Batteries for Electric Vehicles

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K.V. Vidyanandan
NTPC Limited

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Dr. K.V. Vidyanandan, ***Senior Member, IEEE***
Power Management Institute, NTPC Ltd., India
kvvidyas@gmail.coms

Abstract**—Affordable Electric Vehicles (EVs) are becoming a reality mainly because of the falling price of traction batteries. EV's acceptability is growing with increasing drive range per recharge. Desired attributes of EV batteries include: high energy density, power density, cycle life, safety and low cost. New cell chemistries are being introduced for making batteries smaller, lighter and to store enough energy so that EVs can compete with conventional vehicles. Lithium-ion batteries are currently the most popular EV batteries available in the market. Lithium-ion refers to a large family of cell chemistries, which are characterized by the cathode material and the transfer of lithium ions between the electrodes during the charge/discharge reactions. This paper gives an overview of Li-ion batteries, their limitations, safety concerns and the emerging battery technologies to meet the future requirements.**

Index Terms**—Battery pack, cells, charging, electric vehicles, Li-ion batteries, Li metal batteries.**

I. INTRODUCTION

ELECTRIC vehicles are gaining popularity and becoming more affordable. Highlighted features of EVs include: no green-house gas emissions, lower running and maintenance costs, ability of frequent starts and stops, fast and smooth acceleration (full torque even at the lowest speed), regenerative braking, smooth and silent ride, advanced safety features, fewer moving parts, possible application of sustainable renewable energy to drive it etc.

According to the drive train configuration, electric vehicles can be classified as Battery Electric Vehicle, Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle and Fuel Cell Electric Vehicle (FCEV). All EVs have the regenerative braking systems to recover energy otherwise lost as heat due to friction during braking. Basic arrangement of few EV configurations is shown in Fig. 1 [1].

BEVs are fully-electric vehicles, which are powered by large capacity batteries for traction. Standard BEVs currently available can travel average 200-300 km in single recharge, however, few EVs have up to 500 km or higher drive range.

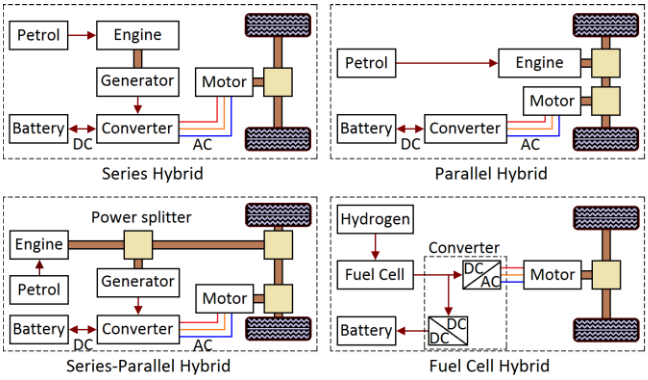


Fig. 1. Architecture of various EV configurations.

PHEVs use both engine and motor powertrains like in a HEV. The difference is that PHEVs use electric motor as the main drive, and hence, they require a larger battery than the standard HEVs. PHEVs start in electric mode, runs on battery and when the batteries are low in energy, the engine starts to charge the battery and thereby extends the electric range. PHEVs can also recharge their battery from an external source. Carbon footprint of PHEVs is less than the HEVs.

In FCEVs, electricity needed to run the EV is generated by a hydrogen fuel cell. Excess energy produced by the fuel cell is stored in a storage system. Since water is the only byproduct of the H_2-O_2 reaction, an advantage of FCEV is that they produce their own electricity without the emission of CO or CO_2. Thus, the carbon footprint of FCEVs is the least among all the HEVs. Another advantage of FCEVs is that refilling of these vehicles need the same amount of time as needed to fill a conventional petrol/diesel car tank.

II. POWER AND ENERGY CAPACITY OF EV BATTERIES

Battery power and energy demands for various types of EVs is shown in Fig. 2 [2]. EV batteries are required to handle high power (up to a hundred kW) and high energy (tens of kWh) capacity within a limited space and weight. In a hybrid EV, only a part of the propulsion power and energy needs is met by the battery. Since all the power and energy needs of a battery EV is met by the battery, size of the battery in a BEV is the largest among all the EVs.

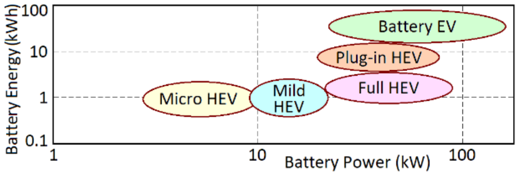


Fig. 2. Battery power & energy demands for various types of EVs.

HEVs are powered by two or more energy sources such as an IC Engine (ICE) and electric motor(s). HEVs can have many configurations such as series hybrid, parallel hybrid, series-parallel hybrid etc. During low power demand periods (e.g. city drive), these vehicles use only the electric mode. When higher power is needed (climbing uphill, high speed etc.), they switch to the engine mode. Power needed by the motor in HEVs is generated by the engine driven generator as they cannot charge their batteries from an external source.

The energy consumption of an EV depends on many factors: vehicle weight, size, body shape, road conditions, driving habit of the driver; size of auxiliary systems such as cooling, heating, lights etc. Typical energy consumption of a mid-sized EV varies between 160 - 200 Wh/km. Standard traction battery size for electric cars can vary between 20 kWh to 60 kWh or even higher for longer drive range. For buses it is in the range of 90 kWh to 150 kWh or higher [3].

After an EV is started from standstill and moving on a flat road, the drive power is used to accelerate the vehicle and to overcome the rolling resistance between tires and road surface. However, once the required speed is reached, less power is needed to maintain the speed by overcoming the rolling resistance and aerodynamic drag force. For accelerating an EV of about 1350 kg mass to about 95 km/h in 10 s, it needs about 61 kW power. For the same vehicle, the peak braking power for bringing the vehicle moving at 95 km/h to stop in 5 s can be as high as about 185 kW. Thus, the power rating requirement during braking is much higher since the deceleration has to happen in a very shorter duration. EV batteries are required to meet the demands from both supplying and absorbing large amount of power [3].

