Lithium-ion Batteries for EVs

Course No: E06-009
Credit: 6 PDH

A. Bhatia

CED CANADA
engineering.ca
CPD FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

TABLE OF CONTENTS

1 CHAPTER - 1: OVERVIEW OF ELECTRIC VEHICLES

The automotive industry is fast moving away from traditional internal combustion (IC) engines towards electric vehicles (EVs). The global fleet of light-duty EVs has grown from a few thousand vehicles just a decade ago to around 10 million vehicles in 2020. The increased acceptance of EVs is the outcome of a number of factors, including technological advancements in battery energy storage, as well as lower costs, faster charging capabilities, and greater interest in global environmental issues and decarbonization.

Currently, the Lithium-ion (Li-ion) battery technology is the core enabling technology for EVs. Like any other battery, Li-ion batteries store energy chemically and release it electrically. Lithium-ion cells allow great amounts of energy to be crammed into a small package, allowing for faster energy extraction. New cell chemistries are being developed to make batteries lighter and store more energy in smaller packs, allowing EVs to have longer driving range per recharge.

To meet the needs of the fast-growing EV market, major breakthroughs in material chemistry are still needed, which include increasing the true range of electric cars from 300 to 600 km without recharging, reducing charging time to less than 15 minutes, and attaining cost parity with IC engines.

1.1 Electric Vehicles (EVs)

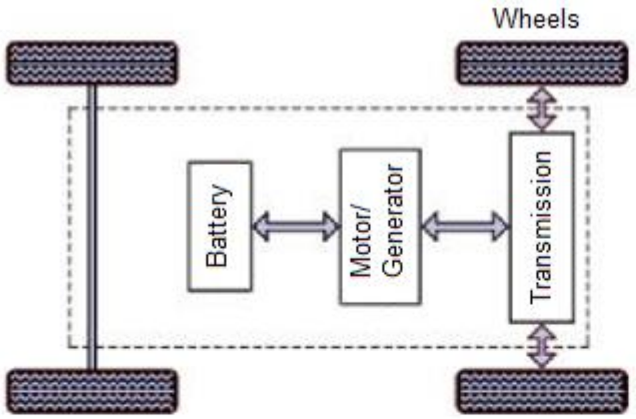
Electric vehicles (EVs) are powered by electricity through series of batteries and drive motors instead of IC engines in conventional vehicles.

Sure, all cars have batteries already, but they're only used to start an IC engine, then the fuel does all the work. In contrast, EVs get their entire energy from batteries for traction. EV battery packs are typically made of a series of connected individual cell modules stacked together to provide a pretty high voltage of 100-400 volts to run an EV. A fully charged battery can last up to 200 kilometers on a single charge depending on the battery capacity.

Compared to conventional fuel vehicles, EVs have a much-simplified drive train. They do not require clutch or multi-speed transmissions because the electric motors produce a consistent amount of torque instantly at any given RPM within a specific range. The differential gear is replaced by using one or two traction motors to drive the front wheels. Depending upon the complexity of the design, the drive motor of an EV can be a single reversible motor/generator or individual motors and generator.

The electric car is powered by three primary components: the motor, the controller, and the batteries. The controller collects and distributes electricity from the batteries to the motor. The accelerator pedal is connected to the potentiometer, which informs the controller about how much power the motor requires.

Basic structure of an EV is shown in Figure below.



Basic Structure of an Electric Vehicle

The battery pack is one of the most important and critical components of an EV and is the major contributor to the cost of the EV. Broadly, there are two types of EVs: Hybrid vehicles and the All-electric vehicle.

a. Hybrid vehicles use both the gasoline and electric motor drivetrains. The battery-powered motor can provide traction independently and/or provides a performance boost to the gasoline engine.
b. For all-electric vehicles, the battery is the only source of energy that provides the traction power. These vehicles will not function without a high-performance battery.

Auxiliary services such as vehicle lighting, air conditioning, hydraulic transmission, braking, and controls are all powered by the battery. The battery pack can be recharged either externally or internally in case of hybrid vehicles.

The figure below shows what an electric car battery looks like, and where the batteries and the motor could be stored in a car.

Tesla Model S

(Source: Wikimedia Commons)

Chassis of Tesla Model S displaing Batteries and Motors

You may notice in the figure that the batteries are covering the entire chassis and connected to the traction motor in the front wheels. The in-wheel arrangement, which uses individual motors at each wheel, is the most recent advancement in electric vehicles. It is possible to regulate the drive torque and braking force independently at each wheel without the need for any complex transmission or drive shaft.

1.2 Comparison of IC Engine Vehicles v/s Electric Vehicles

A brief comparison of IC engine vehicles vs. electric vehicles is shown in the Table below.

Parameters	**IC Engine (ICE) Vehicles**	**Electric Vehicles (EV)**
Powertrain	IC engine	Motor + battery (for all-electric vehicle) Motor + battery + IC engine (for hybrid electric vehicle)
Fuels	Uses only hydrocarbons (Petrol, diesel or CNG)	Battery - uses electricity from many resources (wind, power or thermal)
Specific energy (refer note 1)	High specific energy of fuel	Low specific energy of battery
Power density	High	Low
Emissions	Emits greenhouse gases	No emissions
Travel range	> 300 miles / fill	< 125 miles / charge

Refueling time	Short refilling time (< 5 min.)	Long charging time (0.5-8 hr.)
Volume	Fuel tank takes less space	Battery takes large space
Weight	Fuel weight is very less	Batteries are very heavy
Maintenance	Higher maintenance costs	Lesser maintenance costs
Energy recovery	Braking energy not recovered	Can recover braking energy
Running costs	High	Low
Efficiency	Engine efficiency: ~ 30%	Motor efficiency: ~ 80%
Drivetrain	Needs complex gear, clutch, and differential system	Simple motor
Noise	Noisy	Quiet
Infrastructure	Ample refilling infrastructure	Lacks charging infrastructure
Torque	Need to pick up some speed to deliver maximum torque	Produce maximum torque instantly

Note -1: Specific energy is defined as the amount of energy that can be stored in a battery system per unit weight (Wh/kg). There is another term “energy density”, which is defined as the amount of energy per unit volume (Wh/litre). Both terms – specific energy and energy density – are frequently interchanged.

The biggest advantage of IC engine vehicles is the long driving range due to the high energy density of petroleum fuels. We can drive our cars for more than 300 miles, fill up anywhere in 5 minutes. These cars can last a decade and go hundreds of thousands of miles if they are properly maintained.

In contrast, the EVs powered by batteries have challenges like short driving range, slow recharging, a lack of sufficient charging stations, limited lifetime, fire safety, and high cost, all of which impede their widespread adoption. The EV industry is currently focused on Lithium-ion (Li-ion) batteries, which have proven to be a reliable technology with potentially decreasing costs. However, they are still around a hundred times less efficient than gasoline. The specific energy of petrol is ~12,700 Wh/kg by mass whereas the Li-ion battery has an average specific energy of around 150 - 200 Wh/kg depending on the type of materials used in the battery. Furthermore, compared to IC engine vehicles, the cost of batteries is too expensive, and the battery lifespan is too short.

In the meantime, the car industry has continued to enhance battery performance while lowering costs, driven by growing environmental concerns and oil resource restrictions. EVs have some clear advantages over conventional gasoline vehicles.

1.2.1 Advantages of Electric Vehicles

Electric vehicles have a significant role in transport decarbonization on a macro level. Here are a few advantages of EVs.

a. Eco-friendly - zero tailpipe emissions.
b. Charging an electric car costs much less than paying for an equivalent amount of gasoline.
c. Charging may be done at home or parking lots. Very eco-friendly when the solar or wind generated electricity is used for recharging.
d. Makes little noise and provides fast response to the driver's decisions.
e. Easier to assemble because of few moving parts. The batteries are positioned flat all over the chassis, maintaining a lower center of gravity. This makes them less likely to roll over and improves ride quality.
f. Cheaper to maintain.
g. Tax credits and rebates from the government as you are contributing to a greener environment.

So, why aren't electric cars everywhere already? It's because batteries are expensive, making the upfront cost of an electric car much higher than a similar gas-powered model. In short, electric cars are still not cost-effective, and major improvements in battery technology are required before they can be deployed on a large scale.

1.3 Battery Technology

The most critical component of an EV is the electricity storage system, i.e., the battery. The three common rechargeable battery technologies are:

a. Lead-acid batteries
b. Nickel–Metal Hydride (Ni–MH) batteries
c. Lithium-ion batteries

1.3.1 Lead-acid batteries

Lead-acid batteries are commonly used to start your car engines. These are recharged by using a little generator connected to the engine, called the alternator.

In the early version of General Motors' EV1, lead-acid batteries were used for electric traction. Due to poor specific energy (30-40 Wh/kg) and low energy density (80-100 Wh/L), lead-acid batteries lost the EV market despite being less expensive. At present, these batteries are used for traction only in electric two-wheelers, forklifts, and e-rikshaws.

1.3.2 Ni-MH batteries

Nickel metal hydride (Ni-MH) batteries were introduced in hybrid EVs in 1997. When compared to lead-acid batteries, the Ni-MH batteries were relatively more powerful in terms of specific energy (60-120 Wh/kg) and energy density (140-300 Wh/L). This allows for smaller size and compact space for accommodating batteries, but the major drawback is that these batteries are self-discharging. These batteries lose up to 12.5% of their charge per day under normal room temperature conditions that is exacerbated at high temperatures. This makes Ni-MH batteries less ideal for hotter environments.

1.3.3 Lithium-ion batteries

Lithium-ion (Li-ion) batteries have surpassed lead-acid and nickel-metal-hydride (Ni-MH) batteries in the EV industry. Their high specific energy (150-250 Wh/kg) and high energy density (> 600 Wh/L) are the primary reasons. This implies that Li-ion batteries are substantially lighter and smaller than other types of batteries while maintaining the same storage capacity.

The Li-ion battery is the most used type of battery used in electric vehicles. Li-ion batteries are favored because:

a. They can hold a lot of energy for their weight, which is vital for electric cars because the car can travel further on a single charge with less weight.
b. They have a high energy retention rate and a low self-discharge rate - typically less than 5% per month. This means that Li-ion batteries can hold most of the charge while not in use.
c. They don't suffer from a problem known as the "memory effect". The battery memory effect is a reduction in the longevity of a rechargeable battery's charge, due to incomplete discharge in previous uses.

d. Most lithium-ion battery parts are recyclable, making these batteries a good choice for the environmentally conscious.

Li-ion batteries do have some drawbacks as well.

Comparatively, it is quite an expensive technology. Overcharging and overheating of these batteries is a significant safety concern. Li-ion can experience a thermal runaway, which can trigger vehicle fires or explosions. There had been serval instances where the Tesla Model S, which utilized Li-ion batteries, had infamously caught on fire due to issues with fluctuating charging or damage to the battery. However, great efforts have been made in battery management systems to help improve the safety of vehicles that use Li-ion batteries.

There are many types of Li-ion batteries depending on the exact combination of materials used for the anode and cathode. The most popular for EV use are the nickel cobalt aluminum (NCA), nickel cobalt manganese (NCM), and lithium iron phosphate (LFP) cathodes.

1.4 Key Performance Indicators for Electric Vehicles

The nine key performance indicators of a battery from an electric mobility perspective are listed in the table below.

S no.	Property	Metric	Description
1	Battery rating or Battery capacity	Ah or kWh	Battery capacity gives an idea of how far the EV can be driven (travel range) with the stored energy. A high-capacity battery will be able to keep going for a longer period before going flat/running out of power. Small EVs usually come with batteries of capacity 12–18 kWh, the mid-sized ones have 22–32 kWh pack and the luxury models can have batteries of 60–85 kWh to provide an extended driving range. For buses, it is 90-150 kWh or higher.
2	Capital cost	$/kWh	The upfront cost to buy a battery (excluding O&M). The batteries must be affordable to reduce the overall cost of EVs.
3	Safety	-	Resistivity against thermal runaway. Ability to operate in wide thermal ranges. Use non-toxic materials.

4	Cycle lifetime	# of cycles	Amount of cycles a battery can be discharged from 100% to 20%, until capacity fades to 80% of its original capacity.
5	Specific energy or energy density	Wh/kg or Wh/L	Amount of energy that a battery can hold, measured by weight or volume. The specific energy depends on the design of the cell and the constituents of cathode and anode materials. The specific energy expressed in Wh/kg defines the weight or mass of the battery. Larger the better. The energy density (volumetric capacity) expressed in Wh/L, governs the size and compactness of the battery. Larger the better.
6	Power density	C-rate	The rate at which a battery is discharged relative to its maximum capacity and is directly dependent on its voltage.
7	Energy consumption	Wh/km or km/Wh	The mileage or the energy consumption of vehicle. 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. The typical energy consumption of a mid-sized EV varies between 165 - 250 Wh/km (or 4 to 6 km/kWh). For example, BMW i3 consumes 165 Wh/km and Tesla S85 consumes up to 240 Wh/km.
8	Charging time	C-rate	The rate at which a battery is charged relative to its maximum capacity. Depending on the type of battery, a vehicle recharge may take as little as 30 minutes (via fast charging) or up to a full day (when using Level 1 charging).
9	Reliability	-	The ability to operate in low temperatures or in extreme conditions.

10	Others	-	Other properties, such as maintenance costs, shelf lifetime, self-discharge, or charging efficiency.

1.4.1 Specific Energy and Energy Density of Battery

The most important feature of a battery is its specific energy, often known as energy density. These variables have a direct impact on the EV's weight and size. Let's have a look at an example.

