Chapter 15
Energy Sources for Electric Vehicles

Irfan Ahmed, Aashish Kumar Bohre, Tushar Kanti Bera, and Aniruddha Bhattacharya

Abstract The tremendous increase in pollution levels caused by automobiles energized through fossil fuels as well as the eventual depletion of these fuels has led to an increase in the interest for electric and hybrid electric vehicles. Electric vehicles (EVs) provide cleaner means of transportation with the pollution being limited to the locations of electric power generating plants. They are the vehicles of the future, without any doubt. There has been a tremendous amount of research in EV technology in recent times, and a lot of research has reached mature levels. The only impediment to the complete commercial use of EVs is the energy sources required to power them. In this chapter, we take a look at the conventional sources of energy for EVs, their current status and developments, as well as technologies to look out for in the future. The focus is on the basic working principles of these sources without delving too much into their chemical reactions.

Keywords Battery energy sources · Fuel cells · Ultracapacitors · Ultrahigh-speed flywheels

Nomenclature

EV	Electric Vehicle
NiCd	Nickel–cadmium

I. Ahmed (✉) · A. K. Bohre · T. K. Bera · A. Bhattacharya
National Institute of Technology Durgapur, Durgapur, India
e-mail: ahmed.irfan@ee.nitdgp.ac.in

A. K. Bohre
e-mail: aashishkumar.bohre@ee.nitdgp.ac.in

T. K. Bera
e-mail: tusharkanti.bera@ee.nitdgp.ac.in

A. Bhattacharya
e-mail: aniruddha.bhattacharya@ee.nitdgp.ac.in

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Li-ion	Lithium-ion
NaS	Sodium–sulfur
SoC	State of Charge
DoD	Depth of Discharge
PEM	Proton Exchange Membrane
PAFC	Phosphoric Acid Fuel Cell
SOFC	Solid Oxide Fuel Cell
HEV	Hybrid Electric Vehicle
NiMH	Nickel-metal-hydride
Li-poly	Lithium-polymer
Zn-Air	Zinc-air
SoD	State of Discharge
AFC	Alkaline Fuel Cell
DMFC	Direct Methanol Fuel Cell
MCFC	Molten Carbonate Fuel Cell

15.1 Introduction

One of the prominent features of an electric vehicle (EV) is that it has a portable energy source, which may be chemical or electromechanical in nature. Portable source implies that the energy source must be able to move with the vehicle. There are some exceptions to this rule, such as in the case of electric trains and electric trams. However, in general, the energy source must be portable and implanted inside the vehicle. Examples of chemical sources include batteries and fuel cells; while those of electromechanical sources include flywheels or the motor itself acting as a generator during regenerative braking.

Out of the number of sources that are available, only the battery energy source technology is mature enough to find commercial applications in EVs. The other sources such as fuel cells, ultracapacitors and flywheels, while not yet in commercial use, exhibit potential for the future. This chapter attempts to provide an overview of all these energy sources that can be used as portable sources for EVs, their basic working and current status.

15.2 Battery

The chemical battery is the only energy storage technology mature enough to be used commercially in EV applications. The batteries used for EVs are usually rechargeable (secondary). Earlier lead-acid batteries were mostly employed, but with improvements in technology, the lithium-ion battery is now more commonly used; although this may change in the future as well on account of ongoing research (Iclodean et al.

2017). The different battery technologies do share the same basic working principle and this is where we shall start with.

15.2.1 Battery Basics

Electric as well as hybrid electric vehicles use high-voltage battery packs. Each battery pack consists of individual modules and cells connected in series and/or parallel. Series connection is required to increase the battery pack voltage rating, whereas parallel connection is required to increase the current handling capacity of the pack. A cell is the smallest packaged form that a battery can take. Generally, it is of the order of 1 to 6 V. A single cell is not sufficient for our requirement, so a number of cells are connected in series and/or parallel to form a module. A number of modules connected together form a battery pack.

A battery is a device that stores energy in chemical form and converts it into electrical energy when required. Chemical reactions take place in a battery and involve the flow of electrons from one material to another. These materials are called electrodes. The electrons will flow through an external circuit. This flow of electrons can be utilized to do some useful work. In other words, the flow of electrons is providing an electric current that can be used to do useful work. To balance the electric charge, there has to be a flow of ions also. The electrons flow through conducting wires (external circuit), whereas charged ions flow in the opposite direction inside the battery through an electrolyte. Different combinations of electrodes and electrolytes produce different chemical reactions that determine the working of each battery type, the amount of specific energy that can be stored in the battery, as well as its voltage rating.

The first battery in the world was produced by Alessandro Volta, an Italian physicist, chemist and one of the pioneers of electricity (Britannica 2021). One of Volta's friends, Luigi Galvani, performed an experiment with a frog in which he had tied the frog's legs to a metal. When Galvani touched the frog's legs with an electrode, the legs twitched. This led Galvani to conclude that there was electricity inside the frog. However, Volta did not believe this. He repeated Galvani's experiment, but instead of using the frog, he used metals as electrodes separated by an electrolyte (brine-soaked paper), and proved that the electricity was coming from the electrodes and not from the frog. This is how the first battery was produced. Till today, the same concept that Volta introduced is being used to produce the batteries. The materials have changed, battery sizes and battery technology have improved, but the basic principle still remains the same.

In summary, the essential components of each battery cell are two electrodes (one positive and one negative) and an electrolyte in contact with both the electrodes. Current will flow between the two electrodes only when there is an external connection between the two electrodes; otherwise, ideally, no current will flow between the two electrodes. The functions of the electrolyte are to provide a path for the flow of electric ions and to provide chemical reactions between the electrodes and the electrolyte which result in the production and consumption of electrons and hence to an electric current. The electrolyte should be such that it should allow the flow of ions but not the flow of electrons (Hussain 2003; Chan and Chau 2001; Mi et al. 2011). The essential battery components are described in further detail below.