Few popular batteries and their key features are compared in Table I [4], [5]. As compared to the sp. energy of petrol (13,000 Wh/kg), the batteries are almost 50-100 times less energetic. The significance of low energy density of batteries as compared to petrol can be demonstrated as follows.

With 50 litres of petrol, a conventional engine powered car (e.g. Suzuki SX4 @ 16-20 km/L) can have a travel range of over 700 km. A battery pack with the same amount of energy content as that of 50 litre petrol would be too heavy and extremely large in volume. Based on the current battery technology, a 100 kWh Li-ion battery that can provide around 500 km travel range may weigh between 800-900 kg.

Table I. COMPARISON OF MAJOR BATTERY TECHNOLOGIES

Battery Type	Nominal Voltage (V)	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Specific Power (W/kg)	Life Cycle
Pb-acid	2.1	30-40	100	180	500
Ni-Cd	1.2	50-80	300	200	2000
Ni-MH	1.2	60-120	180-220	200-300	< 3000
ZEBRA	2.6	90-120	160	155	> 1200
Li-ion	3.6	120-250	200-600	200-430	2000
LiPo	3.7	130-225	200-250	260-450	> 1200

Pb-acid: Lead Acid, Ni-Cd: Nickel-Cadmium, Ni-MH: Nickel-Metal Hydride, ZEBRA: Zero Emissions Batteries Research Activity, Li-ion: Lithium-ion, LiPo: Lithium-ion polymer.

III. MAJOR BATTERY TECHNOLOGIES FOR EVs

I. *Historical Developments*

A number of electrochemical batteries capable of powering EVs exist today. The popular chemistries include: Lead-Acid, Ni-Cd, Ni-MH, Li-ion and Li-metal. Energy storage capabilities of these batteries are shown in Fig. 3 [6].

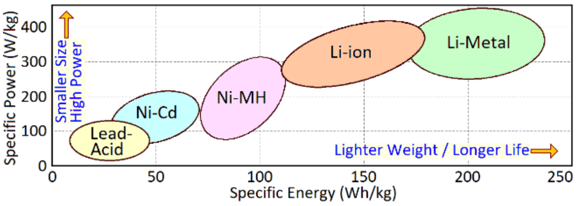


Fig.3. Power and energy capabilities of different batteries.

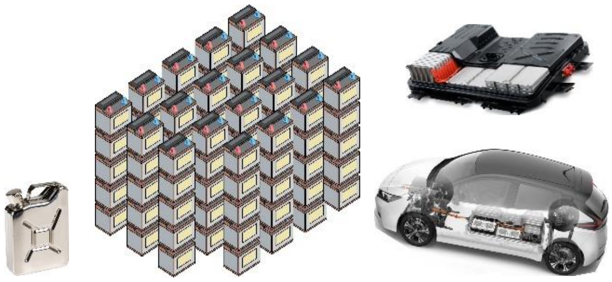
EV batteries are *deep cycle* (DC) batteries as against *shallow cycle* (SC) batteries typically used for automobile start, light and ignition (SLI) applications. DC batteries have thicker positive electrode plates but with relatively less surface area available to take part in electrochemical reactions. In shallow cycle batteries, on the other hand, electrodes are of *sponge type* with larger surface area. This enable SC batteries to deliver high current (and high power) pulses for short durations. DC batteries cannot release large power very quickly as they are designed to provide relatively steady power over sustained periods of time. DC batteries can be discharged down to 30-20% of SOC (state of charge) for over thousand cycles, whereas shallow cycle batteries are usually discharged up to 70-60% with limited cycle life of less than 500. This will vary with battery chemistry and loading pattern. The average usable capacity of an EV battery over a ten-year life span is in the range of only 50-80%.

The desired attributes of a battery from electric mobility perspective are [7]: high specific energy for longer drive distances, high specific power for good acceleration, high safety features, wide operating temperature range, contains low toxic materials, capability of fast charging, long life, and affordable price. The Lead-Acid (LA) battery, developed in 1859 remained the most popular battery for automobile applications since 1890s. During the early 1900s, LA batteries and Nickel-Cadmium (NiCd) batteries were the only options available for powering the EVs. However, electric cars powered by these batteries could not compete with petrol engine cars mainly due to their short drive range, long recharging time for batteries, lack of sufficient charging stations besides being very expensive. Eventually the first generation EVs vanished from the market in the late 1920s.

After the rebirth of EVs in the mid-1990s, LA batteries were in use for electric traction in the early version of General Motor's EV1. Though less expensive, LA batteries lost the EV market due to low specific energy (30-40 Wh/kg), low energy density (80-100 Wh/L) and limited travel range. At present, these batteries are used mainly in electric two-wheelers, forklifts and e-rikshaws only. In 1997, the nickel-metal hydride (Ni-MH) battery was introduced in hybrid EVs. As compared to LA batteries, Ni-MH batteries were relatively more powerful in terms of specific energy (60-120 Wh/kg) and energy density (140-300 Wh/L). Though Ni-MH batteries dominated the HEV market in the early 2000s, they also lost the race with the emergence of Li based batteries.

The most popular battery in today's EVs is based on the Li-ion chemistries. The introduction of Li-ion battery in 1991 led a revolution of the battery market mainly due to their high specific energy (120-250 Wh/kg) and high energy density (~ 600 Wh/L). As of now, Li-ion batteries are the lightest and long-lasting batteries available for electric vehicles.