Consider a standard gasoline car, such as the Toyota Corolla, which has a range of 200 kilometers on 20 gallons of gasoline. Assume a mileage of 10 kilometers per liter. With a density of about 890 kg/m^3, 20 liters of gasoline would weigh 17.8 kg.

$$\frac{20\text{ litre x }890\text{ kg/m}^3}{1000\text{ litre/m}^3} = 17.8\text{ kgs}$$

Now, if you need a 200 km comparable range from an EV, the battery size would be 50 kWh, assuming a battery mileage of 4 km/kWh.

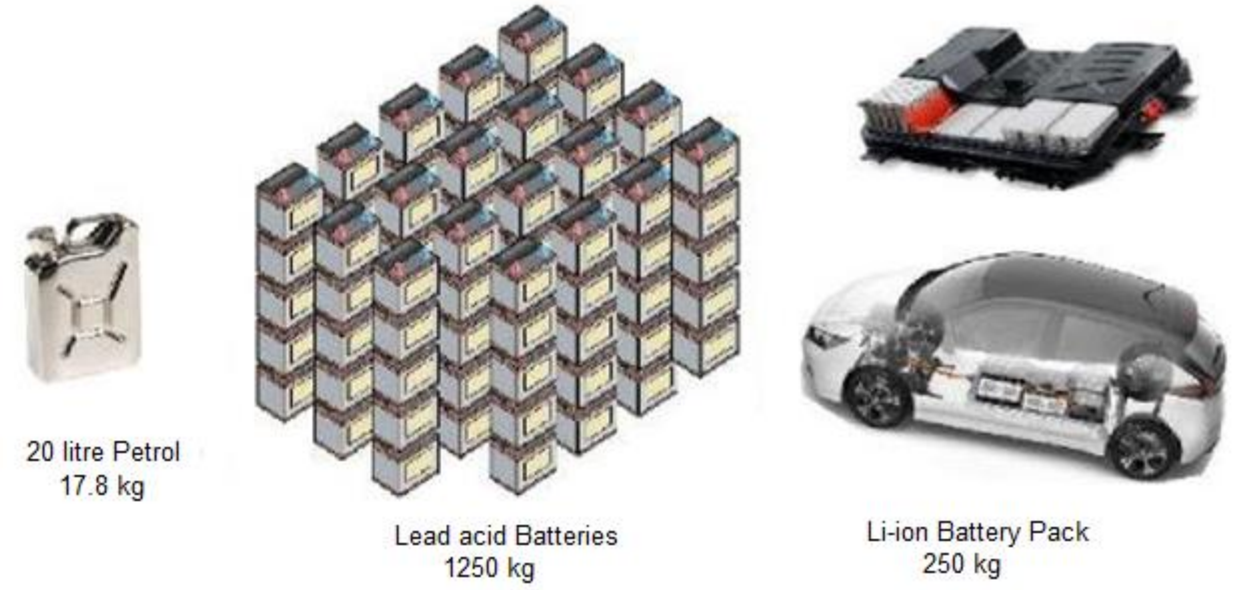
$$\frac{200\text{ km}}{4\text{ km/kWh}} = 50\text{ kWh}$$

When you choose a state of art 50 kWh-capacity Li-ion battery with a specific energy of 200 Wh/kg, the weight would be approximately:

$$\frac{\text{Energy capacity (kWh)x }1000}{\text{Specific energy (Wh/kg)}} = \frac{50\text{ x}1000}{200} = 250\text{ kg}$$

The equivalent lead-acid battery will weight roughly 1250 kg with a specific energy of 40 Wh/kg.

$$\frac{\text{Energy capacity (kWh)x }1000}{\text{Specific energy (Wh/kg)}} = \frac{50\text{ x}1000}{40} = 1250\text{ kg}$$



Size Comparison for a Travel Range of 200 Kms

Clearly, a battery pack containing the same amount of energy as a 20-liter gasoline tank would be too heavy and enormous in volume. When comparing Li-ion batteries to lead-acid batteries, the Li-ion battery pack is substantially lighter and more compact due to its high specific energy.

Li-ion batteries are experiencing continuous technological improvements and are providing higher energy density and lower manufacturing costs. The current achieved highest gravimetric and volumetric energy densities at the cell level are 250 Wh/kg and 670Wh/L (based on 18650-type cells). The costs have fallen dramatically due to technology, production volume and market dynamics. The battery pack costs have dropped from $1,000/kWh to <$250/kWh in the last decade.

1.5 Lithium Ion Battery Pack for EVs

The Li-ion battery pack for EVs comprises of 3 parts:

a. Cells
b. Modules
c. Pack

Lithium -ion cell

Pouch or Cylindrical Cell

Module

Module for Pouch Cells

Pack

Pack for Pouch Cells

1.5.1 Cells

A ‘cell’ performs the primary functions of a rechargeable ‘battery’. Cells come in varied formats:

a. Cylindrical Cells
b. Pouch Cells
c. Prismatic Cells

1.5.2 Module

A 'module' is a structure that connects multiple cells, providing them with a mechanical support structure and thermal interface. Modules are designed according to cell format, target pack voltage and vehicle requirements.

1.5.3 Pack

A ‘pack’ is formed by connecting multiple ‘modules’ with sensors and a controller and then housing the unit in a case. Electric vehicles are equipped with batteries in a ‘pack’ state which are connected to the powertrain.

We will learn more about the battery construction later in this course.

1.6 Challenges Facing EVs

The most important thing influencing the customers’ preference towards EVs is the battery technology – its reliability, durability, safety, etc.

Batteries need improvements in the following:

a. Range or mileage
b. Battery charging
c. Lifespan/number of cycles
d. Battery costs
e. Environmental issues

f. Safety issues

1.6.1 Range or Mileage

The number one source of concern among customers is the "range or mileage" from the EVs. The customers are concerned about getting stranded due to poor battery performance or the inability to locate a charging station before the battery runs out.

Based on current battery technology, a pure EV with a driving range of 300-400 miles on a single charge is not feasible, since it would necessitate a battery larger than 100 kWh that can weigh over 900 kg.

Batteries are the key differentiators between the various EV manufacturers. Manufacturers have spent millions to improve the range of EVs. The primary differentiation between the various EV manufacturers is the batteries. Manufacturers have invested millions of dollars to increase the range of electric vehicles. Current generation of EVs are capable of traversing equivalent or more distance than a conventional vehicle can travel with a full tank (Tesla Model S 100D has a range of almost 564 km on 19″ wheels when the air conditioning is off).

The travel range is further affected by the vehicle's speed, driving style, the load it is carrying, the terrain it is travelling on, and the energy-intensive services it is operating, such as air conditioning.

1.6.2 Battery Charging

The next major goal of EV makers is to charge the battery at rates comparable to refilling a gasoline or diesel automobile. Two conditions must be met to achieve this goal:

a. The charger must be capable of providing a large amount of power, and
b. The battery must be able to absorb a high amount of power at a faster rate

The availability of rapid chargers while keeping a decent cycle life is one option to address the long charging time. Tesla, for example, has created its own high-voltage DC supercharger that can deliver a full charge in less than 20 minutes. Furthermore, research is being conducted on future charging systems that may not even require a physical connection and will be able to charge wirelessly.

Future battery systems may combine ultra-capacitors with batteries that can have very high charge and discharge rates to address the long charging time.

Use of plug-in hybrid (PHEV) vehicles, which benefit from a dual-energy feed and can be driven without the need to be plugged in is another option.

1.6.3 Lifespan

The lifespan of Li-ion batteries is generally expressed in terms of the number of charge-discharge cycles they can withstand before their capacity degrades. Temperature, discharge current, charge current, and state of charge ranges are all factors that affect battery cycle life (depth of discharge).

Advanced Li-ion cell can withstand around 1000 charge-discharge cycles if used very carefully and still be able to hold 80% of its initial capacity. Typically, battery management chips are incorporated into the battery packs, which enhances battery life by controlling the charge and discharge rates.

The large battery packs are costly, and they may need to be replaced one or more times before the EVs reach their full life cycle. For example, electric cars tend to last around a decade or longer, usually 10 to 15 years. Battery degradation in EVs may result in a considerable reduction in range and the eventual battery replacement. The current battery technology in automotive applications is likely to last up to 5 years.

1.6.4 Battery Costs

The EV sales are constrained by the cost of batteries. The larger the EV, the more batteries it will have, and the more expensive it will be. That's why most of the EVs available today are typically smaller or mid-sized.

Three critical constituents of battery cathode material are cobalt, nickel, and manganese. The estimated prices of cobalt, nickel, and manganese in the year 2018 were USD 61,499/ton, USD 11,701/ton, and USD 2,000/ton respectively. The drop in Cobalt content can obviously have a considerable impact on the battery's cost. Increasing the battery's nickel and manganese content is certainly beneficial.

The current mainstream battery technologies operate on NMC 111, NMC 442, and NMC 532. The percentage of nickel, manganese, and cobalt in the combination is represented by each digit in the number. The Nickel: Manganese: Cobalt ratios in NMC 111, NMC 442, and NMC 532, for example, are 1:1:1, 4:4:2, and 5:3:2, respectively. The new battery trends point to NMC 811, which has a Nickel: Manganese: Cobalt ratio of 8:1:1. This would result in a decrease in cobalt use and battery costs while having no substantial impact on performance.

According to Bloomberg New Energy Finance, the global average cost of lithium-ion batteries in 2018 was under $200 per kWh, down from roughly $1,000 in 2010. The US Department of Energy (DOE) analysis indicates that once battery pack costs fall below $125 per kWh, owning and operating an electric car will be comparable with a gas-powered car. The deadline has been set for 2022.

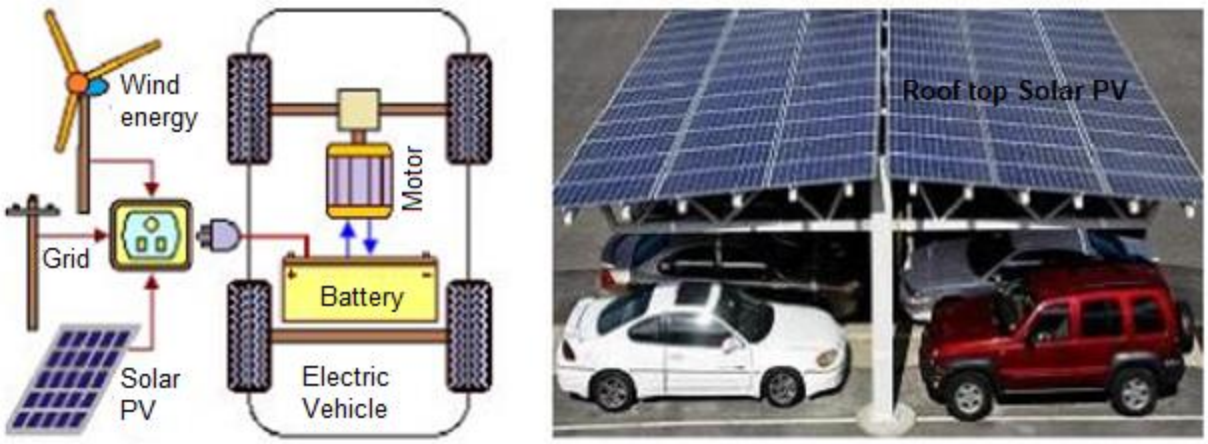
The cost of batteries is expected to decrease significantly as the market increases and production scales up, often through large-scale factories that are sometimes referred to as “Gigafactories”. By 2025, Tesla hopes to have battery packs costing less than $100 per kWh. Tesla aims to build more Gigafactories in New York and Europe in addition to the one in Nevada. Battery costs will continue to fall as battery production capacity grows, which is very favorable for future market penetration of EVs.

1.6.5 Environmental Issues

While most of the population believes that the batteries and EVs are emission-free and a good solution to urban air pollution, the battery production process consumes the most energy and has environmental impacts related to the mining.

Furthermore, electric vehicles move emissions from the street (where you and I breathe them) to the power plant, which most people consider to be a positive. Most of the power is still generated by burning fossil fuels, primarily coal or natural gas, which has significant environmental consequences. So perhaps these batteries aren't as clean as we believe.

Using renewable energy resources such as wind or solar PV is one method to address the charging problem. For example, during the idle parking time, the parking lot rooftop solar PV can provide battery charging.