15.2.1.1 Electrodes

To produce a flow of electrons, we need to have a source material where the electrons are produced, and a destination material where the electrons are consumed (How a battery works, nd). These materials are called the cell's electrodes. The electrons are produced through chemical reactions at the electrode called the anode or negative electrode, and are again consumed through chemical reactions at the cathode or positive electrode. The battery terminology uses the anode notation for the negative electrode or the electrode at which electrons are produced, whereas the positive electrode or the electrode at which electrons are consumed is called the cathode. The electrodes are generally different types of metals or other chemical compounds. The anode material should be such that a chemical reaction between the anode and the electrolyte should produce electrons. These electrons get accumulated at the anode and should not be able to flow to the cathode unless there is an electrical connection between the anode and the cathode. On the other hand, the cathode material should be such that a chemical reaction between the cathode and the electrolyte must be able to absorb/accept electrons received from the anode. The electrons flow should only be through an external connection between the anode and the cathode; no flow of electrons should be possible through the electrolyte.

The technical chemical term for a reaction that involves an exchange of electrons is a reduction–oxidation reaction, more commonly called a redox reaction. So electricity is generated in a chemical cell because of a redox reaction. This redox reaction can be separated into two half-reactions. In the case of an electrochemical cell, one half-reaction occurs at the anode and the other half-reaction occurs at the cathode. Reduction is the gain of electrons, and is what occurs at the cathode. At the cathode, electrons are being accepted because of a chemical reaction. The cathode is gaining electrons, and this process of gaining of electrons is called as reduction; we say that the cathode is reduced during the reaction. Oxidation is the loss of electrons. We say that the anode is oxidized; the anode is giving up electrons. The electrode materials should be such that they should interact chemically with the electrolyte to facilitate the redox reaction.

15.2.1.2 Electrolyte

The earlier electrolytes used were predominantly liquids, but now we also have gels and solid substances being used as electrolytes (Li et al. 2016). The only condition is that they must be able to allow the movement of charged ions, while not allowing the flow of electrons through them. In other words, the electrolyte should be such that it has high and selective conductivity for ions that take part in the electrode chemical reactions, but it should be a non-conductor for electrons. They should also be able to react with the materials of the anode and cathode in order to aid in the redox reaction. Ideally, the electrolyte will not allow the flow of electrons, but in practice some electrons will be able to flow through the electrolyte. That is why, even when we are not using the battery, it will self-discharge. The amount of self-discharge depends on the type of battery being used. Some batteries discharge up to 10–20% in a month, whereas some discharge by only 2–4% in a month.

Electrons have a negative charge, and we are sending electrons from the anode to the cathode; so we are sending negative charge from the anode to the cathode. To maintain charge balance, there has to be a flow of positive charge also in the same direction. This positive charge flow will be in the form of positive ions. These positive ions will flow from the anode to the cathode through the electrolyte. So the electrolyte provides a medium through which charge balancing positive ions can flow through.

At the anode, the electrode material will be involved in a chemical reaction with the electrolyte to produce electrons (oxidation); whereas at the cathode, another chemical reaction will take place between the material of the cathode and the electrolyte due to which electrons will be absorbed by the cathode (reduction). The electrons flow through the external wire, while the electrolyte provides a pathway for the transfer of positively charged ions to balance the negative flow. This flow of positively charged ions is just as important as the flow of electrons through the external circuit. The charge balancing role performed by the electrolyte is necessary to keep the entire process running.

The electrolyte can be acidic or alkaline, depending on the type of battery. Traditional batteries such as lead-acid and nickel–cadmium use liquid electrolytes. Advanced batteries currently under development such as nickel-metal-hydride and lithium-ion batteries use an electrolyte that is gel, paste or resin. Lithium-polymer batteries use a solid electrolyte (Hussain 2003).

15.2.1.3 Separator

The separator is an electrically insulating layer of material that physically separates electrodes of opposite polarity. Effective separators must possess high porosity so that they will have low electrical resistance, low pore diameter in order to achieve good separation and, finally, resistance to oxidation and stability in highly acid conditions (Vincet and Scrosati 1998). Separators must be permeable to ions; they must allow the flow of ions but not the flow of electrons. Present-day separators are made from synthetic polymers or glass filters.

15.2.2 Types of Batteries

The basic working principle of all batteries is the same. The only things that change are the materials that are being used for the electrodes and the electrolyte and the associated chemical reactions. Different types of batteries are in commercial production, each suited to its own specific application.

There are two basic types of batteries: primary batteries and secondary batteries (Hussain 2003). Primary batteries are those which cannot be recharged. They are designed for a single discharge. Examples are lithium batteries used in watches, calculators, cameras, etc. and manganese dioxide batteries used to power toys, radios, torches, etc. Secondary batteries are those which can be recharged by flowing current in a direction opposite to that during discharge. The chemical reactions are the reverse of those during discharge. Secondary batteries can be reused after charging. However, after every successive charge and discharge, the condition of the battery will go on deteriorating. There is a limit to how many times/cycles the battery can be charged and discharged. All the batteries used for electric vehicles are secondary batteries.

The major types of rechargeable batteries considered for EV and HEV applications are as follows (Hussain 2003):

- Lead-acid (Pb-acid)
- Nickel–cadmium (NiCd)
- Nickel-metal-hydride (NiMH)
- Lithium-ion (Li-ion)
- Lithium-polymer (Li-poly)
- Sodium–sulfur (NaS)
- Zinc-air (Zn-Air)
- Sodium nickel chloride.