The weight advantages of Li-ion batteries over lead-acid batteries can be demonstrated as follows. With 20 litre petrol, a conventional family car can have a drive range of over 250 km. For covering 250 km, an electric car will require about 32 kWh energy. Considering a depth of discharge (DOD) of 80%, a battery capacity of 40 kWh will be needed to deliver 32 kWh. To realize 40 kWh using a standard 12V, 35Ah lead-acid automotive battery weighing 10.5 kg, it will require 95 LA batteries aggregating to about 1000 kg. However, a Li-ion battery of 40 kWh (e.g. 2018 Nissan leaf: 192 NMC cells @ 3.65 V and 56.3 Ah as 24 modules with 8 cells/module) weighs only about 273-296 kg [8], [9]. This results in a weight gain of 70% over LA battery of the same kWh, besides substantial reduction in the battery space. Furthermore, since the LA batteries cannot be discharged below 50%, the actual travel range of the EV with 40 kWh LA battery will be around 155 km only. The relative size comparison of petrol can, lead-acid battery and Li-ion battery are shown in Fig. 4.



20 L Petrol 15 kg.
95 no., 35 Ah Lead-Acid batteries, 1000 kg.
Li-ion EV battery pack 273-296 kg.

Fig. 4. Size comparison of three systems for a travel range of 250 km.

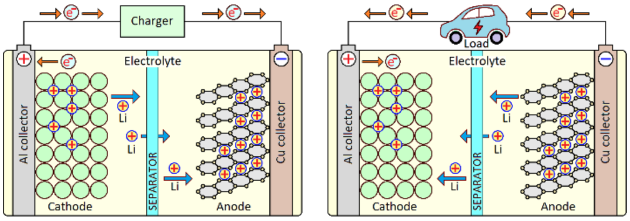
II. *Lithium-ion Batteries*

Lithium (atomic no. 3) is the lightest metal with a molecular weight of 6.941 g/mol. Li has the highest electro-chemical potential (-3.05 V relative to the standard hydrogen electrode) which makes it one of the most reactive of metals. Lithium based batteries are available in two types: Li and Li-ion. Pure Li batteries are primary cells (non-rechargeable) and Li-ion batteries are secondary cells (rechargeable). Li batteries use lithium metal as anode and can have a higher energy density than Li-ion batteries. Li primary cells are used in defense applications, watches, pacemakers in heart patients, remote controls, toys etc. Some of the popular lithium primary cells are: Energizer, Duracell etc. used in remotes of TVs, ACs, button cells used in watches etc. Li-ion batteries are increasingly used in small to high capacity applications such as cell phones, portable PCs, tablets, power tools, electric vehicles and bulk storage for renewable energy.

Major components of a Li-ion cell are: positive (cathode) and negative (anode) electrodes, an aqueous electrolyte and a separator. Cathode is made from lithium metal oxides or phosphates ($LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$ etc.) and for the anode, graphite is the standard choice. The liquid electrolyte composed of a mixture of lithium salts (e.g. $LiPF_6$) and an organic solvent (e.g. diethyl carbonate). The function of electrolyte is to transport positive Li ions between the anode and cathode during charging and discharging cycles. The electrodes are isolated by an insulating layer called separator. The function of separator is to prevent short circuiting of anode and cathode in case of drying up of the liquid electrolyte due to internal faults or abnormal conditions.

The working of a Li-ion battery (shown in Fig. 5) is as follows: When the charger is connected across the battery, at the cathode (+) side, Li atoms are separated from the lithium oxide or phosphate. Since a Li atom is highly unstable, it instantly decomposes to a Li ion (Li^+) and an electron (e^-). The positively charged Li ions are attracted towards the anode and flow through the electrolyte and get trapped in the graphite layers. Electrons, due to their negative charge, cannot pass through the electrolyte, and hence, forced to flow through the charger to the negative electrode. When all the Li ions from the cathode reaches the anode, the battery is considered to be fully charged. Thus, during charging, Li ions are extracted from the cathode and implanted into the anode.

The Li ions at the anode are not in a stable state. When the cell is connected across a load (i.e. during discharging), Li ions and electrons move from anode to cathode and get deposited on the cathode as the stable metal oxide. When all the Li ions from the anode have moved back to the cathode, the battery is fully discharged and needs recharging.



Charging Discharging

Fig. 5. Working of a Li-ion battery during charging & discharging.

The redox (reduction-oxidation) reactions that occur in a typical Li-ion battery is as follows.

at cathode $$CoO_2 + Li^+ + e^- \rightarrow LiCoO_2 \qquad (1)$$

at anode $$LiC_6 \rightarrow C_6 + Li^+ + e^- \qquad (2)$$

overall $$C_6Li + CoO_2 \rightleftarrows C_6 + LiCoO_2 \qquad (3)$$

Based on the positive electrode (cathode) material, Li-ion batteries can be classified as: Lithium Cobalt Oxide ($LiCoO_2$) or LCO, Lithium Manganese Oxide ($LiMn_2O_4$) or LMO, Lithium Titanate ($Li_4Ti_5O_{12}$) or LTO, Lithium Iron Phosphate ($LiFePO_4$) or LFP, Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) or NMC and Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) or NCA [10]. Nominal voltage of most of these cells varies between 3.2-3.7 V. The open circuit voltage (OCV) at different DOD of two popular Li-ion cells ($LiCoO_2$ and $LiFePO_4$) are shown in Fig. 6.

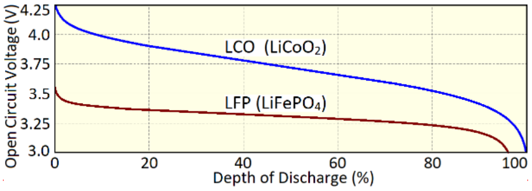
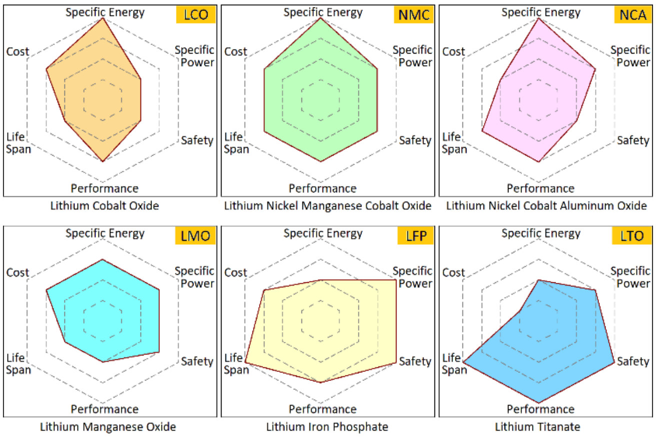


Fig. 6. OC voltage at different Depths of Discharge for two Li-ion cells.