Renewable Charging

1.6.6 Safety Issues

The following potential risks and dangers exist with the high-voltage batteries:

a. Electric danger (short-cut)
b. Fire and explosion
c. Danger out of chemical reactions
d. Thermal danger out of high temperatures
e. Mechanical danger because of the higher weight of the battery components

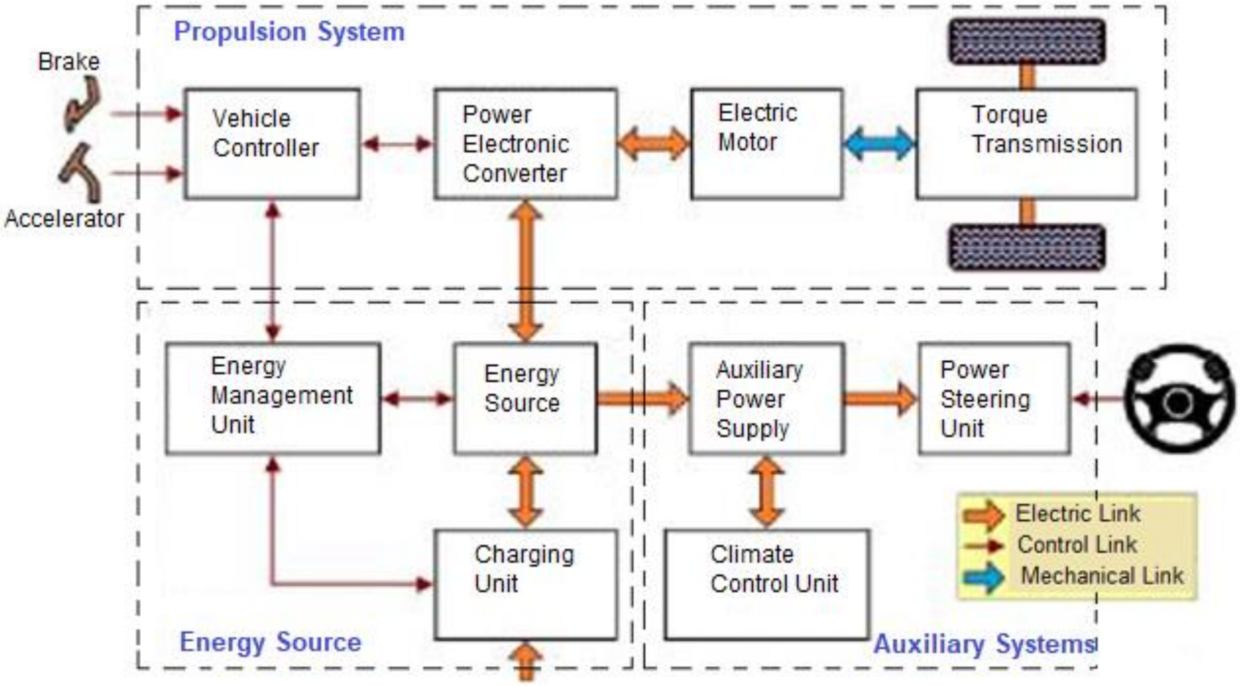
Because of the special characteristics and risks of the battery technology, a battery management system is required for Lithium-ion battery, which monitors and manages the battery's performance (temperature, current, voltage, isolation, etc.) while in use.

2 CHAPTER - 2 TYPES OF ELECTRIC VEHICLES (EVs)

An electric vehicle (EV) is a vehicle that is powered entirely or at least in part by electricity (battery).

An electric vehicle's drive train is made up of three key subsystems: propulsion, energy storage, and auxiliary subsystems.

a. The **propulsion** system consists of the controller, power electronic converter, electric motor, transmission system.
b. The **energy** source section includes the energy source, energy management unit and the energy charging unit.
c. The **auxiliary** subsystem consists of power steering unit, climate control unit, and auxiliary supply unit.



Basic Arrangement of an EV Drivetrain

This chapter will provide a few essentials of EVs.

2.1 Types of EVs

According to the drive train configuration, electric vehicles can be classified into 3 basic categories:

a. All Electric Vehicle (AEV)

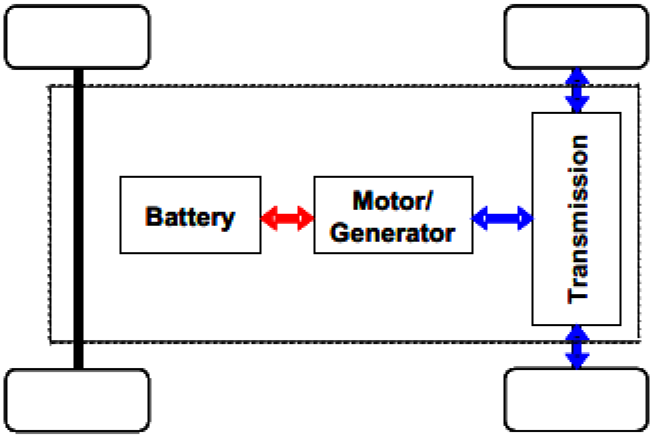
b. Hybrid Electric Vehicle (HEV)
c. Plug-in Hybrid Electric Vehicle (PHEV)

All EVs have the regenerative braking systems to recover energy otherwise lost as heat due to friction during braking.

2.2 All-Electric Vehicle (AEV)

All-electric vehicle (AEV), also known as a "Battery Electric Vehicle (BEV)," is a vehicle that is powered entirely by rechargeable battery packs. There is no additional fuel source, and no internal combustion engine used (ICE). As a result, the AEVs usually have larger storage batteries than hybrid electric vehicles (HEVs).

A basic AEV system is shown in the Figure below.



Schematic of All Electric Vehicle (AEV) Powertrain

The motor gives propulsion to the wheels and is powered by a battery pack, as shown in the figure. When the battery pack's capacity is depleted, it is recharged outside. The amount of time it takes to charge is determined by the charger's configuration and operating power level. The turbochargers can entirely recharge a vehicle in less than 30 minutes, whereas traditional home plug charging might take up to 24 hours.

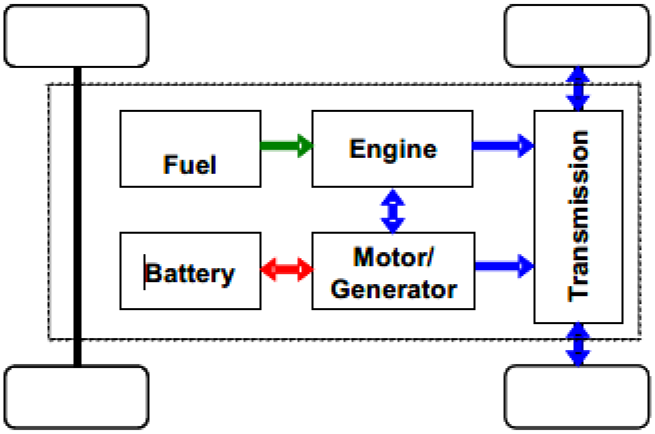
Examples: AEVs on the market include the Nissan Leaf, Tesla Model S and X, Chevrolet Bolt and Spark, and BMW i3 BEV.

2.3 Hybrid Electric Vehicles (HEV)

A hybrid electric vehicle (HEV) uses both an IC engine and electric motor drive trains. The main driving power is the IC engine, but the two drive trains can work together to increase performance by filling in the gaps between gear shifts and delivering speed boosts when needed. The electric motor is powered by batteries, which are charged by the engine-driven generator. The batteries do not need to be plugged into external source for recharge.

A hybrid car employs its electric motor as its workhorse during slow driving (e.g. city travel, traffic jams, or idling at stoplights), reducing the need to use gasoline on its other engine. Mileage, fuel efficiency, power, turbo-lag, and emissions are all improved. The electric motor also offers assistance during accelerating, passing, and hill climbing when the conventional gasoline engine works heavily. A traditional car loses energy while coasting and braking. In hybrid cars, however, the energy is used to recharge the batteries.

A simple Hybrid system is shown in the Figure below.



Schematic Arrangement of HEV

A hybrid vehicle is much more complex and costly because it has two powertrains. Aside from that, compared to vehicles with a single powerplant, upkeep is more expensive. Hybrid electric vehicles are attractive because they lessen range anxiety and increase the reliability of long-distance travel.

Examples: The most widely driven HEVs include Acura NSX, Honda Insight and Toyota Prius.

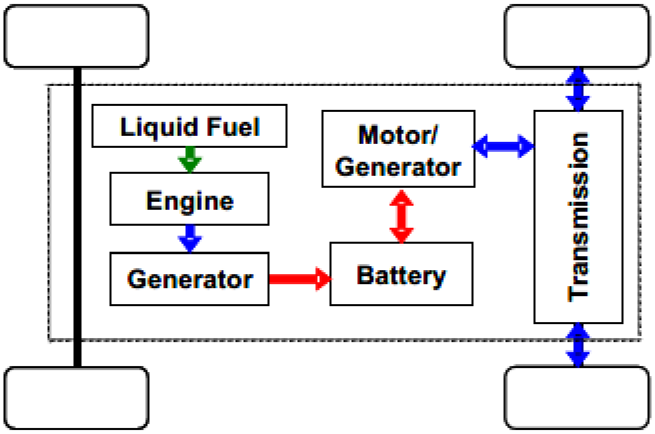
2.3.1 Different Types of HEVs

There are two main types of hybrid vehicles: the series (or "mild") hybrid vehicle and the parallel (or "full") hybrid vehicle. These titles have a lot to do with how the electric motor and the engine work together to provide power to the vehicle.

2.3.1.1 Series PHEVs

The Series Hybrid Vehicle connects the gas-fueled engine to the battery by means of a generator, which converts the mechanical energy produced by the engine into electrical energy that is stored in the battery. The battery, in turn, powers the electric motor that moves the vehicle. Thus, the engine itself has no direct connection to the transmission and does not contribute directly to turning the wheel axle.

When the traction load demand is large, the IC engine coupled to a generator charges the battery. For small trips, liquid fuel is not used at all and a fully charged battery capacity will suffice the mileage. During braking and coasting, the motor can also function as a generator.



Schematic of a Series Hybrid powertrain

Series hybrids are the most efficient in driving cycles that require frequent stops and starts such as for delivery vehicles, urban buses and stop and go city driving.

The drawbacks of Series hybrid are:

a. Requires separate generator and motor sections (which means more systems and higher costs)
b. Requires a large size drive motor rated for maximum power requirements, such as climbing uphill. However, since series hybrids use a bigger electric machine in the propulsion system, their energy recovery capability is much higher than other HEVs. Example: Nissan e-Power.

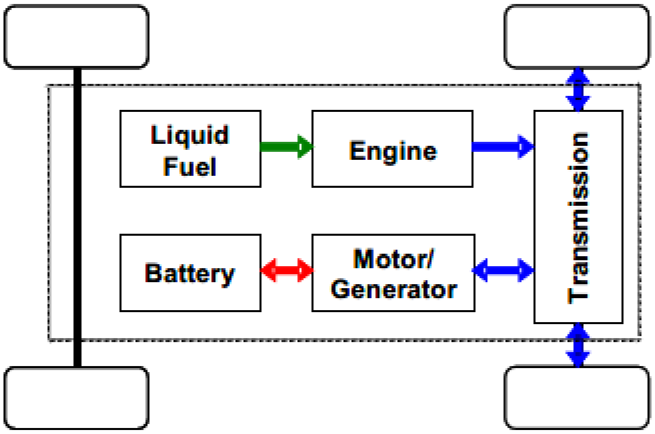
2.3.1.2 Parallel Hybrid EVs

The Parallel Hybrid Vehicle allows for both the engine and the electric motor to be independently connected to the transmission. This means that any of the two drivetrains can be used to propel the vehicle at any moment, or both can work simultaneously during periods of high-power demand. Since the engine is smaller, this design offers the advantage of being able to provide more power or acceleration to the vehicle.

Electric-only functioning is typically limited at low speeds (between 10 and 50 kilometers) before switching to gasoline to power the internal combustion engine. The generator and motor are usually combined into one unit in most HEV designs. The given torques are summed together in parallel driving mode. When only one of the two drives is in use, the other is disengaged through a clutch.

The drawback of parallel HEV is the need for complex mechanical systems and control algorithms because of the need to efficiently couple the motor/generator and engine in a way that maintains drivability and performance.

Example: Honda: Insight and Civic.



Schematic of a parallel hybrid powertrain

2.4 Plug-in Hybrid Electric Vehicles (PHEVs)

A plug-in hybrid electric vehicle works using many of the same principles as the ordinary hybrid vehicles discussed previously. The primary difference is that it aims to provide customers "the best of both worlds" by incorporating plug-in charging technology into the design.

Unlike normal HEVs, PHEV batteries can be recharged from any external power source, whereas standard HEV batteries can only be recharged via the engine-driven generator or regen-braking. PHEVs start in electric mode and run on battery power. When the battery power runs out, the engine kicks in to charge the battery, extending the electric range.

Examples: Toyota Prius was the first commercial hybrid car launched in 1997 and is still the most successful car today. The other examples are Chevrolet Volt, Ford Fusion Energi, and BMW 330e.

2.5 Efficiency Features of EVs

2.5.1 Regenerative Braking

Regenerative braking is a term used to describe another way in which an electric vehicle can be more efficient with energy. It works like this: when the engine (or battery) is used to speed up the car, a certain amount of chemical (or electrical) potential is converted into kinetic energy. But when the vehicle brakes and slows down, this energy is lost to the environment as heat.
Regenerative braking works by capturing some of the kinetic energy lost while braking and converting it into electrical energy that may be stored in the battery and used later.

2.5.2 Power-Split Devices

A power-split device is unique to the hybrid vehicle and is key to the hybrid's success as an alternative transportation vehicle. It works much like its name suggests. It performs just as its name says. It enables an engine to split its power so that it can use its energy to do two tasks at the same time, namely:

a. Propel the vehicle
b. Charge the battery

This device is important in a hybrid vehicle since it allows the battery to be charged without using power from the grid. It also allows the electric motor and engine to work independently or in tandem to propel the vehicle.
The battery is the only source of energy in an electric vehicle. Until now, the energy density of these batteries has been low, which means you'll have to carry more weight to do the same amount of work as a gasoline-powered vehicle. The challenge is exacerbated by the fact that the electric car must be heavier and hence more difficult to accelerate. The hybrid overcomes these issues by obtaining a portion of its energy from gasoline while also ensuring that it is used in the most efficient manner possible. This is largely due to the power-split device.