Out of these, only the lead-acid, lithium-ion, lithium-polymer and nickel-metal-hydride have been commercially used for EV applications. The lead-acid battery was actually discovered around 1860. The basic process is still the same; there are improvements, but the improvements are minor. It is the earliest type of rechargeable battery that was created. It has a low energy-to-weight ratio, also a low energy-to-volume ratio. To have a high amount of energy, the weight as well as the volume of the battery will be quite high. It does, however, have a relatively large power-to-weight ratio as compared to other batteries. It can provide short bursts of high power. That is the reason why the lead-acid batteries are very popular to provide the high current required by starter motors. The batteries used in earlier cars to provide the high current to start the motor were lead-acid batteries. They were perfectly suited for that purpose on account of their high power-to-weight ratio. However, their energy-to-weight ratio is poor, as is their energy-to-volume ratio. When EVs started becoming popular, around the late 1990s, the lead-acid battery was a sufficiently mature technology. They were also easily available and had a low cost. That is why the earlier EVs used lead-acid batteries. However, they constituted around 25–50% of the final vehicle mass. Also, the efficiency of the lead-acid battery is 70–75%, and decreases at lower temperatures. The nickel-metal-hydride battery was the next to be considered for commercial EV applications. It was also a relatively mature technology. The NiMH battery is even less efficient than the lead-acid battery; its efficiency is around 60 to 70%. It does, however, have a high specific energy of 30–80 Wh/kg, as compared to 30–50 Wh/kg for the lead-acid battery. Note that these efficiencies are ideal or theoretical. They depend on the temperature and will continuously decrease as the battery continues to be used. The NiMH batteries have exceptionally long lives; typically, 160,000 km and over a decade of service for the first-generation Toyota RAV4 EVs. (The second-generation Toyota RAV4 EVs used the Li-ion battery instead.) The drawbacks of the NiMH battery were its poor efficiency, its high self-discharge and poor performance in cold temperatures. Due to these reasons, the NiMH battery was superseded by the Li-ion and Li-poly batteries. Both of them are similar batteries. They were initially developed and commercialized for use in laptops and consumer electronics. Their high energy density and long cycle life have now made them the most popular choice for EV applications.

The nickel–cadmium battery, which used nickel-oxide-hydroxide and metallic cadmium as electrodes, had good cycle life and performance at low temperatures as well as the ability to deliver their full rated capacity at high discharge rates. However, it was costly than the lead-acid battery and had a high self-discharge rate; and was supplanted by the NiMH battery. Disposal of toxic metal cadmium was also an issue. Perhaps, the best battery to be considered was the sodium–sulfur (NaS) battery, also known as the molten salt battery. It was constructed from liquid sodium and sulphur. It had high energy density, high charge and discharge efficiency, long cycle life and was made from inexpensive materials. It was, however, difficult to manufacture and was hazardous. Thus, safety and manufacturing difficulties led to the abandonment of the technology.

15.2.2.1 Lead-Acid Battery

The lead-acid battery was the most popular choice for EVs for a considerable period of time. At the time electric vehicles started gaining some traction, the lead-acid battery was the most developed battery technology. Also, it was high-powered, inexpensive, safe and reliable. Hence, the lead-acid battery, which was earlier used for starting the car, started being used for driving the EVs also. Recycling structure was also well established. It had three significant features: low cost, easy availability of raw materials and ease of manufacture. However, its specific energy was low, its cold temperature performance was poor and it had a short calendar and cycle life. In fact, the battery life was less than the car life; around every three years the battery had to be replaced.

In the lead-acid battery, the negative electrode (anode) is made of spongy or porous lead (Pb), whereas the positive electrode (cathode) is made from lead oxide (PbO_2). The electrolyte used is sulphuric acid (H_2SO_4).

During cell discharge, at the anode, the lead will interact with the sulphuric acid to produce lead sulphate ($PbSO_4$) and two electrons. These electrons flow through the external conductor to reach the cathode. At the cathode, the lead oxide will absorb the two electrons in a chemical reaction with the sulphuric acid to produce lead sulphate and water.

During battery charging, the lead sulphate is once again broken into lead and lead oxide. However, some amount of lead sulphate, in the form of a fine white powder, keeps on depositing on the electrodes. On account of this, the internal resistance of the cell goes on increasing with time. Also, as H_2SO_4 is consumed, the electrolyte conductivity goes on decreasing. The lead sulphate deposited on the electrodes in a dense fine grain form leads to sulfatation. This reduces cell capacity significantly. The lead sulphate is not soluble in water, and keeps on depositing on the plates as well as electrodes. As a result, the battery capacity as well as efficiency keeps on decreasing.

The chemical reactions during charging of the lead-acid battery are opposite to those during discharging. The lead sulphate will be converted back to the reactant states of lead and lead oxide. For this, a current has to flow into the positive electrode through an external source; the electrons have to flow in the opposite direction from the positive electrode to the negative electrode. The external source delivers electrical energy to the cell, where it gets converted into chemical energy and can be stored. At the positive electrode, the lead sulphate consumes the water produced at the time of discharging and produces lead oxide, $4H^+$ and SO_4^{2-} ions and two electrons. At the negative electrode, the lead sulphate consumes the two electrons to produce lead and SO_4^{2-} ions.

The lead-acid battery continues to be popular for a lot of applications. However, it is not suited for driving the electric vehicle over long distances. Specifically, its low specific energy is a major hindrance, causing a considerable increase in the volume and mass of the battery for driving the EV. Other better suited battery technologies have now been developed, as a result of which, the lead-acid battery is no longer being used for driving long range electric vehicles.