Comparison of few important features of six Li-ion cells are shown in Fig. 7 [11], [5]. The attributes compared are: specific energy, specific power, safety, performance, lifespan and cost. The farther the coloured shape extends along a given axis, better the performance in that attribute.



Lithium Cobalt Oxide Lithium Nickel Manganese Cobalt Oxide Lithium Nickel Cobalt Aluminum Oxide

Lithium Manganese Oxide Lithium Iron Phosphate Lithium Titanate

Fig. 7. Comparisons of important attributes of Li-ion chemistries.

As can be seen from Fig. 7, there is no single Li-ion chemistry which possesses all the desired capabilities to be considered as an ideal EV battery. To realize a battery having reasonably high energy density, better safety features besides good current delivery, a mix of many materials such as cobalt, nickel, manganese and iron phosphate etc. are used in Li-ion batteries. Fig. 8 shows the specific energy density vs. volumetric energy density of major Li-ion batteries.

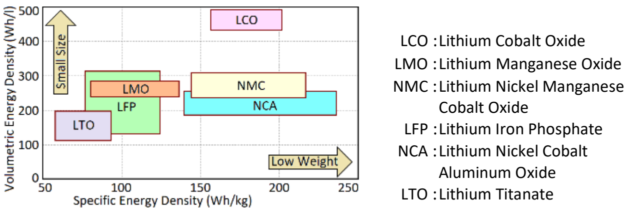


Fig. 8. Comparison of Li-ion cells.

Table II summarizes various features of Li-ion batteries [10]. Cobalt-based (LCO) cells are generally used in portable gadgets such as cell phones, cameras, laptops etc. to get long runtime. However, LCO chemistry is thermally very unstable and can easily become a potential fire hazard. Manganese based LMO cells have better thermal stability as they can withstand up to 250°C before becoming unstable. LMO cells have very low internal resistance and can deliver high current and thus, these batteries are used for power tools and medical devices. LCO batteries are not used in EVs mainly due to their high costs. At present, manganese and nickel-based Li-ion batteries are the standard choice for EV traction.

TABLE II. COMPARISON OF LITHIUM-ION BATTERIES

Type	Cell Voltage (V)		Sp. Energy (Wh/kg)	Cycle life (cycles)	Charge Rate
	Normal	Range			
LCO	3.6	3.0–4.2	150–200	500–1000	1C
LMO	3.7	3.0–4.2	100–150	300–700	1C
LFP	3.2	2.5–3.65	90–140	1000–2000	1C
NCA	3.6	3.0–4.2	200–260	500	1C
NMC	3.6	3.0–4.2	150–220	1000–2000	1C
LTO	2.40	1.8–2.85	50–80	3000–7000	5C

Li-ion cells are available in a variety of shapes, sizes, and capacity ratings. Capacities of these batteries ranges from around 10 Wh for cell phones, 60-100 Wh for laptops, 20-100 kWh for EVs and up to tens of MWh for grid level backup and wind/solar energy storage systems. The three standard Li-ion cell configurations are: Cylindrical, Prismatic and Pouch as shown in Fig. 9. Both prismatic and pouch cells are flat and rectangular, but prismatic has a hard-case whereas pouch has a soft-pack. Cylindrical cells are relatively less expensive, can have high specific energy and generally used in portable devices. These cells have good mechanical stability and can withstand high internal pressures without deforming. In prismatic cells, electrodes are in the shape of a flattened spiral whereas in pouch, electrodes are stacked onto each other. Prismatic and pouch cells improve space utilization but they are more expensive to manufacture than cylindrical cells, less efficient in thermal management and have a shorter cycle life than the cylindrical design.

EV traction battery packs are made from small capacity cells. Dozens of small cells are combined in to a module and many modules are grouped to form a battery pack, as shown in Fig. 10. Traditionally, EV battery packs are made from prismatic and pouch cells. One of the reasons for this was due to the large surface area of these cells resulting in better heat dissipation. However, cylindrical cells (size: 18650 and 2170) are also currently used in EV battery packs.

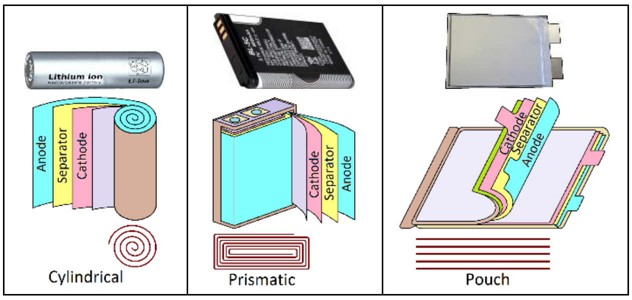


Fig. 9. Standard configurations of Li-ion cells.

Fig. 10. Various stages in making of an EV battery pack.

III. *Lithium Polymer (LiPo) Battery*

Another popular Li-ion based battery is the lithium-ion polymer, or lithium polymer (LiPo) battery. The major difference between Li-ion and LiPo is that a conventional Li-ion cell uses liquid electrolyte whereas in a LiPo cell uses electrolyte in the form of a dry solid, or a porous chemical compound or a gel-like structure. LiPo cells can be made very thin, down to the size of a credit card, due to the lack of liquid electrolyte. Another advantage of solid electrolyte is that it is impenetrable to Li metal dendrites, a major cause for internal short-circuits in conventional Li-ion cells. However, LiPo batteries possesses relatively less energy density as compared to a similar size Li-ion battery. Due to the low weight advantage, LiPo cells find application in compacts devices and radio-controlled aircraft. A comparison of various attributes of Li-ion and LiPo batteries is given in Table III.