2.5.3 Electric Motor Drive/Assist

The electric motor provides additional power to assist the engine in accelerating, passing, or climbing hills. This allows a smaller, more efficient engine to be used. In some vehicles, the motor alone provides power for low-speed driving conditions, where internal combustion engines are the least efficient.

2.5.4 Automatic Start/Shutoff (also called start-stop)

This feature automatically shuts off the engine when the vehicle comes to a stop and restarts it when the accelerator is pressed. This prevents wasted energy from idling. This is the characteristic technology in micro-hybrids, which do not have the regenerative braking and electric drive assist functions of full HEVs.

2.5.5 Comparison of Different EV Variants

The table below provides the comparison of different vehicle variants considering 100-kW power capacity.

Vehicle Type	**Engine**	**Motor**	**Battery**	**Battery Function**
Conventional IC engine	100kW Full transient	Starter motor Stop/start	12V 3kW, 1kWh	Engine starting (3kW, 2-5Wh) Ancillary loads (400W average, 4kW peak, ~1kWh)
AEV	No Engine	100kW Full EV mode	300-600V 100kW, 30-80kWh	Provide sole power and energy source
Series HEV (Mild hybrid)	90-100kW Full transient	3-13kW Torque boost/re-gen	12-48V 5-15kW, 1kWh	Absorb regenerated braking energy
Parallel HEV (Full hybrid)	60-80kW Less transient	20-40kW Limited EV mode	100-300V 20-40kW, 2kWh	Support acceleration
PLUG-IN HYBRID (PHEV)	40-60kW Less transient	40-60kW Stronger EV mode	300-600V 40-60kW, 5-20kWh	Provide primary power and energy

2.6 Commercialization of EVs

The first prototype production car to use lithium-ion batteries was the Toyota Vitz CVT 4, a small car only sold in Japan. It used a four-cell, 12 ampere-hours lithium-ion battery pack to power its electric accessories and restart the engine after an idle stop.

Tesla, the world's largest electric vehicle manufacturer, produces vehicles with battery systems of up to 110 kWh. These vehicles can store enough energy to operate a 60-watt light bulb for 76 days and the Tesla Model S for 400 miles. Their newest battery pack will likely contain several thousands of Tesla's very own 2170 lithium-ion cells. The 2170 Tesla lithium-ion cells are 10-15% more energy efficient than the Panasonic 18650 cells at work in previous models. Tesla's 100kWh battery solution, which is based on the 18650 cell type (18mm x 65mm), has 8,256 cells (12Ah/cell) distributed evenly across 16 battery modules. This cell is capable of driving the Model S for 300 miles. In 2020, the new Tesla Roadster is set to become the first electric car that offers 1,000 km (620 miles) on a single charge.

The new Porsche Taycan, which is Porsche's answer to Tesla's high-performance electric vehicle, the Model S Performance, has a 93.4kWh battery that produces 800V instead of the typical 400V found in most other electric vehicles. The Taycan's battery is made up of 33 battery modules, each with 12 cells, for a total of 396 lithium-ion cells with a storage capacity of 235.8 Wh per cell. Because battery charging speed is limited by current, the higher voltage these cells produce means lighter battery and faster charging. However, this high-power battery system presents unique design challenges and requires more advanced power conversion and current protection for the vehicle's operational subsystems.

The Prius Prime, Toyota's most popular PHEV, has an 8.8 kWh battery pack that allows it to achieve nearly 55 MPG in the city. Drivers can charge the 8.8 kWh battery at home or on the drive, and because the Prius Prime consumes more electricity than gasoline, it saves money at the pump. The Prius Prime is powered by five battery stacks, each containing 19 LI cells (95 cells) that combine to a total capacity of 8.8kWh.

There are numerous successful commercial versions available today, ranging from the most affordable Nissan Leaf to the high-end Tesla Model-S. The major models are shown in the table below as of 2020.

2.6.1 Major EV Models as of 2020

Manufacturer	Model	Range (miles)	Battery size (kWh)	Battery manufacturer	Battery pack assembly location	Battery cell production location
Tesla	Model S	259 – 335	75 or 100	Panasonic/ Tesla	USA	Japan
Tesla	Model X	295	75 or 100	Panasonic/ Tesla	USA	Japan
Tesla	Model 3	220 – 310	50−74	Panasonic/ Tesla	USA	United States
Chevrolet	Bolt EV	238	60	LG Chem	USA	South Korea
Nissan	Leaf	151	30	Automotive Energy Supply Corp.	USA	United States
Fiat	500e	84	24	SB Li-Motive	USA	USA
VW	e-Golf	126	35.8	Samsung SDI Hungary	South Korea	
Ford	Focus Electric	118	33.5	LG Chem	USA	USA
BMW	i3	114	22−33	Samsung SDI	South Korea	Hungary
Kia Soul	EV	111	27	SK innovation	South Korea	South Korea

2.7 Type of Batteries for EVs

The performance of EVs is characterized by its energy capacity and power of battery. It's vital to distinguish between the two.

a. **Energy Capacity:** The amount of energy stored (kWh) by the battery translates to a driving range. A high-capacity battery will be able to keep going for a longer period before going flat/running out of current.
b. **Power:** Power (kW) is the rate at which energy is released.

You need to remember a famous formula E = P * t that can explain the difference.

Energy (E) is the power (P) times the time (t). That means an energy battery is supposed to give power for a longer time than a power battery. Unfortunately, the batteries can be either high-power or high-energy, but not both.

To draw a clearer picture, think of draining a pool. Energy is like the size of the pool, while power is comparable to draining the pool as quickly as possible. A battery with a high energy capacity but low power can perform work for a relatively long period of time. For example, EVs will require a large amount of energy to cover a long driving range before recharging, and material handling vehicles such as industrial forklifts will need good power capabilities for loading and unloading cycles. It’s not about having lots of energy stored but having the ability to extract that energy very quickly.

2.7.1 Selection of the Right Battery

As discussed above, the batteries can be either high-power or high-energy, but not both. Therefore, the term specific power is often used to describe the material combination. The power-to-energy ratio (P/E) is a common way to describe the specific power required for a certain application. Consider the following scenario:

a. The AEVs are engineered to maximize energy capacity because of the desire to achieve longer driving ranges. So AEVs shall have the lowest power-to-energy ratio (P/E ratio) of less than 2 to 3. The battery size of EVs is larger than that for PHEVs or HEVs.
b. The HEV or PHEV are required to deliver maximum power. Most HEVs use batteries to boost a vehicle’s acceleration for a short period. HEV batteries need more power and relatively high P/E values ranging from 15 to 20. The battery capacity is relatively small, just 1-2 kilowatt-hours (kWh).
c. PHEVs use only their electric motor and stored battery power to travel for short distances. A PHEV battery needs both energy and power performance, and therefore the P/E ratio is in the midrange around 8 to 12 - higher than the AEVs and lower than HEVs.

You can also think of AEV as an energy battery and HEV & PHEV as a power + energy battery.

It's worth noting that as a vehicle's mass increases, so does its peak power and stored electrical energy requirement. For example, the peak power for the SUV will have higher P/E ratio compared to the crossover UV. The P/E increases with the mass of the vehicle for the same electric range.

2.7.2 Design Configuration of Batteries

Some batteries have a sad little quirk—if you try and draw too much from them too quickly, the chemical reactions involved can't keep up and the capacity is reduced! So, we need to be careful when we talk about battery energy capacity and remember what the battery is going to be used for. There are two kinds of batteries:

a. Deep cycle batteries
b. Shallow cycle batteries

Technically all batteries for EVs shall be deep cycled batteries. Let's understand the difference between deep cycle and shallow cycle batteries.

2.7.3 Deep Cycle Batteries

Deep cycle batteries are designed to last for a long time. Deep cycle batteries are meant to provide relatively steady power over long periods of time; thus, they can't release large power too fast. These can be discharged up to 80% of their capacity before the control circuit cuts them off and they need to be recharged. Deep cycle batteries have thicker positive electrode plates but with relatively less surface area available to take part in electrochemical reactions.

Some other common applications include smartphones, cameras, laptops, and other consumer devices. The idea is to provide maximum energy content in confined spaces and to deliver maximum run hours before the next recharge. There is no big burst of energy required, it's just a continual drain. A high discharge rate is not needed.

2.7.4 Shallow Cycle Batteries

Shallow cycle batteries are the high-power batteries designed to give relatively quick bursts of energy for a short period. These are typically used for automobile start, light, and ignition (SLI) applications for conventional IC engine vehicles and is not suitable for EVs. All EVs are deep cycled batteries with a proper balance of power and energy for HEVs and PHEVs.

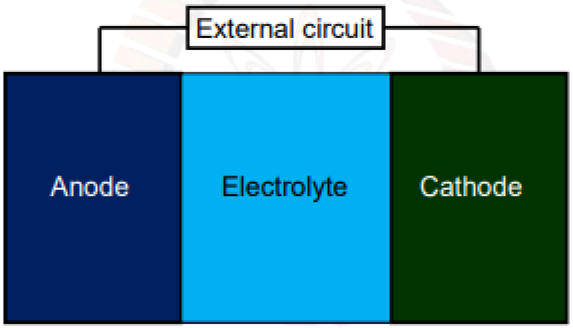
Note that starting an engine requires very large currents for a short period – up to 300 amperes for only a few seconds. This makes power density (not the energy density) a key requirement for such batteries. Once your car is running, the usage of your car battery goes down to nearly zero and the battery automatically recharges (gets energy back again) when the engine begins generating electrical energy through a device called an alternator.

The electrodes of shallow cycle batteries are of sponge type with a larger surface area. This enables shallow batteries to deliver high current (and high power) pulses for short durations. The less you discharge your shallow cycle battery, the more cycles you'll get from your battery (i.e. extend the life of it).

We will discuss the battery principles, rechargeable batteries, components, and cells in subsequent chapters and will focus on Lithium-ion battery technology.

3 CHAPTER - 3: BATTERY BASICS

A battery is a combination of two or more electrochemical cells. These electrochemical cells store chemical energy and convert it to electrical energy. The chemical reactions in a battery involve the flow of electrons from one material (electrode) to another, through an external circuit. The flow of electrons provides an electric current that can be used to do work.



Basic Battery Principle

3.1 Working Principles of Battery

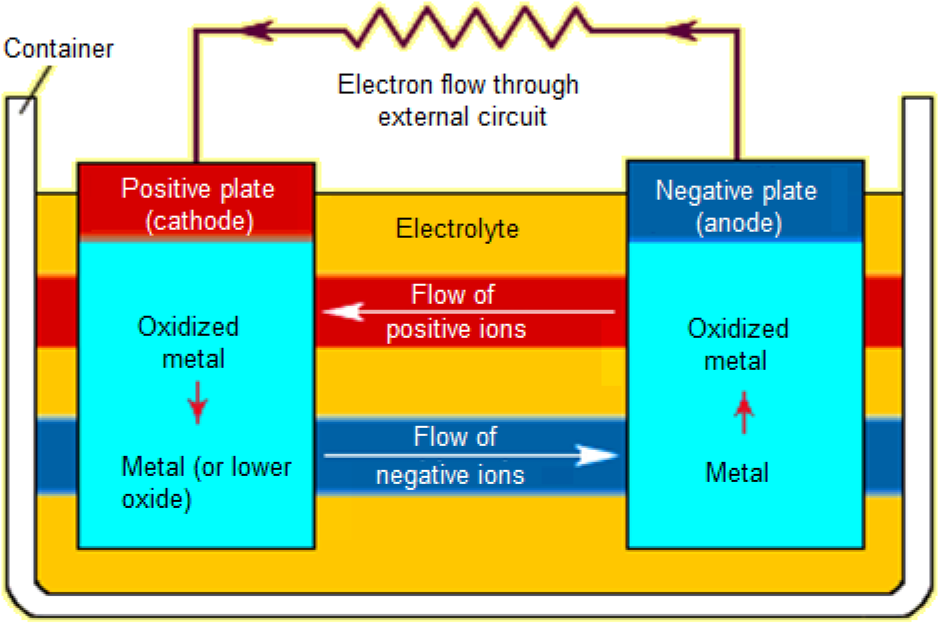
There are three main parts to this cell: the anode, cathode, and electrolyte.

a. The anode is the **negative** electrode that gives up electrons to the external circuit. It is usually a highly reactive metal.
b. The cathode is the **positive** or oxidizing electrode that accepts electrons in the external circuit. It is usually a moderately reactive metal.
c. The electrolyte that facilitates the flow of cations (positive ions) or anions (negative ions) from one electrode to the other.

The electrolyte is placed between the two electrodes and there is an element known as a separator placed between the electrodes. This is porous to the electrolyte and prevents the two electrodes from contacting each other.

An external electric circuit (technically not part of the cell) is a metal wire and a load that carries electrons from the anode terminal to the cathode terminal.

The schematic indicating the flow of electrons is shown below.



Electrochemical Cell

Now, let's look at what's going on inside. The positive terminal of the battery is connected to a positive electrode that is mostly concealed inside the battery (seen on the left and colored red). This is referred to as the cathode.

The negative terminal, commonly known as the anode and colored blue, is made up of the battery's outer shell and the battery's bottom.

Anode →Oxidation→ Loss of electrons

Cathode →Reduction→ Gain of electrons

3.1.1 Anode and Cathode

The positive terminal of a battery is the cathode, and the negative terminal is the anode when it is supplying electric power. The negative terminal is the source of electrons that will flow to the positive terminal via an external electric circuit.