15.2.2.2 Nickel–Cadmium Battery

The nickel–cadmium (NiCd) battery is an alkaline battery; the electrolyte used in the battery is alkaline. In this case, the electrical energy is derived from the chemical reaction of a metal (cadmium) with oxygen in an alkaline electrolyte medium. One major disadvantage of the NiCd battery was its low specific energy due to the addition of the weight of the metal.

In these batteries, the positive electrode is nickel oxide, while the negative electrode is made from metallic cadmium. The alkaline electrolyte is potassium hydroxide (KOH). The practical cell voltage obtainable from NiCd batteries is 1.2–1.3 V. The specific energy is 30–50 Wh/kg, similar to the lead-acid batteries.

The advantages of the nickel–cadmium batteries were superior low-temperature performance as compared to lead-acid batteries, flat discharge voltage characteristic, long life, excellent reliability and lower maintenance requirements. However, they had a number of limitations also. Their cost was high because of the metal involved, as cadmium was highly toxic. In fact, after 2004, the NiCd battery was not allowed in Europe, specifically for home applications. Their power output was also low, and was insufficient for EV applications. The popularity of the nickel-metal-hydride battery, which is a much improved alkaline battery, made the NiCd battery redundant for EV applications.

15.2.2.3 Nickel-Metal-Hydride Battery

The nickel-metal-hydride (NiMH) battery is the successor to the nickel–hydrogen battery. A number of hybrid electric vehicles have used the NiMH battery for providing electric power for traction purposes. Its operating voltage is almost the same as the NiCd battery, with a flat discharge characteristic. The specific energy is 60–80 Wh/kg, which is higher than the lead-acid and NiCd batteries. The specific power can be as high as 250 W/kg.

The NiMH battery also uses nickel oxide as the material for the positive electrode, but the negative electrode is a metal hydride. When certain metals are exposed to hydrogen, they have the ability to absorb that hydrogen. They also have the ability to release that hydrogen when required. Such metals, which can absorb hydrogen, are called as metal hydrides. Fine particles of certain metallic alloys, when exposed to hydrogen at certain pressures and temperatures, absorb large amounts of hydrogen to form metal hydride compounds. Metal hydrides can absorb and release hydrogen many times without getting deteriorated.

The advantages of the NiMH battery are a much longer life cycle than lead-acid batteries, as well as being safe and abuse tolerant. Abusive conditions for a battery include short circuiting a battery, overcharging a battery, physically deforming a battery. The NiMH is abuse tolerant. Specifically, the exceptionally long-life cycle of the NiMH battery is a significant advantage. However, its cost is relatively higher, has a higher self-discharge rate as compared to the NiCd battery and has poor charge acceptance capability at elevated temperatures and low cell efficiency. Although the NiMH battery was used to drive EVs and Hybrid EVs (HEVs) earlier, they are no longer preferred on account of the improvements in the lithium-ion battery technology.

15.2.2.4 Lithium-Ion Battery

The lithium-ion (Li-ion) battery is one of the most promising batteries for EV applications. Right now, the Li-ion battery is the battery of the future that will dominate the EV and HEV applications for decades. Of course, it is possible that some other battery technology may come along and replace the Li-ion battery, but right now, the Li-ion battery is the most promising battery for the future. The reason is that lithium metal has a high electrochemical reduction potential (3.045 V) and lowest atomic mass (6.94). Reduction potential is related to the oxidation potential, or the redox potential. The tendency of a chemical to acquire/release electrons from an electrode and thereby be reduced or oxidized is called the reduction potential. Lithium has the potential to acquire large number of electrons. It is possible to generate up to 3.045 V, while still having the lowest atomic mass. This shows promise for a battery of 3 V cell when combined with a suitable positive electrode. However, lithium metal is highly reactive with moisture, which limited their use earlier. It was only the discovery in the late 1970s that lithium can be intercalated (absorbed) into the crystal lattice of cobalt or nickel to form lithium cobalt oxide ($LiCoO_2$) or lithium oxide nickel ($LiNiO_2$) that paved the way toward the development of lithium-ion batteries.

The Li-ion battery uses lithium intercalated (absorbed) carbons (Li_xC) in the form of graphite or coke as the negative electrode. The positive electrode is made up of lithium metallic oxides. The most satisfactory lithium metallic oxide is the cobalt oxide, but it is very expensive. Another lithium metallic oxide is the lithium oxide nickel ($LiNiO_2$). It is structurally more complex but costs less and its performance is similar to cobalt oxide electrodes. Manganese oxide based positive electrodes are also under research because manganese is cheaper, widely available and less toxic.

During discharge, at the negative electrode, the Li_xC discharges to produce carbon, lithium ions and electrons. The electrons will move toward the positive electrode through the external circuit, while the lithium ions move in the same direction through the electrolyte. At the positive electrode, the lithium ions recombine with the electrons and the metallic oxide to produce lithium cobalt oxide.

The features of a Li-ion battery include high specific energy, high specific power, high energy efficiency, good high temperature performance, low self-discharge and recyclable components. The Li-ion battery has features which are ideal for battery use for EV applications. However, it contains flammable electrolytes and can explode when exposed to abusive conditions.

15.2.2.5 Lithium–polymer Battery

The lithium-polymer (Li-poly) battery is similar in working to the Li-ion battery, except that it uses solid-sate electrolytes, i.e. solids capable of conducting ions but which are electron insulators.