TABLE III. COMPARISON OF LI-ION AND LIPO BATTERIES

Attribute	Lithium-Ion	Lithium Polymer
Electrolyte	Liquid	Solid
Energy Density	High	Low
Weight	Heavier	Lighter
Charging time	Longer (4-8 hr.)	Relatively shorter
Efficiency	85-95%	75- 85%
Ageing	Fast	Slow
Self-discharge	Low	Very low
Cycle life	Shorter	Larger
Safety	Chances of fire etc.	Relatively safer
Cost	Cheaper	Expensive

IV. ISSUES AND CHALLENGES WITH LI-ION BATTERIES

Many technical challenges and safety issues inherent to Li-ion batteries are to be addressed for realizing optimum performance from EVs. Major challenges of Li-ion batteries are: capacity fading, limited cycle life, charge/discharge rate, charging method and hysteresis. Other concerns are: material recyclability, environmental impacts and high cost.

a. Capacity Fading

Capacity fading in a rechargeable battery refers to the irreversible loss in its usable energy and power capacity over time and usage. Reduction in energy capacity limits a vehicle's travel range and reduction in power capacity limits its acceleration rate and regenerative brake power.

Major reasons for performance fade in Li-ion batteries are due to degradation of anode, cathode, electrolyte, separator and current collectors. A battery is generally considered usable till it reaches 80% of its initial capacity. Currently, the issue with capacity fade is addressed by providing oversized batteries to realize satisfactory performance till the end of the battery life, which is typically between 5 to 10 years.

EV batteries are subjected to driving phases followed by a long parking phase during which the battery is either plugged into a charger or remains in standby mode. A battery incurs *calendar life loss* due to storage and *cycle life loss* due charge/ discharge cycling. Calendar fade is the performance deterioration of the battery over time whether it is used or not and cycle fade is the performance deterioration with usage.

The usable capacity of a battery can be defined as [12]

$$C_{usable} = C_{initial} \times CCF \qquad (4)$$

CCF is the capacity correction factor which is calculated as

$$CCF = 1 - (\text{Cycle life losses} + \text{Calendar life losses}) \qquad (5)$$

The capacity of a Li-ion battery is correlated to the amount of Li ions that can be shuttled back and forth between the cathode and anode as the battery is cycled. During charge/ discharge process, some of those ions get stripped out of the cathode and end up at the anode. As the number of Li ions get trapped at the anode increases after each cycling, their participation in the subsequent charge/discharge reactions reduces. This is the cycle life loss.

When a Li-ion battery is idle and does not subjected to charging/discharging, the Li ions begin to react with the electrode material and the electrolyte, and form a chemical compound at the electrode-electrolyte interface. This thin layer, called the Solid Electrolyte Interface (SEI), is formed during the first charge/discharge cycle of the battery. It prevents the exposure of Li ions and electrode material to the electrolyte. However, as the battery ages, the SEI layer begins to grow and interact with more electrode material and Li ions resulting in gradual wearing of these materials. This is the calendar life loss. Though the calendar life loss rate is much slower than the cycle life loss rate, it does have an impact on the subsequent degradation of the battery [13].

Other reasons for battery capacity fade include: increase in ambient and cell temperatures, increase in internal impedance, high discharge rate, very high DOD etc. Capacity fade has a high correlation with its cell temperature. This is due to material decay and increase in cell resistance. Rise in cell resistance results in a reduction in cell output voltage leading to a drop in delivered power. Average capacity loss in Li-ion batteries per cycle ranges between 0.025–0.048% cycle [14]. Fig. 11 shows impacts of various factors and their relationship leading to capacity fade in Li-ion batteries.

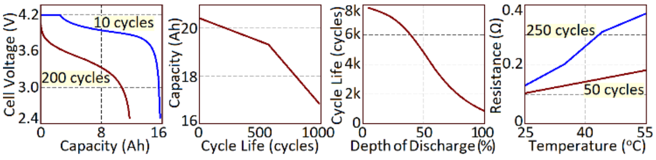


Fig. 11. Various factors leading to capacity fade in Li-ion batteries.

b. *Safety Issues*

Several safety incidents involving Li-ion batteries have been reported since early 1990. This include incidents related to cell phones, laptops, aircrafts and electric vehicles. A Li-ion battery stores a large amount of energy in a rather small packing. While powering a device such as a cell phone or an EV, energy from the battery is released in a controlled manner. However, when the energy is released rapidly and uncontrollably (e.g. due to an internal short-circuit resulted from a crash), the battery may explode or even catch fire. The biggest challenge with EV batteries is that even after a battery fire is extinguished, it can reignite as the undamaged cells of the battery pack can still get hot and release energy.

Safety issues in Li-ion batteries arise due to many reasons, significant among them are: overcharge, over-discharge, thermal runaway, dendritic growth, and gas evolution [15].

i. Overcharging

Li-ion cells have a very narrow range of operating voltage and temperature. Fig. 12 shows the usable and unusable voltage regions of a typical Li-ion cell. The safe voltage range is between 2.3 V (min. discharge) to 4.2 V (max. charge) [16]. Typical charging plot of a Li-ion cell is shown in Fig. 13. The charging occurs in three steps: constant current charge (bulk charge), constant voltage charge (saturation charge) and trickle charge. A Li-ion cell is considered fully charged when its voltage reaches the nominal value (4.2 V) and the charging current drops to about 3% of the rated value. Overcharge occurs when excessive energy is forced in to the battery in the form of trickle current after its designed capacity is reached. Li-ion cells cannot absorb overcharge. Forcing even a small continuous current after reaching full charge (SOC: 100%) will result in increasing cell voltage. When the cell voltage reaches around 4.7 V, the electrolyte and solvents breakdown and form flammable gasses. Pressurization of these gases result in battery swelling along with high cell temperature, which, in worst condition, may lead to explosion and fire.