Let's quickly clear up one point of confusion. You might remember learning in school that the cathode is the negative electrode and the anode is the positive electrode. That, however, only applies to things like electrolysis (passing electricity through a chemical to split it up).

Batteries are like electrolysis going backwards (they split up chemicals to make electricity) so the terms anode and cathode are switched around. To avoid confusion, sometimes it's best not to use the terms anode and cathode at all. It's better to say, "positive terminal" and "negative terminal" and then it's always clear what you mean, whether you're talking about batteries or electrolysis—or anything else with a cathode.

3.1.2 What was so special about the electrodes?

It's worth noting that the electrodes of a cell are always constructed of two distinct materials (never the same metal). This is the key to understanding how and why batteries work: one substance "likes" to give up electrons while the other pulls them out through the outside circuit. This flow of electrons from one electrode to the other results in an electric current. There would be no net movement of electrons and no current if the two terminals of a battery were made of the same material.

The terminal voltage is the potential difference between the battery's terminals. When the battery is not carrying any current, such as when it is not connected to any circuit, the terminal voltage visible is the open-circuit voltage, which equals the battery's EMF.

3.2 Classification of Batteries

There are two groups of batteries:

3.2.1 Primary Batteries

Primary batteries are non-chargeable and disposable type. These are used in low-power applications and for infrequent use such as toys, flashlights, and most remote controls.

3.2.2 Secondary Batteries

Secondary batteries are rechargeable. These batteries are designed for frequent usage and have high discharge rates. Mobile phones, laptops, autos, UPS, electric vehicles, and a variety of other portable electronic gadgets are examples of secondary batteries.

3.2.3 Wet Cells

Wet cell batteries contain a liquid electrolyte. Due to the liquid nature of wet cells, insulator sheets are used to separate the anode and the cathode. The flooded lead-acid battery is an example of the wet cell.

3.2.4 Dry Cells

In dry cell batteries, no free liquid is present. Instead, the electrolyte is a paste, just moist enough to allow current flow. This allows the dry cell battery to be operated in any position without worrying about spilling its contents. The valve-regulated lead-acid (VRLA) battery is a dry cell battery.

3.3 Battery Characteristics

The key battery characteristics are:

3.3.1 Voltage

Voltage is the force at which the reaction driving the battery pushes electrons through the cell. This is also known as electrical potential and depends on the difference in potential between the reactions that occur at each of the electrodes, that is, how strongly the cathode will pull the electrons (through the circuit) from the anode. The higher the voltage, the more work the same number of electrons can do.

3.3.2 Current

Current is the number of electrons that happen to be passing through any one point of a circuit at a given time. The higher the current, the more work it can do at the same voltage. Within the cell, you can also think of current as the number of ions moving through the electrolyte, times the charge of those ions.

3.3.3 Power

Power is voltage x current.

The higher the power, the quicker the rate at which a battery can do work—this relationship shows how voltage and current are both important for working out what a battery is suitable for.

3.3.4 Capacity

Capacity is the power of the battery as a function of time, which is used to describe the length of time a battery will be able to power a device for. A high-capacity battery will be able to keep going for a longer period before going flat/running out of current.

Battery capacity is measured in either watt-hours (Wh), kilowatt-hours (kWh), or ampere-hours (Ah). The most common measure for battery is Ah, which is defined as the number of hours a battery can provide a current at the nominal voltage of the battery. The unit Ah is commonly used because the battery voltage will vary throughout the charging or discharging cycle. But in application of EVs, the battery capacity is typically expressed in terms of kilowatt-hours. Choosing an EV with a higher kWh rating is like buying a car that comes with a larger gas tank in that you'll be able to drive for more miles before needing a "fill up".

You can approximately arrive at the number of Watt-hours your battery provides if you know the battery's nominal voltage (V) and capacity in ampere-hours (Ah):

Wh = Ah x V

Example:

A 12-volt battery with a capacity of 500 Ah allows energy storage of approximately;

100 Ah x 12 V = 1,200 Wh or 1.2 KWh.

3.3.5 Specific Energy or Energy density

The amount of energy a device can hold per unit weight (Wh/kg) is known as specific energy, whereas the amount of energy a device can hold per unit volume (Wh/liter) is known as energy density. The higher the energy density of a battery, the smaller and more compact the battery may be, which is always a positive when you need it to power anything you want to keep in your pocket. It’s even a plus for EVs—the battery must fit in the car somehow!

3.3.6 Charging and Discharging Rates

The charging/discharging rates affect the rated battery capacity. When the battery is being discharged very quickly (i.e., the discharge current is high), then the amount of energy that can be extracted from the battery is reduced and the battery capacity is lower. This is because the necessary components for the reaction to occur do not always have enough time to move to their required positions. Only a fraction of the total reactants is converted to other forms, and therefore the energy availability is reduced. Alternately, when the battery is discharged at a very slow rate using a low current, more energy can be extracted from the battery and the battery capacity is higher.

A common way of specifying battery capacity is to express it as a function of the time it takes to fully discharge the battery (note that in practice the battery often cannot be fully discharged). In describing batteries, charge and discharge rates of a battery are denoted by the C-rates. For example;

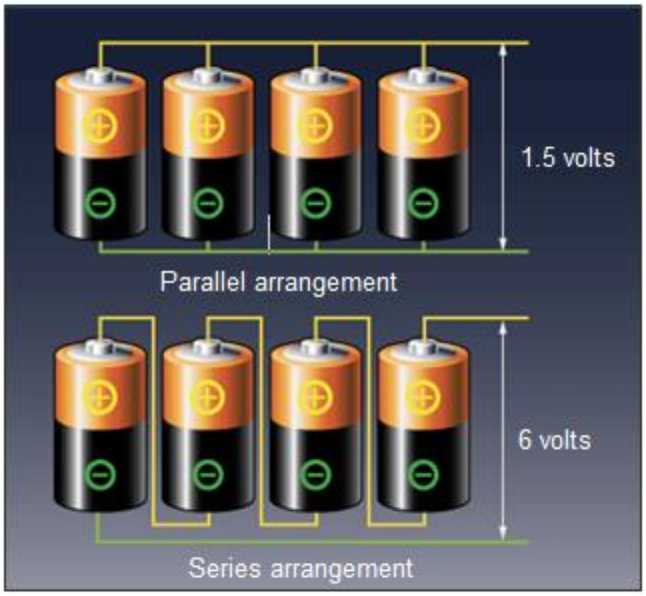
a. 1C Rate → refers to full charging or discharging of battery in 1 hour
b. 2C Rate → refers to full charging or discharging of battery in 30 minutes
c. C/2 or 0.5C Rate → refers to full charging or discharging of battery in 2 hours.

3.3.6.1 Charging and Discharging Regimes

Each battery type has its own set of limitations and requirements when it comes to charging and discharging. Nickel-cadmium batteries, for example, should be virtually totally discharged before charging; lead-acid batteries should never be fully discharged more than 50%, while Li-ion battery manufacturers recommend a maximum discharge of 80 percent. Furthermore, the voltage and current during the charge cycle will be different for each type of battery. Typically, a battery charger or charge controller designed for one type of battery cannot be used with another type.

3.3.7 Cell Connections

Cells in batteries may be connected in parallel, in series, or in a combination of the two. When cells are connected in series, the voltage of the battery increases but the capacity in ampere-hours (Ah) does not change. By contrast, when cells are connected in parallel, the capacity in ampere-hours of the battery (Ah) increases but the voltage stays the same.



Cells in Series and Parallel Arrangement

Example -1:

The parallel arrangement of the four AA batteries, each with 1.5 V and 3 mAh current will provide 1.5 V and 12 mAh.

Example -2:

The series arrangement of the four AA batteries (1.5 V, 3 mAh) will provide 6 V and 3 mAh.

3.3.8 Cut-Off Voltage

Many battery types cannot be discharged below a particular point without causing irreparable damage to the battery. This level is known as the "cut-off voltage," and it is determined by the battery's type, temperature, and discharge rate.

3.3.9 Battery Lifespan

The life of a battery is measured in years if it is kept fully charged or in charge/discharge cycles. For example:

a. Applications where the battery is regularly charged and discharged (such as EVs), the most appropriate measure of a lifetime is the number of charge/discharge cycles over which the battery maintains a given fraction of its capacity.
b. Applications such as in uninterruptable power supplies, which do not frequently experience charge/discharge cycles, battery lifetime is more appropriately specified in years.

Here you need to understand two terms “# Cycle” and “Depth of Discharge (DOD)”.

3.3.9.1 Battery Cycle

A discharge and recharge cycle are the two stages of a battery's life cycle. Charging energizes your battery, while discharging depletes it. That's how a cycle works.

Its usable life is determined by the number of charge/discharge cycles. The more frequently a battery is charged and discharged, the shorter its lifespan will be. It’s generally not recommended to discharge a battery entirely otherwise the life of the battery will be drastically reduced.

When evaluating batteries for your application, a comparison is normally made for battery cycle life @ 50% DOD. At 50% DOD, the battery has 50% of its energy capacity discharged before it begins charging again.

3.3.9.2 Depth of Discharge (DOD)

We learned that many battery types cannot be discharged below a particular point without causing irreparable damage to the battery. The Depth of Discharge (DOD) of a battery determines the fraction of power that can be withdrawn from the battery. It is calculated relative to the overall capacity of the battery and is expressed as percentage.

Example 1:

If the DOD of a battery is given by the manufacturer as 25%, then only 25% of the battery capacity can be used by the load.

Example 2:

If you have a Tesla Powerwall that holds 13.5 kilowatt-hours (kWh) of electricity and you discharge 13 kWh, the DoD is approximately 96.3 percent.

$$\frac{13\ x\ 100}{13.5} = 96.3\%$$

Example 3:

If a 100 AH battery is discharged for 20 minutes at a current of 50A, the depth of discharge is

$$\frac{50\ x20}{60} = 16.7\%$$

The battery manufacturers typically specify a maximum recommended DoD for optimal performance of the battery. For example, if the manufacturer of a 10-kWh battery recommends a maximum DoD of 80 percent, you shouldn't use up to 8 kWh from the battery without recharging. Therefore, you can notice that a higher DoD means you can use more of the energy being stored in your battery. Many modern Lithium-ion batteries these days advertise a DoD of 100 percent.

3.3.9.3 Relationship between Battery Cycles and DOD

In most battery technologies, there is a correlation between the depth of discharge and the cycle life of the battery.

Higher charge/discharge cycles mean higher degradation, or lower lifespan.

Higher DOD means fewer charging cycles. For example, a battery may have 15,000 cycles at a DOD of 10 percent, but only 3,000 cycles at 80 percent DOD.

Therefore, a battery with higher DOD and how much you discharge it at each use before a recharge will increase the battery's useful lifespan.

3.3.9.4 Battery State of Charge (SoC)

State of Charge (SoC) is inverse of DOD. It is normally used when discussing the current state of a battery in use, or is the level of charge of a battery relative to its capacity. It can be thought of as an equivalent of the fuel gauge – i.e. the level of charge relative to its capacity at any given moment.

For example, for a battery at 80% SoC and with a 500 Ah capacity, the energy stored in the battery is 400 Ah.

The units of SoC are percentage points (0% = empty; 100% = full).

A common way to measure the SoC is to measure the voltage of the battery and compare this to the voltage of a fully charged battery. This measurement provides only a rough idea of the battery state of charge.

3.3.9.5 Temperature

Another factor affecting the useful life of battery is the operating temperature.

In a hot environment (over 90°F), batteries can overheat, reducing their lifespan. The battery is also harmed by extremely cold temperatures since it must work harder and at a greater voltage to charge. To extend the life of your battery, keep it in a temperate atmosphere that is neither too hot nor too cold.

3.3.10 Self- discharge

The primary batteries lose around 8% to 20% of their charge over the course of a year even when not in any use. Secondary rechargeable batteries self-discharge even faster. Each month, they normally lose roughly 10% of their charge. They usually lose about 10% of their charge each month. Self-discharging is caused by non-current producing side chemical reactions. Warmer air temperatures can hasten the battery's self-discharge by speeding up the side chemical reactions. Lowering the temperature can delay the rate of side reactions.

3.3.11 Battery Efficiency

The overall battery efficiency is specified by two efficiencies: the columbic efficiency and the voltage efficiency.

3.3.11.1 Columbic Efficiency

The ratio of the number of charges that enter the battery during charging to the number that can be retrieved from the battery during discharging is known as columbic efficiency. The losses that lower columbic efficiency are mostly due to charge loss due to secondary reactions in the battery, such as water electrolysis or other redox reactions. In general, the columbic efficiency may be more than 95%.

3.3.11.2 Voltage Efficiency

The voltage difference between charging and discharging a battery is known as voltage efficiency, and this difference is generated by over-potential.

Every rechargeable battery must be charged at a higher voltage than it discharges; the difference is crucial in determining the battery's efficiency.

3.3.12 Maintenance Requirements

The type of battery used has a significant impact on the battery's maintenance requirements. Some battery reactions produce gases and other products that modify the volume of the battery's components. A hermetically sealed battery has less maintenance requirements because it does not exchange any materials with its surroundings.