The Li-poly battery has the highest specific energy and power, good cycle and calendar life, and all the advantages of the Li-ion battery. Also, because the electrolyte is a solid, the battery can have any desired shape. They are still not being used for EV applications, but research is ongoing. If the Li-poly battery does get commercialized for EVs, they will provide a huge space advantage. Also, because they have a solid electrolyte, they are ideally suited for moving applications. The only disadvantage is that the battery cell has to be operated in the range of 80 to 120 °C.

15.2.2.6 Zinc-Air Battery

The Zinc-air (Zn-Air) battery is similar to the conventional batteries in the sense that it generates electric power from chemical reactions (Review 2020). However, in most respects, its working is more similar to that of a fuel cell. These batteries have a gaseous positive electrode of oxygen, whereas the negative electrode is metallic zinc. The Zn-Air battery is an alkaline battery and uses potassium hydroxide (KOH) as an electrolyte. The amount of electric power generated can be controlled by controlling the flow of oxygen (air). Electrical recharging of the battery is not possible; in this sense, it is similar to a primary cell. However, once the battery is discharged completely, the zinc electrode can be mechanically replaced with fresh zinc.

Zn-Air batteries have a high specific energy. Its other inherent features such as safety and lower cost ensure that it is a promising technology for future EV applications. Although the alkaline electrolyte is still widely used, Room Temperature Ionic Liquids and Quasi-Solid Flexible Electrolytes are also being researched for use as electrolytes in Zn-Air batteries (Peng et al. 2020).

15.2.3 Battery Parameters

Battery Capacity: Battery capacity is the amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode. Battery capacity is measured in ampere-hour (Ah), where 1 Ah = 3600 C and 1 C is the charge transferred by a current of 1 A in 1 s.

The theoretical capacity of a battery Q_T is given by $Q_T = xnF$ C, where x is the number of moles of the limiting reactant associated with complete discharge of the battery, n is the number of electrons produced by the negative electrode discharge reaction and $F = Le_o$. Here L is the number of molecules or atoms in a mole, also known as the Avogadro constant (6.022 × 1023) and e_o is the electron charge (1.601 × 10–19 C). Thus F is a constant whose value is equal to 96412.2 C/mol. Limiting reactant is the reactant which is consumed fully and which decides the amount of product that is formed. In terms of Ah, the theoretical capacity is given by $Q_T = 0.278\ Fm_R n/M_m$ Ah, where m_R is the mass of the limiting reactant in kg and M_m is the molar mass of the limiting reactant in grams/mol.

If the capacity of a single cell of a battery is Q_{Tcell}, and a number of cells are connected in series to form a battery, then the capacity of the whole battery is also Q_{Tcell}. Thus the capacity of a battery is the same as the capacity of an individual cell when cells are connected in series. If the capacities of individual cells are different, then the capacity of the battery will be the same as the capacity of the smallest cell in the battery.

The practical capacity of a battery is always much lower than the theoretical capacity due to practical limitations. The practical capacity can be obtained by integrating the current drawn from the battery with respect to time from the instant at which the battery is fully charged to the instant at which the battery terminal voltage becomes equal to the cut-off voltage.

Discharge rate: The discharge rate is the current at which the battery is discharged. It is expressed as Q/h rate, where Q is the rated battery capacity and h is the discharge time in hours.

Suppose the capacity of a battery is 100 Ah (1Q = 100 Ah) and the battery is discharged in 5 h, then the discharge rate is Q/5 = 100 Ah/5 h = 20 A. If the same battery is discharged in 0.5 h, the discharge rate is Q/0.5 = 200 A. Thus, the battery discharge rate will determine the amount of time for which the battery will last before it runs out of charge. The higher the discharge rate of the battery, the shorter is the time for which it can be used before recharging.

State of Charge: The state of charge (SoC) is the present capacity of the battery at any instant of time. It is the amount of capacity that remains after discharge from a top-of-charge condition. The SoC is a very important parameter for a battery. It is somewhat analogous to the amount of fuel in a conventional vehicle at any instant of time.

The SoC of a battery is decided by the amount of current that is drawn from the battery since it was fully charged. It can be determined by integrating the current drawn from a battery over a duration of time and then subtracting this integral from the theoretical capacity of the battery.

State of Discharge: The state of discharge (SoD) is just opposite to the SoC. It is a measure of the charge that has been drawn from a battery. The SoD can be obtained by integrating the current drawn from the battery over a duration of time. The state of charge of a battery is the difference between the theoretical capacity of a battery and the SoD. If the SoD of a battery is known, the SoC of the battery can be determined, and vice versa.

Depth of Discharge: The depth of discharge (DoD) is the percentage of battery capacity (rated) to which a battery is discharged. Basically, the DoD expresses the SoD as a percentage of the rated theoretical capacity of a battery.

Battery terminal voltage: Battery terminal voltage is the voltage obtained across the terminals of the battery with load applied to it. It depends on the state of charge of the battery as well as the charging/discharging current of the battery.

Cut-off voltage: The cut-off voltage of a battery is the minimum allowable voltage from a battery. If the battery terminal voltage falls below the cut-off voltage, the battery is assumed to have discharged and can be used only after recharging.

15.3 Fuel Cell

Having studied the battery in considerable detail, let us now take a look at some alternative energy sources. The first alternative energy source that we will consider is the fuel cell. The fuel cell is under research and is a promising technology for the future.

A fuel cell is an electrochemical device that produces electricity by means of a chemical reaction. Similar to a battery, it also converts chemical energy into electrical energy and uses redox reactions to achieve this end. However, batteries will produce electricity as long as there is stored chemical energy, after which they have to be recharged; whereas, in the case of a fuel cell, there is no stored chemical energy. As long as fuel is supplied to the fuel cell, it will continue to produce electricity. Once the fuel supply is stopped, the fuel cell will stop providing electrical energy.