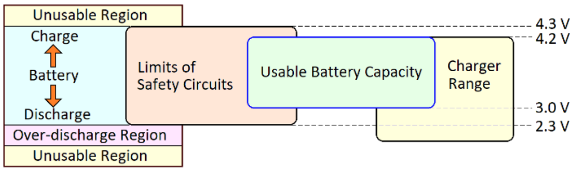


Fig. 12. Usable and unusable regions of a typical Li-ion cell.

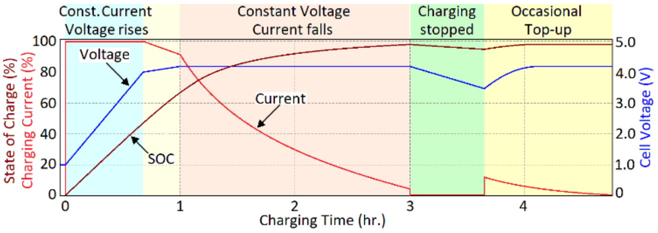


Fig. 13. charging plot of a typical Li-ion cell.

Another consequence of overcharging is lithium plating. With excessive current flow after reaching full charge, lithium ions cannot be accommodated quickly within the layers of the carbon, and as result, Li ions accumulate on the anode. This is known as lithium plating. The consequence of this is a loss of capacity and subsequent dendrite growth.

Overcharge can be prevented by switching off the charger when the cell voltage reaches the designated value. Once the charger is switched off, cell voltage begins to drop and stabilizes at around 3.7 to 3.9 V.

ii. Over-discharge (Current-Collector Dissolution)

As shown in Table-II, cell voltage range of major Li-ion batteries is 2.5 - 4.2 V. When a cell is discharged below the specified lower voltage limit, a condition known as over-discharge occurs. This happens in battery packs having cells arranged in series-parallel configurations to realize high voltage and current. Since it is impossible to have all the cells in a pack at the same state of charge; during discharging, the cells with lower capacity are demanded to deliver the same amount of energy as that from other cells. Over-discharge of a Li-ion cell results in the dissolution of copper current collector at the anode. Over a period of time, this copper can get deposited on other components and leads to an internal short. This also results in permanent capacity fade or failure.

iii. Thermal Runaway

The safe working temperature range of a typical Li-ion cell, as shown in Fig. 14, is around 15ºC to 50ºC [17]. Cycle life of the battery reduces significantly at temperature below 15ºC and slightly above 50ºC. However, beyond 60ºC cell temperature, fast reduction in life besides the danger of battery going in to thermal runaway is very high.

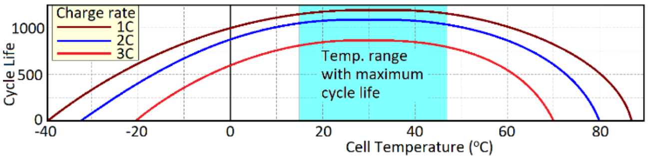


Fig. 14. Working temperature range of a typical Li-ion cell.

Internal resistance of Li-ion cells varies between 80 - 100 mΩ. During charge/discharge cycles, significant amount of heat is produced due to I^2R and chemical reactions. As a result, cell temperature rises by about 5 - 8ºC towards the end of the charging. Once the cell temperature exceeds around 60 °C due to any reason, it will initiate many side reactions such as decomposition of SEI layer at the anode. These reactions produce more heat accelerating further reactions leading to still more heat release. This is known as *thermal runaway*. Under such conditions, cell temperature rises rapidly to 300-400°C or higher in a very short period leading to melting or vaporization of various chemicals in the cell. The outcome will be a gassing, leaking or smoking battery which may explode or catch fire quickly. In majority of EV battery fire incidents reported, thermal runaway was one of the major causes. Major stages involved in the thermal runway of a Li-ion battery is shown in Fig. 15 [18] and the possible causes of thermal runaway in EV batteries is shown in Fig. 16 [19].

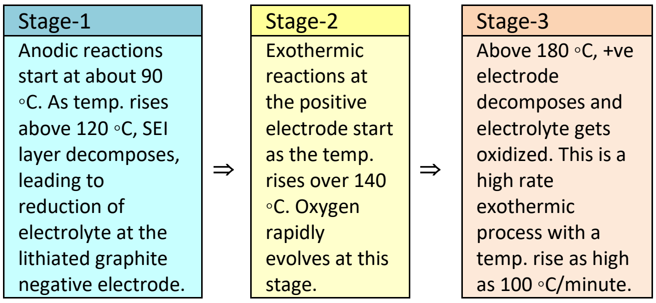


Fig. 15. Important stages of thermal runaway in Li-ion batteries.

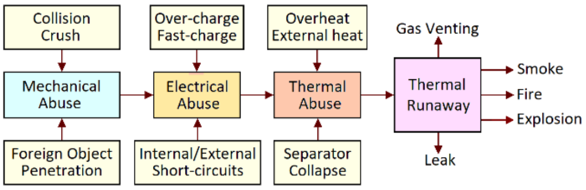


Fig. 16. Possible causes of thermal runaway in EV batteries.

Increase in cell temperature reduces the battery useful life. As a rule of thumb, for every 10°C increase in temperature of a battery, its reaction rate doubles. Thus, one hour of battery operation at 35°C is equivalent to two hours at 25°C.

iv. Lithium Dendrite Formation

Lithium dendrite formation is another technical challenge in Li-ion batteries. Though the causes of dendritic growth are still under debate, the mechanism can be briefly represented as follows. During charging of a Li-ion battery, lithium does not form a homogeneous flat layer on the carbon anode. Instead, uneven structures called dendrites in the shape of whiskers are formed. After several charge/discharge cycles of the battery, dendrites begin to grow towards the cathode direction. The growing Li whiskers can pierce the thin membrane separator (thickness: 20-25µm) and touch the cathode resulting in cell short circuit. Various stages involved in the formation of Li dendrite is shown in Fig. 17.