3.3.13 Battery Safety and Disposal

Most battery systems contain toxic metals or dangerous chemicals. Each type of battery's safety rules should be carefully examined. Cadmium, for example, is extremely hazardous and is used in nickel-cadmium batteries. The evolution of hydrogen is a possible concern for lead-acid battery systems. Because most batteries contain dangerous and/or corrosive materials, they should not be properly disposed. The metals in lithium-ion batteries (cobalt, copper, nickel, and iron) are considered safe for landfills.

3.4 Battery Definitions, Terms & Terminology

Some more useful terms and definitions describing the batteries are listed in the Table below:

Anode	The definition for the anode is the electrode at which an oxidation reaction occurs. This means that the anode electrode is a supplier of electrons. However, the electron flow reverses between charge and discharge activities. As a result, the positive electrode is the anode during charging and the negative electrode is the anode during discharging. To prevent confusion, the anode is normally defined for its activity during the discharge cycle. In this way the term anode is used for the negative electrode in a cell or battery.
Battery	A battery is the generic name for a unit that creates electrical energy from stored chemical energy. Strictly it consists of two or more cells connected in an appropriate series / parallel arrangement to provide the required operating voltage and capacity to meet its operating requirements.
Cathode	The definition of a cathode is the electrode in a battery or other system at which a reduction reaction occurs. The electrode takes up electrons from an external circuit. Accordingly, the, the negative electrode of the battery or cell is the cathode during charging and the positive electrode is the cathode during discharging.

	To prevent confusion, the cathode is normally specified for the discharge cycle. As a result, the name cathode is commonly used for the positive electrode of the cell or battery.
Capacity	The capacity of a battery or cell is defined as the amount of energy that it can deliver. Battery capacity is normally specified in amp-hours or as watt-hours.
Cell	The definition of the cell is the basic electrochemical unit that is used to create electrical energy from stored chemical energy or to store electrical energy in the form of chemical energy. A basic cell consists of two electrodes with an electrolyte between them.
Charge rate or C-rate	In describing batteries, discharge current is often expressed as a C-rate to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For example, in case of 100 Ah battery, a 1C rate is 100 amps and 2C rate would be 200 amps and C/2 rate would be 50 amps. The C-rate is also described as the rate at which the battery is discharged or charged, relative to its capacity. For example, a. 1C Rate => Discharge or Charge in 1 hour b. 2C Rate => Discharge or Charge in ½ hour c. 5C Rate => Discharge or Charge in 12 minutes d. 0.1C Rate => Discharge or Charge in 10 hours e. 0.5C Rate => Discharge or Charge in 2 hours
Constant-Current Charge	This refers to a charging process where the level of current is maintained at a constant level regardless of the voltage of the battery or cell.
Constant-Voltage Charge	This definition refers to a charging process in which the voltage applied to a battery is held at a constant value over the charge cycle regardless of the current drawn.
Cycle Life	The capacity of a rechargeable cell or battery changes over its life. The definition of the battery life or cycle life of a battery is the number of cycles

	that a cell or battery can be charged and discharged under specific conditions before the available capacity falls to a specific performance criterion - normally 80% of the rated capacity.
Cut-off voltage	As a battery or cell is discharged, it has a voltage curve that it follows - the voltage is generally falling over the discharge cycle. The definition for a cell or battery of the cut-off voltage cell or battery is the voltage at which the discharge is terminated by any battery management system. This point may also be referred to as the End-of-Discharge voltage.
Deep Cycle	A charge -discharge cycle in which the discharge is continued until the battery is fully discharged. This is normally taken to be the point at which it reaches its cut-off voltage, typically 80% of discharge.
Depth of Discharge (DOD) (%)	The percentage of battery capacity that has been discharged and is expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge.
Electrode	The electrodes are the basic elements within an electrochemical cell. There are two in each cell: one positive and one negative electrode. The cell voltage is determined by the voltage difference between the positive and the negative electrode.
Electrolyte	The definition of the electrolyte within a battery is that it is the medium that provides the conduction of ions between the positive and negative electrodes of a cell.
Energy Density	The volumetric energy storage density of a battery, expressed in Watt-hours per liter (Wh/liter).
Rated Capacity	The capacity of a battery is expressed in Ampere-hours (Ah) and it is the total charge that can be obtained from a fully charged battery under specified discharge conditions.
Self-Discharge	It is found that batteries and cells will lose their charge over a period even when not in use. This self-discharge is normal, but varies according to several variables including the technology used and the conditions. Self-discharge is normally expressed in a percentage of the rated capacity lost

	per month and at a given temperature. The self-discharge rate of a battery or cell is very dependent upon the temperature.
Separator	The separator is a membrane used within a cell to prevent the anode and cathode shorting together. With cells being made more compact, the space between the anode and cathode becomes much smaller and as a result the two electrodes could short together causing a catastrophic and possibly explosive reaction. The separator is an ion-permeable, electronically non-conductive material or spacer that is placed between the anode and cathode.
Specific Energy	The gravimetric energy storage density of a battery, expressed in Watt-hours per kilogram (Wh/kg).
State of Charge (SOC) (%)	An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time.
Trickle charge	This term refers to a form of low-level charging where a cell is either continuously or intermittently connected to a constant-current supply that maintains the cell in fully charged condition. Current levels may be around 0.1C or less dependent upon the cell technology.

4 CHAPTER - 4: RECHARGEABLE BATTERIES

A reversible battery is one in which chemical reactions in the battery can occur in both directions. The reactions go one way when the battery is discharging, and the battery gives out power. When the battery is charging, the reactions go the opposite direction, and the battery absorbs power.

Four common rechargeable battery technologies are:

a. Lead-acid batteries
b. Nickel–Cadmium (Ni-Cd) batteries
c. Metal Hydride (Ni–MH) batteries
d. Lithium-ion batteries

4.1 Lead-acid Batteries

The lead-acid batteries were the first rechargeable batteries ever made and are still widely used due to their low cost and reliability. Each battery cell consists of:

a. Negative electrode: spongy lead
b. Positive electrode: lead oxide
c. Electrolyte: diluted sulfuric acid (flooded cell)

As the battery discharges, both electrodes become coated with lead sulfate and the sulfuric acid is largely converted into water, while electrons flow out around the external circuit to provide power.

In the fully charged state, a 2V electric potential exists between the cathode and the anode. This means that a battery with 6 cells will have an overall rating of 12 volts.

4.1.1 Types of Lead-acid Batteries

Lead-acid batteries are further divided into two categories: Flooded cell and Sealed or Valve regulated lead-acid (SLA or VRLA) batteries. The intrinsic chemistry of the two types is identical, however VRLA batteries do not require electrolyte or water. Instead, gel or Absorbed Glass Mat is used (AGM).

Gel sealed batteries use silica to stiffen or “gel” the electrolyte solution, greatly reducing the gasses and volatility of the cell. Since all matter expands and contracts with heat, batteries are not truly sealed, but are “valve regulated”. This means that a tiny valve maintains slight positive pressure.

AGM batteries (Absorbent Glass Mat) are a type of valve-regulated lead-acid battery (VLRA) in which the electrolyte is contained in glass mats rather than flooding the plates freely. This eventually raises the surface area large enough to hold enough electrolyte for the cell's lifetime. These are slowly phasing out gel technology.

Sealed VRLA type batteries find applications in UPS (uninterrupted power supplies), emergency lighting, home inverters, power backup, cellular towers, internet hubs, and many other applications.

The pros and cons for lead-acid battery systems are:

4.1.1.1 Pros:

a. Cheap, sturdy, sustainable, easy to handle
b. Reliable and mature technology
c. Capable of high discharge currents.
d. Good performance at low and high temperatures.
e. No block-wise or cell-wise building management system (BMS) required

4.1.1.2 Cons:

a. Very heavy, bulky, and not suitable for deep cycling.
b. The specific energy of the batteries is quite low; 35-40 Wh/kg.
c. In most designs, the cycle life is limited to 500 cycles.
d. Slow charging time and it can take up to 16 hours for a full charge.
e. Suffer from voltage drop. When a lead-acid battery gets to a 50% state of charge, the voltage will usually drop to a point where appliances will not work as they should.
f. Need to store battery in charged condition to prevent sulfation, which may degrade the performance and cycle life of the battery.
g. Has short typical cycle life - 300 to 500 cycles.
h. Need regular maintenance in the form of watering, equalizing charges, electrolyte levels and keeping the terminals clean for wet batteries.
i. The charging voltage must be regulated as the maximum voltage applied is limited by the ambient temperature, due to the risk of hydrogen gas generation.
j. Adverse environmental impact because of toxic lead metal.

4.2 Nickel–Cadmium (Ni–Cd) Battery

Nickel-cadmium (Ni-Cd, pronounced "nicad") batteries contain:

a. Positive electrode: nickel hydroxide
b. Negative electrode: cadmium

c. Electrolyte: alkaline solution

It has a long cycle life and can be recharged quickly, but it may experience voltage depression or memory effect, which means that the maximum charge voltage and hence the energy capacity will decrease if discharged continuously.

Because of the hazardous cadmium in Ni-Cd batteries, they are now rarely used and have given way to Nickel Metal Hydride (Ni-MH) batteries. Earlier, these were commonly used to replace disposable 1.5-volt batteries in portable electronic equipment such as flashlights, laptop computers, drills, and power tools etc.

The pros and cons are of Ni-Cd batteries are:

4.2.1.1 Pros:

a. Rugged and high cycle count.
b. Only battery that can be ultra-fast-charged with little stress.
c. Long shelf-life; can be stored in a discharged state.
d. Simple storage and transportation; not subject to regulatory control.
e. Good low-temperature performance.

4.2.1.2 Cons:

a. Cadmium is a toxic metal; cannot be disposed in landfills.
b. Relatively low specific energy compared with newer systems.
c. Suffers from memory effect, needs periodic full discharge.
d. High self-discharge; needs recharging after storage.
e. Low cell voltage of 1.20 V requires many cells to achieve high voltage.

4.3 Nickel–Metal Hydride (Ni–MH) Battery

Nickel-metal hydride (Ni-MH) batteries are like sintered nickel-cadmium (Ni-Cd) batteries, but instead of a Cd electrode, they feature a metal hydride electrode. The cost is high because of the use of Ni and rare earth metals in the hydride store.

Each cell of Ni-MH battery contains:

a. Positive electrode: potassium hydroxides
b. Negative electrode: alloy of nickel, titanium, vanadium, and other metals.
c. Electrolyte: alkaline solution

4.3.1.1 Applications

They are widely used for consumer applications because they are not restricted in the same way as Ni-Cd cells. Previously, they were widely used in hybrid electric vehicles; however, the trend is moving toward lithium-ion batteries currently.

The key pros and cons for the Ni-MH battery are:

4.3.1.2 Pros:

a. Safe, tolerant to abuse rapid recharge capability, long life, less expensive than lithium-based battery systems.
b. Compared to the Ni-Cd battery, the Ni-MH provides 40 percent higher specific energy and less affected by voltage depression, but the main advantage is the absence of the toxic cadmium.
c. Greater service advantage over other primary battery types at extreme low-temperature operation (–20°C).
d. Maintenance free and is tolerant to over-discharge and overcharge.

4.3.1.3 Cons:

a. High self-discharge, not suitable for shallow cycling, lower specific energy and specific power than lithium-based battery systems.
b. Limited service life: If repeatedly deep-cycled, especially at high load currents, performance starts to deteriorate after 200–300 cycles.
c. These generate significant heat during charge and require a longer charge time than the Ni-Cd. The trickle charge is critical and must be controlled carefully. These issues make these batteries less effective for rechargeable electric vehicles, which is why they are primarily used in hybrid electric vehicles.
d. It has about 50% higher self-discharge compared with the Ni-Cd batteries.

4.4 Lithium-ion (Li-ion) Battery

Lithium-ion (Li-ion) technology was introduced into the market by Sony in the early 1990s and was commercialized in 1991. Since then, they've achieved tremendous gains in performance, lowering the cost per kWh of new cells. In comparison to other rechargeable batteries, the technique provides a high energy content, low self-discharge, and good cycle performance.

Each cell of Li-ion battery contains:

a. Positive electrode: oxidized cobalt material

b. Negative electrode: carbon material
c. Electrolyte: lithium salt solution in an organic solvent

4.4.1.1 Applications

Lithium-ion batteries can be used practically anywhere that a lead-acid or Ni-MH battery can be used. Li-ion batteries are already proliferating in many applications. Here are some examples:

a. **Portable power packs:** Li-ion batteries are lightweight and more compact than other battery types, which makes them convenient to carry around within cell phones, laptops, and other portable personal electronic devices. They also power drones and a host of cordless power tools and gadgets.
b. **Uninterruptible Power Supplies (UPSs):** Li-ion batteries provide emergency back-up power during power loss or fluctuation events for IT servers, data centers or the medical and health care facilities to guarantee consistent power supply to life-saving medical equipment.
c. **Electric vehicles (EVs):** Most EVs manufactured today make use of Li-ion batteries as they offer a much better power to weight ratio, higher specific energy (kW/kg), deep discharge capabilities, and higher charge cycles compared to other rechargeable batteries.
d. **Personal mobility:** Lithium-ion batteries are used in wheelchairs, bikes, scooters, and other mobility aids for individuals with a disability or mobility restrictions. Unlike cadmium and lead batteries, lithium-ion batteries contain no chemicals that may further harm a person's health.
e. **Renewable energy storage:** Li-ion batteries also provide great synergies with clean energy storage technologies such as solar and wind power generation. The batteries can be used to store excess energy during high production periods and use it during non-production periods. They fulfill a valuable role in balancing supply and demand, and in grid stabilization.

