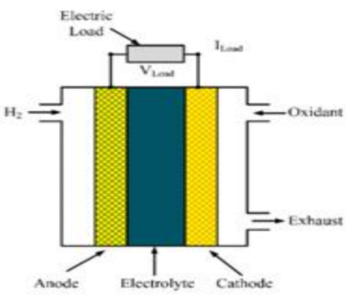

Figure 35: Fuel Cell Configuration [10]

Today hydrogen production is very expensive and less efficiency is transferred to from well-to-wheel pathway. The below give figures shows the entire pathway for energy transfer for battery and hydrogen powered vehicles. For battery energy the entire pathway is 77% efficient. Whereas for FCV's, the energy from the electric plant is used for the electrolysis process to produce hydrogen gas from water.

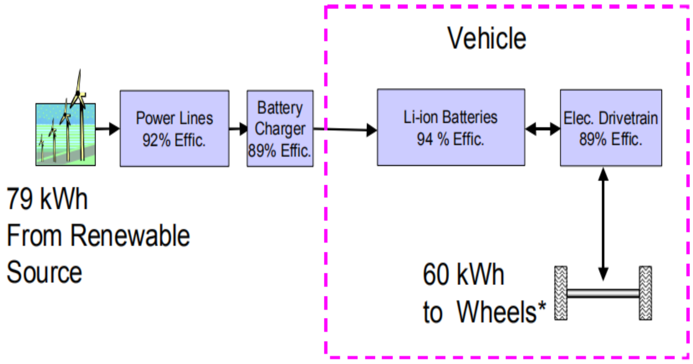

Figure 36: Well-to-Wheel Energy Pathway for Battery Electric Vehicle. [32]

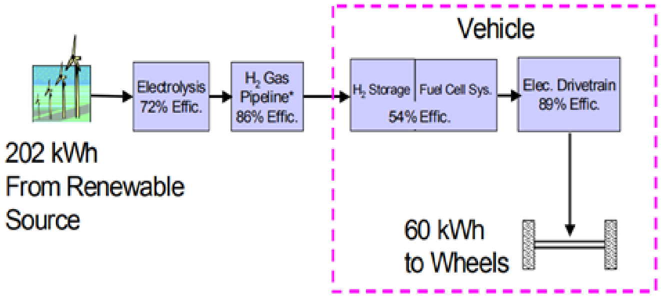

Figure 37: Well-to-Wheel Energy Pathway for Fuel Cell Vehicle [32]

As concluded from the above figure 36 and figure 37, a lot of energy goes into production and use of hydrogen as a fuel for fuel cell vehicle and a major amount of this energy is produced with fossil fuels which put severe stress on Power Grid.

- FCEVs have higher purchase prices than conventional vehicles, and similarly to BEVs, this is attributed to their electrochemical power supply. The hydrogen storage tank and fuel-cell system are the most expensive components because of the inclusion of expensive materials and equipment such as platinum, carbon fibre, humidifiers and heat exchangers. The cost of nearly all these components will decline considerably with increased manufacturing volumes, with the main exception being platinum-group metal (PGM) catalysts owing to their scarcity. [30].

7. CONCLUSION AND FUTURE DEVELOPMENT

Even though a lot of development and revolution has been made in terms of Green transportation and it has been presented through this paper, but there is a lot to do in future to make these Vehicles feasible and economically viable. The paper presents an overview of the Technological roadmap of the technologies from the earliest to the recently developed technology for EV's. Detailed analysis of different Electric Vehicles is performed to know the advantages and disadvantages of each type- HEV, BEV, FCEV. A study on different components that makes EV run is laid out with the earliest and recent development in them—Batteries, Motors, Power convertors and Super capacitors. Through the study, it was concluded that Li-ion battery and Permanent brushless AC motor are the most attractive ones for future application In EV's considering their price and energy density. Different Power-train configuration for Hybrid as well as for pure electric vehicle was studied with proper emphasis on energy flow and energy management systems. Lastly, a discussion on Fuel-cell Electric is presented to make the basics for future development, as this technology will most probably run our vehicles in future with zero emissions and very less cost. Furthermore, this paper provides with basic analysis and information for future research in the Electric Vehicle domain.

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