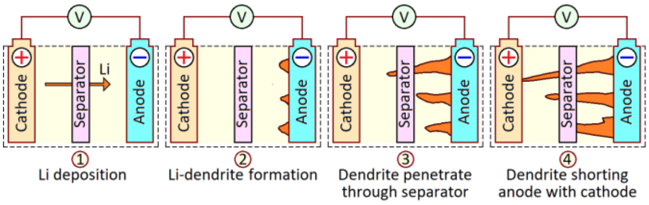


Fig. 17. Lithium dendrite formation in a Li-ion battery.

Lithium dendrite growth results in capacity fading, reduced lifetime besides internal short-circuit, generation of high temperature and battery explosions or fire. Few methods have been proposed to reduce the formation of dendrite which include use of solid electrolytes, alloying Li anodes with other metals and use of additives to improve the uniformity at the solid electrolyte interface.

v. Gas Evolution

Generation of gas in Li-ion batteries occurs mainly due to the decomposition of electrolyte and its reactions with the positive/negative electrodes. The quantity of gas generation will vary depending up on the battery state. During normal charge/discharge cycles, gas liberation will be very little. However, during abnormal conditions such as overcharge, over-discharge, thermal runaway etc., gas generation will increase and may lead to pressurization followed by explosion. In some high-power Li-ion battery system, a safety valve is provided to release the gas.

c. Charging Methods

Charging an EV battery at rates comparable to the refuelling of a petrol/diesel car is the ultimate dream of the EV fraternity. To realize this goal, two requirements are to be fulfilled. (a) The charger must be capable enough to provide large amount of power, and (b) the battery should have the ability to absorb high amount of power at a faster rate. Among these, availability of a battery with fast charging capability while maintaining reasonable cycle life is the real challenge.

The standard EV chargers currently used are the home or private charger and the public charger. Private chargers include AC Level-1 (L1) and Level-2 (L2) chargers. In both L1 and L2 chargers, single-phase AC is fed into the vehicles, where it is converted into DC by an onboard charger. A L1 charger (120V, 16A, 1.9kW) will add approximately 5-8 km of travel range per hour and a L2 charger (240V, 15A, 2.5/3.0 kW) will add up to 25-40 km of travel range in one hour. A completely depleted EV battery could take up to 20 hours to fully recharge using a L1 charger while it takes up to seven hours using a L2 charger. Public chargers can have AC L1/L2 charging points and DC off-board chargers. A Level-1 DC charger at output voltage of 48V, 60V or 72V with power rating between 10 - 15 kW can feed current in the range of 25 - 200 A. A Level-2 DC Charger at output voltage of 480V, 600V and up to 1000V can provide power outputs between 30 - 150 kW or even higher.

Charge and discharge rates of a battery are denoted by the C-rates. 1C-rate refers to full charging in one hour; 2C-rate refers to full charging in 30 min., and C/2 or 0.5C means two hours to fully charge. The C-rates of Li-ion batteries are shown in Table II. The Level-1 and Level-2 chargers, both AC and DC, typically recharges the battery much less than the 1C rate and therefore needs many hours to fully charge the battery. However, to quick recharge a battery, particularly during a long trip, DC superchargers are also available. A supercharger can refill up to 80% SOC in a battery within about 15-30 minutes, and can add 100-150 km or higher travel range within 20 minutes. However, supercharging will lead to severe stresses in the battery on account of chemically liberated heat as well as I^2R. Hence the important criterion for opting for superfast charging is monitoring and control of cell temperature.

Typical fast charging pattern of a Li-ion battery consist of single or multiple constant-current constant-voltage (CCCV) step charging [21]. Fig. 18 compares the standard charging and the fast step charging of Li-ion batteries and the effects of these charging on their cycle life. Fast step charging involves charging the battery with a relatively high constant current during low SOC regions, and with increasing SOC, the charging current is decreased in steps. This philosophy is indented for limiting the cell temperature and thereby limiting the degradation; however, lithium plating will still occur and eventually reduce the cycle life.

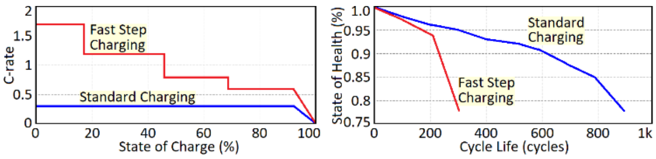


Fig. 18. Comparison of standard charging and fast charging of a typical Li-ion battery and the impact on cycle life.

In order to limit lithium plating and temperature driven degradation, some fast chargers provide pulse charging in which high charging currents are injected intermittently.

V. WAY FOREWORD AND FUTURE BATTERY TECHNOLOGIES

Lithium-ion batteries dominated the consumer market for over 20 years, powering devices ranging from small portable electronics to electric vehicles. Though cost of these cells is coming down, their future as the battery of choice for EVs is not very promising. The main reason for this is due to the fact that the electrode materials currently used in Li-ion batteries are reaching their performance limits. The specific capacity of present cathode materials is in the range of 100-180 Ah/kg and that of the graphite anode is 372 Ah/kg. In order to achieve longer drive range (600-800 km) in EVs per battery charge, lighter batteries with lower volume must need higher energy density electrode materials. Besides, other technical issues such as long charging times, limited cycle life and safety are still major concerns of Li-ion batteries.

For higher energy densities than the current Li-ion chemistries, metallic lithium is being proposed for the anode material. Fig. 19 represents the energy capacity of positive and negative electrode materials presently used and under considerations for the next generation Li-based rechargeable batteries. It can clearly be seen that the energy capacity of Li metal is almost 10-fold higher than graphite, which is the most common current anode material [6].

Important upcoming Li based battery technologies are: Lithium-metal (Li-metal), Lithium-air (Li-air), Lithium-sulfur (Li-S) and Solid-state Lithium. Fig. 20 shows the specific energy capacities of current and future batteries [22].