The pros and cons for the Li-ion battery are:

4.4.1.2 Pros:

a. High specific energy (>250 Wh/kg) and potential for yet higher capacities.
b. Much higher charging rate with no adverse effects - can accept a high rate of charge over 100 Amps in some cases.

c. Relatively very low rate of self-discharge (<5% per month), which means they can be left unattended for months.
d. High cycle life in the thousands and achieve discharge >80%.
e. Completely maintenance-free. No periodic discharge is needed.
f. All lithium-ion cells are “deep cycle”, meaning they can be fully charged and discharged.
g. The performance characteristics of a Li-ion battery can be modified by changing the choice of materials used for the electrolyte, cathode, and anode.

4.4.1.3 Cons:

a. High cost, expensive to manufacture.
b. Not as robust as other rechargeable technologies. They require protection circuitry to ensure protection from being overcharged and discharged too far.
c. Degradation at high temperature (above 45°C) and when stored at high voltage.
d. Impossibility of rapid charge at freezing temperatures (<0°C, <32°F).
e. Shipment of larger quantities of Li-ion batteries may be subject to regulatory control.
f. Not fully mature – changes in metal and chemical combinations affect battery test results.
g. Subject to aging, even if not in use. Storing the battery in a cool place and at 40% state of charge reduces the aging effect.

4.5 Selection Considerations

In the construction of batteries, there are several variables to consider. Some characteristics are more important than others depending on the type of application. For example, the energy density of a battery used to start a standard IC engine is irrelevant; instead, a high discharge rate or shallow battery is required. However, in electric vehicle applications, a deep cycle battery with a high specific energy and energy density is critical since it determines the battery's size and weight, as well as the vehicle's mileage and compactness.

The following is a list of parameters that may be considered for a given type of battery.

a. **Physical characteristics:** size, shape weight
b. **Voltage:** nominal, maximum, minimum, discharge profile
c. **Load current:** rate, constant power, constant resistance, pulsed
d. **Duty cycle:** continuous, intermittent, cyclic
e. **Charge/discharge cycle:** cycling (float), deep cycle, efficiency of charging
f. **Temperature range:** maximum, minimum, and nominal
g. **Service life:** required operation time

h. **Safety:** failure rates, leakage, off-gassing, toxicity, disposal
i. **Environment:** vibration, acceleration, orientation
j. **Maintenance:** regular upkeep, replacement
k. **Cost:** initial, life-cycle cost

Let's compare few critical parameters for different rechargeable batteries in the Tables below.

Table-1

Battery Type	**Nominal Voltage (V)**	**Specific Energy (Wh/kg)**	**Energy Density (Wh/L)**	**Specific Power (W/kg)**	**Life Cycle**
Lead-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
Li-ion	3.6	150-300	200-600	200-430	2000

Table -2

Battery Type	**Charge Time**	**Self-Discharge per month**	**Regular Maintenance**	**Thermal Safety**	**Toxic metals**
Lead-acid	8 -16 h	4 - 8%	Yes (flooded) No (VRLA)	Stable	Lead
Ni-Cd	1h typical	20%	Yes	Stable	Cadmium
Ni-MH	2- 4 h	30%	Moderate	Fuse protection	None
Li-ion	< 1 h	2 - 5%	Not required	Protection circuit mandatory	None

Table -3

Battery Type	**Memory effect**	**Peak Load Current**	**In Use Since**	**Costs**	**Applications**
Lead-acid	No	5C	Late 1800s	$60/kWh to $ 120 for VRLA type	Car battery (SCI), backup power
Ni-Cd	Yes	20C	1950	$800/kWh	Portable electronic devices
Ni-MH	Yes, less than Ni-Cd	5C	1990	$600/kWh	HEVs, portable devices
Li-ion	No	>30 C	1991	$300 - $700/ kWh	Electric vehicles, consumer electronics

Note that the cell chemistries have a wide range of various properties and parameter settings, therefore these tables are merely a simplified description. Consult the data provided by the manufacturer.

Comparison Summary

Li-ion battery characteristics overweigh all other rechargeable batteries. Practically, these can be used in any situation where a lead-acid battery or Ni-MH is being used.

The Li-ion batteries offer the following advantages:

a. Have the highest specific energy and energy density.
  - Li-ion batteries have a high specific energy capacity, which means they are lighter for a given capacity. The weight of the batteries is a significant factor in getting the best performance out of electric vehicles.
  - Li-ion batteries have a high energy density, which means they are physically smaller for a given capacity. The energy density is an important metric in portable systems such as mobile phones, laptops, and medical instruments.

b. Have the highest power to weight ratio.

c. High performance features, such as low internal resistance, a deeper discharge depth, a low self-discharge rate. Each lithium-ion cell produces roughly 3.6 V, which is higher than Ni-MH (1.2 V/cell) and lead-acid cells (2 V per cell). For a given battery capacity, a higher voltage means fewer cells are required, which simplifies power management.
d. Li-ion batteries can survive higher charge cycles. The lifespan of the battery can be as high as 10 years and can be further increased by limiting the depth of discharge (DoD), discharge rate, and temperature.
e. Li-ion batteries are non-toxic and don’t give off dangerous fumes. They have no memory effect, a detrimental process where repeated partial discharge/charge cycles can cause a battery to ‘remember’ a lower capacity.

The most significant disadvantage is the cost: depending on the material combination of the cathode and anode, Li-ion is the most expensive rechargeable battery.

There are certain other flaws, particularly in terms of safety. At high voltages, Li-ion batteries can overheat and be harmed. This can result in thermal runaway and combustion in some situations. Safety devices are required for Li-ion batteries to limit voltage during charging. For lithium batteries, a Battery Management System (BMS) is required. The BMS uses protective circuits that limit the charging voltage and currents.

We will discuss more about Lithium-ion battery technologies in next chapter.

5 CHAPTER - 5 LITHIUM-ION BATTERIES

We learnt in the previous chapter that Li-ion batteries can be used practically in all applications wherever a lead-acid or Ni-MH battery can be used.

Lithium-ion batteries and cells come in a range of shapes, sizes, and capacities. These batteries have capacities ranging from:

a. 10 Wh for cell phones
b. 60-100 Wh for laptops
c. 20-100 kWh for EVs
d. Up to tens of MWh for grid-level backup and wind/solar energy storage systems.

As per the 2018 data, the Li-ion batteries are used in:

a. More than 8 billion smartphones
b. More than 3 million electric cars currently on the road, with annual sales growth in 2018 greater than 50 percent
c. Some 300,000 electric buses operating on regular commercial routes
d. More than 200 GWh of storage in smartphones, tablets, and laptops
e. More than 15 GWh of stationary battery storage
f. More than 100 GWh of battery storage in power tools

5.1 Types of Lithium Batteries

Lithium-based batteries are available in two types: Pure Lithium batteries and Li-ion batteries.

5.1.1 Pure Lithium Batteries

Pure Lithium batteries are primary cells, which must be discarded once their charge is exhausted. These are disposal batteries and are non-rechargeable. Examples include the primary cells such as Energizer, Duracell, etc. used in remotes of TVs, ACs, button cells etc.

Example of Lithium Metal Cells and Batteries

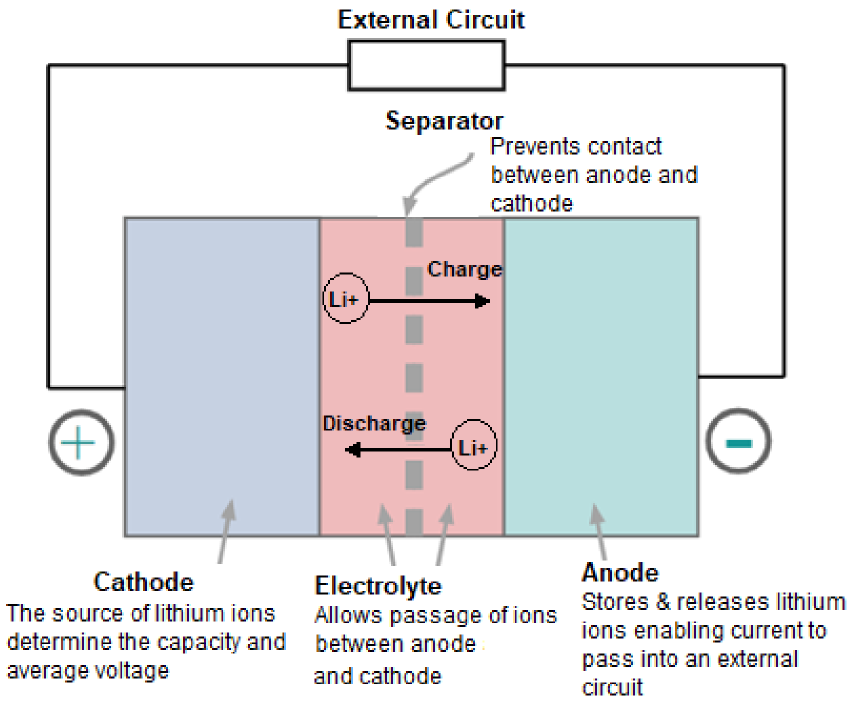
5.1.2 Lithium-ion Batteries

Lithium-ion batteries (abbreviated Li-ion batteries) are secondary types that can be recharged using an external electric charger. Today, most attention is given to secondary types, particularly Li-ion batteries, because of their widespread application in cell phones, laptop and EVs.

Example of Lithium Ion Cells and Batteries

5.2 Lithium-ion Battery Fundamentals

All batteries have 4 main components: a positive electrode (cathode), a negative electrode (anode), an electrolyte and a separator.



Basic Schematic of Lithium-ion Battery Cell

a. When the battery is charging, the positively charged lithium-ions flow from the positive electrode (cathode), through the electrolyte/ separator, to the negative electrode (anode) where they are stored. Electrons flow from the negative electrode to the positive through the outer circuit (the power supply). When no more lithium-ions will flow, the battery is fully charged.

b. When the battery is discharging, the lithium-ions are de-intercalated (move) from the negative electrode (anode) to the positive electrode (cathode). Electrons flow back to the anode through the outer circuit. When all ions have moved back, the battery is fully discharged and needs recharging.

Note: The direction of current is opposite to the movement of electrons.

5.2.1 Lithium-ion Battery Components, Functions, and main Materials

Components	**Functions**	**Materials**
Cathode (positive electrode)	Emit lithium-ion to anode during charging Receive lithium-ion during discharging	Lithium metal oxide powder. Lithium cobalt oxide Nickel, Cobalt, Aluminum Nickel, Manganese, and Cobalt
Anode (negative electrode)	Receive lithium-ion from anode during charging Emit lithium-ion during discharging	Aluminum foils coated with graphite
Electrolyte	The electrolyte carries positively charged lithium-ions from the anode to the cathode and vice versa through the separator.	A mixture of lithium salts and organic solvents such as ethylene carbonate, diethyl carbonate, etc.
Separator	Prevent short circuit between cathode and anode Pass lithium-ions through pores in separator	Micro-porous membranes

5.2.2 Boosting Lithium-ion Capacity

The most straightforward way to boost a battery’s capacity is to increase how many lithium-ions can be stored in either electrode.

Most of the improvements in battery life so far have been made by manufacturers creating cathodes out of some combination of nickel, manganese, and cobalt. The crystal structures of these metals, when combined, store lithium-ions more efficiently. They also make the ions’ movement through the cathode to the anode easier than other materials.

5.3 Lithium-ion Battery Materials

Although lithium-ion batteries are generally referred to by their generic name, there are several different types of lithium-ion batteries.

a. Cathode Active Materials | LFP, LCO, LMO, NMC, NCA, CSG
b. Anode Active Materials | Graphite, Graphene, LTO
c. Packaging Materials | Pouches, Cases, Cans, Tabs
d. Electrolyte | Lithium Hexafluorophosphate ($LiPF_6$)
e. Battery Grade Lithium | Li-OH, Li_2CO_3
f. Anode Foils | Copper, Nickel
g. Cathode Foils | Aluminum
h. Binders | PVDF, SBR

All Li-ion batteries generally work in a similar way. The main differences are the anode and cathode materials. The anode and cathode materials are the most significant distinctions. Most anodes in lithium-ion batteries are graphite, but cathodes are made of a variety of materials depending on the battery's intended application.

5.4 Cathode Materials

When designing Li-ion battery cells, there is a balance between high specific power and high specific energy. Different designs and material choices give the cell either greater specific power or specific energy, which is why cells are divided into power and energy cells. The following chemistries and variations of the cathode materials give the cell different properties:

5.4.1 Lithium cobalt oxide (LCO)

Categorized as High Energy, High Risk

Lithium Cobalt Oxide (LCO) batteries are comprised of lithium carbonate and cobalt and have a high specific energy, making them a popular choice for mobile electronics like smartphones, laptops, and digital cameras.

Cobalt is an important component of cathode materials because it allows for higher specific energy (energy density), structural integrity, and longer runtime, but it also has some disadvantages, such as toxicity, low thermal stability, and a high price.

The pros and cons of LCO batteries are:

5.4.1.1 Pros:

Most common, high specific energy and energy density

5.4.1.2 Cons:

High costs (60% cobalt), relatively short life, and low thermal stability.

5.4.2 Lithium Manganese Oxide (LMO)

The cathode material in lithium manganese oxide (LMO) is manganese oxide. It outperforms LCO in terms of power and thermal stability, but it has a lower energy density and cycle life.