The fuel cell has a negative terminal called the anode and a positive terminal called the cathode. It has two inlets. One inlet is for the hydrogen. Some fuel cells require pure hydrogen while some can work even if there is some impurity in the hydrogen. The other inlet is for the oxygen. There is no need to provide pure oxygen; supply of air is sufficient.

At the negative electrode, the electrode material will react with the hydrogen and split the hydrogen atom into hydrogen ions and electrons. The hydrogen (H^+) ions, which are essentially two single protons, will move through the electrolyte placed between the electrodes to the positive electrode while the electrons will move through the external circuit to constitute a current flow. At the positive electrode, the hydrogen ions will combine with the electrons and the oxygen to produce water. Thus the output of the fuel cell obtained from the outlet is water. Unreacted hydrogen is also obtained from the outlet, as is the unused air. This is the basic working of a fuel cell. As long as fuel in the form of hydrogen, as well as air, is being supplied to the fuel cell, the fuel cell will continue to produce electricity. As soon as the flow of hydrogen is stopped, the fuel cell will stop the production of electrical energy. The amount of electrical energy produced will depend on the material of the electrodes as well as the rate of flow of hydrogen. Thus, the amount of electricity produced from a fuel cell at any instant of time can be controlled by controlling the rate of flow of hydrogen. The energy conversion process is instantaneous as long as the negative electrode is maintained within an operating temperature range.

The advantages of a fuel cell over a battery for EV applications are as follows:

- There is no need to charge a fuel cell. No charging stations are required for fuel cells.
- The fuel system is similar to a petrol vehicle. Instead of petrol, hydrogen is being used as fuel. Just like a petrol vehicle, knowing the amount of hydrogen in reserve, the distance that can be traversed can be estimated. The hydrogen can be refueled as desired.
- The hydrogen capacity can be varied depending on the EV capacity and application. For smaller/short-run vehicles, the hydrogen storage capacity can be smaller, whereas for larger vehicles or vehicles designed for long runs, the hydrogen storage capacity can be appropriately increased.

In spite of these advantages, the fuel cell is still not being used for commercial EV applications. This is because there are a lot of disadvantages of using fuel cells, and the disadvantages are currently outweighing the advantages. Until the disadvantages are removed, the fuel cell cannot be used in practice. These disadvantages are as follows:

- Hydrogen is highly flammable. As such, there are safety issues in the usage of the fuel cell for commercial applications.
- Storage of hydrogen is a very big issue. It is not as simple as storage of petrol or diesel. Hydrogen storage is a refined and complex technology. Storage and

management (containment) of hydrogen is a huge hindrance that is hampering the growth of fuel cells as an energy source for EVs.

However, extensive research is being carried out for making fuel cells viable for EV applications in the future.

15.3.1 Types of Fuel Cells

15.3.1.1 Alkaline Fuel Cell (AFC)

The alkaline fuel cell uses an aqueous solution of potassium hydroxide (KOH) as an electrolyte. The original fuel cells used acidic electrolytes. The performance of an alkaline electrolyte is as good as an acidic electrolyte while being significantly less corrosive toward the electrodes. The AFC shows very high electrical efficiency as compared to other fuel cells, as high as 60%. However, they require pure hydrogen as fuel, as there can be no impurity in the fuel. The AFC operates at low temperatures (80 °C); they are therefore suitable for EV applications.

15.3.1.2 Proton Exchange Membrane (PEM) Fuel Cell

The PEM fuel cell uses a solid electrolyte instead of an acidic or alkaline solution. Nafion is an example of a solid polymer electrolyte. This fuel cell also operates at low temperatures (80 °C), and hence is suitable for EV applications. Its electrical efficiency is lower than that of the AFC, about 40%. However, the construction is rugged and simple, which is a huge advantage. They can also tolerate impurity in the fuel as compared to the AFC which require pure hydrogen.

15.3.1.3 Direct Methanol Fuel Cell (DMFC)

In case of DMFC, instead of storing hydrogen, methanol is stored. Storage and containment of methanol is much easier than storage of hydrogen. The methanol is reformed on board to supply hydrogen to the fuel cell. The DMFC works on temperatures in the range of 90–120 °C to facilitate the reformation of methanol into hydrogen. The electrical efficiency of the DMFC is low, only about 30%. The technology is still in the design and research stage because the search for a good electrocatalyst to reform the methanol efficiently and to reduce oxygen in the presence of methanol is ongoing.

15.3.1.4 Other Fuel Cell Types

There are some other fuel cell types also. One of them is the Phosphoric Acid Fuel Cell (PAFC), which is the oldest type of fuel cell. The electrolyte used is phosphoric acid and the cell operating temperature is around 200 °C. The efficiency is reasonable at around 40%. However, because of the high operating temperature, it is not considered for EV applications. It is also quite bulky.

Another type of fuel cell is the Molten Carbonate Fuel Cell (MCFC). It operates directly from coal at temperatures of around 600 °C. It requires carbon monoxide or carbon dioxide on the cathode side and hydrogen on the anode. The MCFC uses carbonate as the electrolyte. The efficiency is considerably higher at around 50%. Because the MCFC operates at very high temperatures, the excess heat can be used for cogeneration to have an improved efficiency. Cogeneration means that the excess heat can be used for other purposes also such as home heating. The very high operating temperature is, however, a deterrent in the use of MCFC for EV applications.