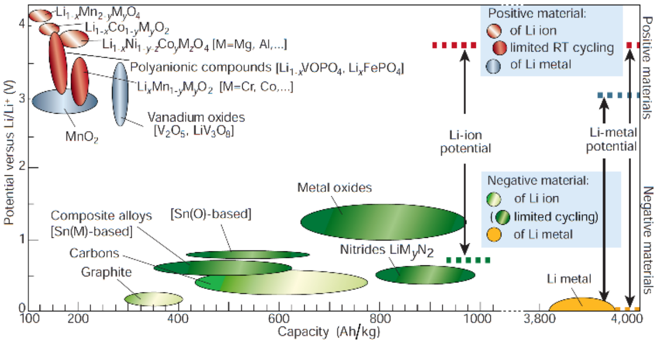


Fig. 19. Energy capacity of electrode materials presently used and under considerations for the next generation Li-based cells [6].

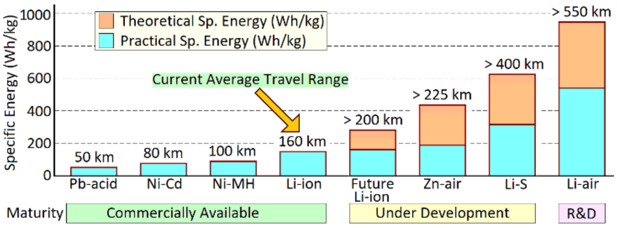


Fig. 20. A comparison of current and future battery capabilities [22].

The new battery technologies use solid electrolytes as against liquid electrolyte in conventional batteries. Major advantages of solid-state batteries include:

- Faster charging (up to 6x faster)
- Increased energy density (2x energy per unit volume)
- Increased cycle life (10 years, compared to 3 in Li-ion)
- Non-flammable components
- Very low leakage currents
- Wide temperature range, -20 to 100ºC

Battery technology has improved considerably during the last thirty plus years. Much research and development are being put on cell chemistry to improve their performance while ensuring that the batteries are compact, lightweight, safer and cost competitive.

REFERENCES

[1] M. Ehsani, Y. Gao, S.E. Gay, and A. Emadi, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, New York: CRC Press, 2005.

[2] H.B. Meiwes, J. Drillkens, B. Lunz, J. Muennix, S. Rothgang, J. Kowal, and D.U. Sauer, "A review of current automotive battery technology and future prospects", Proc. of the Inst. of Mech. Engineers, Part D: Jr. of Auto. Engineering, 227(5), pp. 761–776, April 2013.

[3] K. Young, C. Wang, L.Y. Wang, and K. Strunz, "Electric Vehicle Battery Technologies", in *Electric Vehicle Integration into Modern Power Networks*, R. García-Valle and J.A.P. Lopes (Ed), New York: Springer; 2013.

[4] https://www.epectec.com/batteries/cell-comparison.html

[5] Y. Miao, P. Hynan, A.V. Jouanne, and A. Yokochi, "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements", Energies 2019, 12, 1074, pp. 1-20, Mar 20, 2019.

[6] J.M. Tarascon, and M. Armand, "Issues and challenges facing rechargeable lithium batteries", *Nature*, vol. 414, no. 6861, pp. 359-367, Nov. 2001.

[7] "The Octagon Battery – What makes a Battery a Battery", available at https://batteryuniversity.com/learn/article/the_octagon_battery_what_makes_a_battery_a_battery

[8] https://aar.com/standards/pdfs/2018_LEAF-first-responders-guide.pdf

[9] https://insideevs.com/news/338432/nissan-leaf-40-kwh-battery-deep-dive/

[10] https://batteryuniversity.com/

[11] Is Li-Ion the Solution for the Electric Vehicle? Available online: https://batteryuniversity.com/learn/

[12] O. Erdinc, B. Vural and M. Uzunoglu, 'A dynamic lithium-ion battery model considering the effects of temperature and capacity fading', Int. Conf. on Clean Electrical Power, pp. 383-386, Capri, Italy, June 2009.

[13] B. Balagopal, C.S. Huang, M. Chow, 'Effect of Calendar Aging on Li Ion Battery Degradation and SOH', 43rd Annual Conf. of the IEEE Ind. Ele. Society (IECON 2017), pp. 7647-7652, Beijing, China.

[14] R. Spotnitz, 'Simulation of capacity fade in lithium-ion batteries', Jr. of Power Sources, vol. 113, pp. 72-80, 2003.

[15] J. Wen, Y. Yu and C. Chen, 'A Review on Lithium-Ion Batteries Safety Issues: Existing Problems and Possible Solutions', *Materials Express*, vol. 2, no. 3, pp. 197-212, Sept. 2012.

[16] https://www.mpoweruk.com/lithium_failures.htm

[17] S. M. Rezvanizaniani, Z. Liu, Y. Chen, and J. Lee, 'Review and recent advances in battery health monitoring and prognostics technologies for electric vehicle (EV) safety and mobility', *Jr. of Power Sources*, no. 256, pp. 110-124, 2014.

[18] M.S.H. Lipu, M.A. Hannan, A. Hussain, M. M. P.J. Ker, M.H.M. Saad and A. Ayob, "A review of state of health and remaining useful life estimation methods for lithium-ion battery in electric vehicles: Challenges and recommendations', Jr. of Cleaner Production, vol. 205, pp. 115-133, Dec. 2018.

[19] X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia and X. He, "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review*", Energy Storage Materials*, vol. 10, pp. 246–267, May 2018.

[20] Y. Xing, E.W.M. Ma, K.L. Tsui, and M. Pecht, 'Battery Management Systems in Electric and Hybrid Vehicles', Energies, no. 4, pp. 1840-1857, Oct. 2011.

[21] D. Kim, J. Kang, T. Eom, J. Kim, J. Lee and C. Won, 'An Adaptive Rapid Charging Method for Lithium-Ion Batteries with Compensating Cell Degradation Behavior', Applied Science, no. 8, 1251; pp. 1-12, July 2018.

[22] "Mesoporous Materials for Advanced Energy Storage and Conversion Technologies", edited by S.P. Jiang, J. Liu, CRC Press, 2012.

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