The solid oxide fuel cell (SOFC) uses a solid ionic conductor as an electrolyte which reduces corrosion problems. However, to achieve adequate ionic conductivity, the system must operate at very high temperatures, around 1000 °C. Hence the SOFC is also not considered for EV applications. Intermediate Temperature SOFC (ITSOFC) is also undergoing research. The intermediate temperatures are still quite high for this fuel cell to be considered for EV applications. These fuel cells are more suitable for stationery applications.

15.3.2 Reformers

Some fuel cell types, such as the DMFC, use a hydrocarbon such as methanol, ethanol, diesel, biogas or natural gas instead of pure hydrogen as a fuel. While this solves the problem of storage and transportation of hydrogen, the fuel cell has to extract hydrogen from the hydrocarbons. For this purpose, the fuel cell system must then include a reformer system (Sundén 2019).

The reformer system consists of a reformer which converts the original fuel to a hydrogen containing gas, and a clean-up system, which removes carbon monoxide and sulphur from the gas to make it appropriate for the fuel cell. The clean-up system will thus remove the unwanted gases and will provide hydrogen to the fuel cell. The hydrogen thus provided to the fuel cell will not be exactly pure as can be produced in a laboratory or industry. Hence, the efficiency of such fuel cells will be slightly less as compared to those fuel cells which utilize pure hydrogen.

15.4 Ultracapacitors

Having studied the battery and fuel cell in some detail, let us now turn our attention and briefly discuss two energy sources which are by themselves not sufficient to power an electric vehicle. However, they can be used in conjunction with a battery or fuel cell to enhance the vehicle performance. The first such energy source is the ultracapacitor.

If the battery alone is used as an energy source for an EV, the discharge profile of the battery is highly variable. The average power required from the battery is relatively low. When moving on a level surface with more or less constant speed, the power required by the vehicle is relatively low. Whereas, if the vehicle is moving up a gradient, or at the time of acceleration, the power required is much higher. The ratio of this peak power to average power can be as high as 16:1 for high performance EVs. In fact, the amount of energy required for acceleration and during transient conditions is around 2/3rd of the total amount of energy over the entire vehicle ride. Based on present battery technology, the design of batteries has to carry out a trade-off between the specific energy, specific power and cycle life. It is difficult to simultaneously obtain high values of these three performance parameters.

A battery with high specific power will provide very fast acceleration and deceleration, but the battery will discharge very fast. On the other hand, a battery with high specific energy will last longer between discharge cycles but will be unable to provide fast acceleration. Both these requirements are contradictory. A battery designed for high specific power will have a low specific energy, while a battery designed for high specific energy will be unable to provide high power for short durations of time. Thus, both these requirements cannot be satisfied simultaneously. This difficulty has led to suggestions that EVs may be powered with a pair of energy sources, and is an option that is being explored. Out of these two sources, the main energy source, which is usually the battery, is optimized for the range. That means that the battery must last for a longer duration between charging and discharging. The auxiliary source is optimized for acceleration and going up a gradient. The auxiliary source should be such that it can be recharged from the main source during less demanding driving conditions or during regenerative braking. One of the auxiliary sources which has received wide attention is the ultracapacitor.

Ultracapacitors are derivatives of conventional capacitors in which the energy density has been increased at the expense of power density to make the device function more like a battery. Normal capacitors can charge and discharge at a fast rate; they have a high power density and a very poor energy density. In case of ultracapacitors, the power density is sacrificed so as to increase the energy density. Also, the capacitance is much higher in case of ultracapacitors or super capacitors as compared to normal capacitors. It is in farads whereas for normal capacitors it is in microfarads or millifarads. The power and energy densities of ultracapacitors are of the order of 10^6 W/m^3 and 10^4 Wh/m^3, respectively. The energy density is still much lower as compared to batteries, but the discharge times are much faster and the life cycle is much more. Because the ultracapacitor can discharge much faster, it is able to provide high power for a short duration of time.

Because the specific energy of ultracapacitors is low, they cannot be used as the sole energy source for an electric vehicle. It is not possible to have an EV powered solely by an ultracapacitor because the ultracapacitor will discharge very fast. Still there are a number of advantages that can be obtained from using the ultracapacitor as an auxiliary energy source. If the battery and ultracapacitor are used together to form a hybrid energy system for an EV, the specific energy and specific power requirements of the EV energy source can be decoupled. The specific energy requirement is now handled by the battery, whereas the specific power requirement is handled by the ultracapacitor. The battery can now be optimized for specific energy. This is nothing but a sort of load equalization for the battery, as it is obtained using a flywheel in case of variable speed electric drives. At the time of high power demand, the ultracapacitor will provide the power to drive the EV along with the battery. While the EV is running on constant speed, the ultracapacitor can be charged from the battery. It can also be charged during regenerative braking conditions. Since the battery is no longer required to provide high power, it does not have to discharge at a high current. Hence, the available energy, endurance and life of the battery is significantly increased. Also, because the time constant of the ultracapacitor is much less as compared to the battery, it can provide much faster acceleration as well as recovery of energy during regenerative braking. The battery does not have the capability to absorb power at a high speed for the short duration of regenerative braking, but the ultracapacitor does. It can accept charge at a much faster rate and can be charged to a greater extent than the battery during the short interval for which regenerative braking occurs. Because of this combined effect of load equalization and efficient energy recovery, the vehicle range can be greatly extended.

The targets set by the US Department of Energy state that the near-term specific energy and specific power for ultracapacitors should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg (Hussain 2003). So far, none of the available ultracapacitors can fully satisfy these goals. If current state-of-the-art ultracapacitors are used as an auxiliary source for EVs, the vehicle weight will increase by about 300 kg and the volume of the ultracapacitor will also be prohibitive. That is why, till now, ultracapacitors are not being used in practice. Things may change in the future with further research and development in the field of ultracapacitors.

15.5 Flywheel

Flywheels have been in use for a long time for load equalization in variable speed electrical drives. For load equalization, the flywheels are expected to have a large moment of inertia; the reason being that flywheels work on the principle of storing and releasing energy. When the flywheel is running at a speed greater than the normal speed due to the absence of load or the load being light, or when it is accelerating, it stores kinetic energy. When the full load is applied and the flywheel decelerates, the kinetic energy is released to the load. This comes in use in case of load equalization in variable speed drives, especially where the load is applied intermittently.

Would it be possible to have an EV powered solely by a flywheel? Surprisingly, there was a bus that did exactly that; that too, not today but 80 years ago. This flywheel powered bus was developed by the Oerlikon Engineering Company of Switzerland. The bus was called the 'Gyrobus'. The bus is not in use anymore, but was in actual use in the 1940s. It used a flywheel that weighed around 1500 kg and was spun at speeds up to 3000 rpm.

The flywheel was initially charged by using an electric motor, specifically the squirrel cage induction motor. Charging the flywheel implies bringing it up to its maximum speed so that it stores kinetic energy. On account of the large moment of inertia of the flywheel, this stored kinetic energy was considerable. This charging was done at a charging point, where the induction motor responsible for charging the flywheel was connected to an electrical supply. Once the flywheel was charged to its maximum speed, the electrical motor was disconnected from the supply. The flywheel now acted as a prime mover for the induction machine, so that it started working as a self-excited induction generator. This generated power was used to power the electric motor that drove the bus. As the bus moved, the flywheel basically kept releasing its kinetic energy and its speed went on decreasing. After some appropriate distance, a charging point was located to charge the flywheel again; it again discharged while driving the bus, and so on. A fully charged Gyrobus could typically travel up to 6 km on a level route with speeds ranging from 50 to 60 km/hr. Charging a flywheel took between 30 s and 3 min. The Gyrobus had its advantages: quiet operation, pollution free and did not require any rails. The disadvantage was that it required a very large flywheel which had to be repeatedly charged after short distances. As a result, the Gyrobus service was discontinued as soon as buses with IC engines became available.

In order for the flywheel to store a large amount of kinetic energy, it is not necessary that the flywheel have a large moment of inertia. Instead, the flywheel can be designed to have a small moment of inertia but a high rotating speed. Such a flywheel uses a lightweight composite rotor with tens of kg and rotates at the order of ten thousands of rpm and is called an ultrahigh-speed flywheel. It stores energy in mechanical form during periods of cruising or regenerative braking while it generates electrical energy to meet the peak power demands during periods of starting, acceleration and hill climbing.

If the flywheel is to be used as an energy source for an electric vehicle, the weight of the vehicle increases to account for the weight of the flywheel. So instead of using a flywheel with a large weight, it is better to use a flywheel that is lightweight but rotates at a faster speed. Hence ultrahigh-speed flywheels are preferable for EV applications.

Ultrahigh-speed flywheels have high specific energy, high specific power and high efficiency for conversion between electric and mechanical energies. They can recharge rapidly with high efficiency during regenerative braking leading to a remarkable improvement in the vehicle range. Note that this is the case only with ultrahigh-speed flywheels and not with conventional flywheels. The ultrahigh-speed flywheel can enhance the usable energy, endurance and cycle life of a battery when used in conjunction with it. However, even though the concept is very good, there are significant problems with the use of flywheels for EVs due to which they are still not being used for practical applications. The first such problem is gyroscopic forces. Gyroscopic forces come into play whenever an EV with a flywheel tries to deviate from its path. For example, when the vehicle is moving along a straight path initially, the flywheel tends to move along that straight path. Now if the vehicle tends to turn, the flywheel opposes this motion. The vehicle control will therefore be slightly difficult. The second problem hampering the use of flywheels for EVs is failure containment. If due to some fault, the ultrahigh-speed flywheel, rotating at a speed of 10,000 rpm, comes out of its enclosure, it will have devastating consequences. Progress needs to be done on these two issues before the flywheel can be used in practice for EV applications.

There has, however, been interest in using the flywheel as a stationery energy storage system. Instead of using the flywheel on the vehicle, it can be kept stationery and can be used as an energy storage system in a charging station. The power levels required for EV charging stations are in the MW range. This power demand is highly fluctuating and depends on the number of vehicles being charged at the station at any time as well as their SoC. This large fluctuation in the power demand at a charging station can be equalized to a certain extent by using the flywheel as an energy storage system at the charging station.

15.6 Conclusion

This chapter has considered four energy sources for EVs in brief. These sources were the battery, the fuel cell, the ultracapacitor and the flywheel. All these sources had their particular advantages and drawbacks. Notable advantages are the maturity and low cost of batteries, the outstanding specific energy and high fuel efficiency of fuel cells, the enormous specific power and instantaneous charge/discharge capability of ultracapacitors and the outstanding specific power and practically unlimited cycle life of ultrahigh-speed flywheels. Still, none of the energy sources can fulfil all the demands of EVs; no source is entirely self-sufficient. In essence, no energy source can provide high specific energy and high specific power simultaneously. However, this limitation can be overcome by the hybridization of two energy sources; one with high specific energy (battery or fuel cell) and one with high specific power (ultracapacitor or flywheel). The hybridization of three or more sources together would be quite complex and hence is not considered. The advantage of hybridization is that the responsibilities can now be divested. EV sources such as batteries and fuel cells can be optimally designed for high specific energy, while sources such as ultracapacitors and flywheels can be optimally designed for high specific power. The cycle life and production cost of these sources can be lengthened and minimized, respectively.

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