Previously, LMO batteries were utilized to power Nissan Leaf vehicles. It's now mainly used to make NMC batteries by blending it with nickel and cobalt.

The pros and cons of LMO batteries are:

5.4.2.1 Pros:

It has a low internal resistance, low costs, high thermal stability and provide enhanced safety as a result, making them ideal for medical devices, material handling vehicles such as forklifts, and power tools.

5.4.2.2 Cons:

Poor energy density and cycle life

5.4.3 Nickel Manganese Cobalt (NMC)

Categorized as Performance with a Price

Lithium Nickel Manganese Cobalt Oxide (NMC) has three active components of nickel, manganese, and cobalt. The chemistry can be optimized for high specific energy (more nickel) or high specific power (more manganese) but not both.

a. Cobalt is known for increased energy density, structural stability, and superior runtime but also brings some drawbacks such as toxicity, low thermal stability, and high price.
b. Nickel is known for its high energy density but poor stability just like cobalt.
c. Manganese offers superior thermal stability and high specific power but gives a low specific energy.

Blending nickel and manganese with cobalt can improve each other's merits. The ratio of Ni:Mn:Co has been gradually shifting from 1:1:1 to 5:3:2, 6:2:2, and 8:1:1 in an effort to lower the quantity of Cobalt required. An even ratio of 1:1:1 is suitable for high-power applications, while higher nickel contents 5:3:2 to 6:2:2 reduce dependence on cobalt.

NMC-based battery technology is well-suited for EV applications energy storage systems (EES) that need frequent cycling.

The pros and cons of NMC batteries are:

5.4.3.1 Pros:

Modular chemistry, safer and cheaper than LCO, good cycle life, high specific energy or high specific power and promising technology.

5.4.3.2 Cons:

Not the best in either highest specific power or energy compared to other chemistries. The high cost of cobalt makes it expensive.

5.4.4 Nickel Cobalt Aluminum (NCA)

Nickel-Cobalt-Aluminum (NCA) is extensively used by Tesla in their EVs.

The strengths of the NCA-system include high energy (up to 240 Wh/kg), high power due to its relatively high specific charge of about 180 mAh-g and an average voltage of about 3.9 V.

The pros and cons of NCA batteries are:

5.4.4.1 Pros:

Good cycle life, superior specific energy capacity, good lifespan, and better capacity retention than NMC.

5.4.4.2 Cons:

Expensive, bad thermal stability rating compared to NMC, which makes it less attractive to the wider EV market. It's rarely used in consumer electronics.

5.4.5 Lithium Iron Phosphate (LFP)

Categorized as Affordable, Safe and Reliable

Lithium iron phosphate (LFP) is a cobalt-free cathode material with the highest thermal stability of any cell type currently available. It's a tough cell with high specific power ratings, long cycle life (95 percent capacity after 1000 cycles at 1C discharge in 25°C), high temperature stability, and good safety, but it has a low energy density.

The pros and cons of LFP batteries are:

5.4.5.1 Pros:

LFP is a cobalt free cathode material and therefore very cost effective.

These batteries are more tolerant at full-charge conditions and are less prone to stress than other Li-ion batteries when subjected to prolonged high voltages.

It offers high power, good thermal stability, excellent safety, long life, and high current.

LFP batteries have low volumetric energy density (~220 Wh/L), which makes them suitable for heavy-duty applications (e.g. buses, trucks, forklifts, e-bikes, etc.).

5.4.5.2 Cons:

Low cell voltage at 3.3 Volt and low specific energy (~120 to 170 Wh/kg compared to other types of Li-ion batteries).

These are less suitable for portable electronics and e-cars. These are expensive when measured in price per kWh compared to other types of Li-ion cells.

5.5 Negative Electrode (Anode) Materials

5.5.1 Graphite Anodes

Carbon-based graphite or amorphous formulations are the dominant anode material. Amorphous carbon has slightly lower energy density but higher charging power when compared to graphite. Both graphite and amorphous formulations are cheap, reliable, and relatively energy dense, especially compared to current cathode materials. But these are fairly weak when stacked up against other potential anode materials, like silicon and lithium.

Graphite anodes also suffer from poor rate capability and lithium dendrite problems upon overcharging, leading to internal short circuits and safety concerns, including fire or explosion owing to its flammable nature.

5.5.2 Silicon Anodes

Silicon is theoretically much better at absorbing lithium ions than graphite, however because of the high-volume expansion of silica during charging, it has a shorter cycle life. When graphite absorbs lithium ions, its volume remains relatively unchanged, whereas in the identical scenario, a silicon anode expands up to four times its original volume.

Many battery companies using composite materials of silicon and graphite. A bigger step would be to develop a commercially viable anode made completely from silicon.

5.5.3 Lithium Titanate Oxide (LTO)

Lithium titanate (LTO) batteries use lithium-titanate nanocrystals instead of graphite in the anode, giving it a greater surface area than graphite carbon and allowing electrons to enter and exit the anode more quickly. This, in turn, makes it one of the more fast-charging batteries in the Li-ion category. These can be used with LMO or NMC cathodes to make a Li-ion cell.

The pros and cons of LTO batteries are:

5.5.3.1 Pros:

a. Very safe, very high cycle life (>4000+), excellent thermal stability and safety, good low-temperature operation (obtain a capacity of 80% at -30°C).
b. LTO can charge extremely fast, enabling a battery cell to reach full charge in five minutes. It can deliver a high discharge current of 10 C, or 10 times the rated capacity.

5.5.3.2 Cons:

a. Low specific energy (around 50-80 Wh/kg) and a low cell voltage of ~2.3V.
b. Very expensive. The average cost is $1000 per kWh basis; however, its high cycle lifetime partly compensates for this on a cost per-cycle basis.

5.6 Electrolyte Chemistry

The electrolyte used in lithium-ion batteries is a mixture of organic solvents with dissolved lithium salts. Several organic solvents are mixed to decrease the electrolyte's viscosity and increase solubility of lithium salts. This increases the mobility of lithium-ions in the electrolyte, resulting in higher battery performance. The materials below are used for making an electrolyte.

5.6.1 Materials Used as Lithium Salts:

a. Lithium hexafluorophosphate ($LiPF_6$)
b. Lithium perchlorate ($LiClO_4$)

c. Lithium hexa-fluoro-arsenate ($LiAsF_6$)

5.6.2 Organic Solvents:

a. Ethyl methyl carbonate (EMC)
b. Dimethyl carbonate (DMC)
c. Diethyl carbonate (DEC)
d. Propylene carbonate (PC)
e. Ethylene carbonate (EC)

5.7 Separator

The separator is a microporous membrane that enables lithium-ion transport but prevents direct contact between the anode and cathode. The separator is made of polyolefin, polyethylene, or polypropylene membrane.

The separator has a safety function called a “shutdown.” If the cell heats up accidentally, the separator melts due to the high temperature and fills its micro-pores to stop lithium-ion flow between anode and cathode.

The separator also prevents dendrites (metal slivers) from growing from the anode to the cathode. When the separator breaks down, these dendrites form an internal bridge between the electrodes, which shorts the circuit, followed by a thermal runaway (an irreversible meltdown).

5.8 Comparison of Li-ion Battery Chemistries

Cathode Material	**Strengths**	**Weakness**
Lithium Cobalt Oxide (LCO) Cathode	High energy High power	High costs Thermally unstable Relatively short life span Limited load capabilities
Lithium Manganese Oxide Spinel (LMO) Cathode	High power and thermal stability Enhanced safety Low cost	Low energy compared to other cathode materials Limited life cycle Need advanced thermal management

Lithium Nickel Cobalt Aluminum Oxide (NCA) Cathode	High specific energy Good specific power Long life cycle Better capacity retention than NMC.	Poor thermal stability compared to NMC Safety issues High costs
Lithium Nickel Manganese Cobalt Oxide (NMC) Cathode	Modular chemistry, safer and cheaper than LCO Good cycle life Ni has high specific energy; Mn adds low internal resistance Can be tailored to offer high specific energy or power	Not the best in either specific power or energy density compared to other chemistries. Nickel has low thermal stability Manganese offers low specific energy The high cost of cobalt makes it expensive.
Lithium Iron Phosphate (LFP) Cathode	Inherently safe; tolerant to abuse Acceptable thermal stability High current rating Long cycle life	Lower energy density due to low operating voltage and capacity.
Anode Materials		
Graphite/Carbon-based Anode	Good mechanical stability Good conductivity and Li-ion transport Good gravimetric capacity	Low volumetric capacity
Lithium Titanate (LTO) Anode	Withstands fast charge/discharge rates Inherently safe Long cycle life	Lower energy density compared to graphitic anodes Cost

Silicon Alloy (Si) Anode	High gravimetric/volumetric capacity Low cost Chemical stability	High degree of mechanical expansion on charging

Li-ion Battery Comparison on Technical Parameters

Cathode	**Anode**	**Specific Energy**	**Power**	**Cycle life**	**Safety**	**Cost**
LCO	Graphite	High	Fair	Fair	Fair	High
NCA	Graphite	High	High	Fair	Fair	High
NMC	Graphite	High	Fair	Low	Fair	High
LMO	Graphite	High	High	Fair	Very Good	Fair
LMO	LTO	Low	Low	High	Good	High
LFP	Graphite	Low	High	High	Very Good	Fair

Source: NPC, 2012.

5.9 Commercial Application of Li-ion Batteries

a. LCO batteries are rarely employed in EVs due to their inherent structural instability, inadequate safety, and high cobalt material cost. Other cathode materials, including as NMC and NCA batteries, have shown to be more successful for EVs than LCO because they have more stable crystal structures.

b. NCA technologies are employed as an alternative to LCO since they are less expensive (Ni is much cheaper than Co). NCA batteries have a high specific energy (> 200 Wh/kg at the cell level) and a long life (> 15 years on the calendar). NCA's energy density is predicted to reach 300 Wh/kg and 700 Wh/L at the cell level by 2025. NCA technology has been effectively used in electric cars such as Tesla products (Model X, Model S, Model 3).

c. NMC battery technology employs a three-material mix (Nickel Manganese Cobalt). Because of its higher specific capacity at lower costs, it is widely employed in the EV market and is predicted to expand its market share to 70% by 2025. Nickel has the advantage of high specific energy, while manganese has low internal resistance.

- NMC-111, NMC-442 and NMC-532 are currently the dominating cathode materials for Li-ion batteries. NMC-111 represents that the percentage contribution of the Nickel, Manganese, and Cobalt are 33.3% each. It has nearly 42% of the EV market share but its costly.
- Nickel-rich NMC chemistries such as NMC-622* and NMC -811 are under development for near-future automotive batteries. * The NMC-622 represents that the percentage contribution of the Nickel, Manganese, and Cobalt are 60, 20, and 20.
- Recalling that the prices of cobalt, nickel, and manganese for year 2018 are USD 61,499/ton, USD 11,701/ton, and USD 2,000/ton, the NMC- 622 battery will represent lower costs than current mainstream battery technology.

d. LMO is not used exclusively as the battery in EVs owing to its low specific energy and poor stability. It does, however, produce a lot of power at a low cost when compared to other cathode materials. These are utilized in forklifts and power tools, among other material handling applications. These are also used in a mixed composition with NMC to increase specific energy and battery life.

   The typical ratio of LMO: NMC is 30:70. The LMO component provides high current boost on acceleration while the NMC part offers the long driving range. The LMO/NMC combination has been employed for most EVs such as the Nissan Leaf, Chevy Volt, BMW i3, etc.

e. The LFP has limited application in hybrid, plug-in vehicles, and electric buses due to their lower specific energy.

On the commercial side, the high cost of batteries is one of the primary impediments to widespread adoption of electric vehicles. Automobile makers will strive to cut battery costs in the near future by employing a variety of cost-effective strategies such as creating low-cost battery materials, boosting production volume, lowering manufacturing costs, and optimizing cell design, among others.

5.9.1 Current Status & Specification of EVs and Batteries

The table below highlights the current state of EV commercialization as well as the battery specifications.

Chemistry		**Cells**				**Battery Packs**		**EV Model**
Cathode	**Anode**	**Producer**	**Cell Volts (V)**	**Sp. Energy Wh/kg**	**Energy density (Wh/L)**	**Energy (kWh)**	**Range (Km)**	
NCA	Graphite	Panasonic	3.6	236	673	60-100	330-500	Tesla S
NCA	Si -C	Panasonic	3.6	236	673	60-100	330-500	Tesla X
NCA	Si-C	Panasonic	3.6	260	683	75-100	350-500	Tesla 3
NMC	Graphite	Panasonic /Sanyo	3.7	130	215	24	190	VW e-Golf
NMC	LTO	Toshiba	2.3	89	200	20	130	Honda Fit EV
NMC	Graphite	Li-Tec	3.65	152	316	17	145	Smart Fortwo
NMC	Graphite	SK Innovation	3.7	-	-	27	145	Kia Soul EV
NMC	Graphite	LG Chem	3.65	186	393	60	383	Chevrolet Bolt
NMC	Graphite	LG Chem	3.7	241	466	41	400	Renault Zoe
NMC-LMO	Graphite	Samsung SDI	3.65	172	312	24	140	Fiat 500e
NMC-LMO	Graphite	LG Chem	3.7	-	-	35.5	160	Ford Focus EV
NMC-LMO	Graphite	LG Chem	3.75	157	275	26	150	Renault Zoe
LMO-NCA	Graphite	AESC	3.75	155	309	24	135	Nissan Leaf

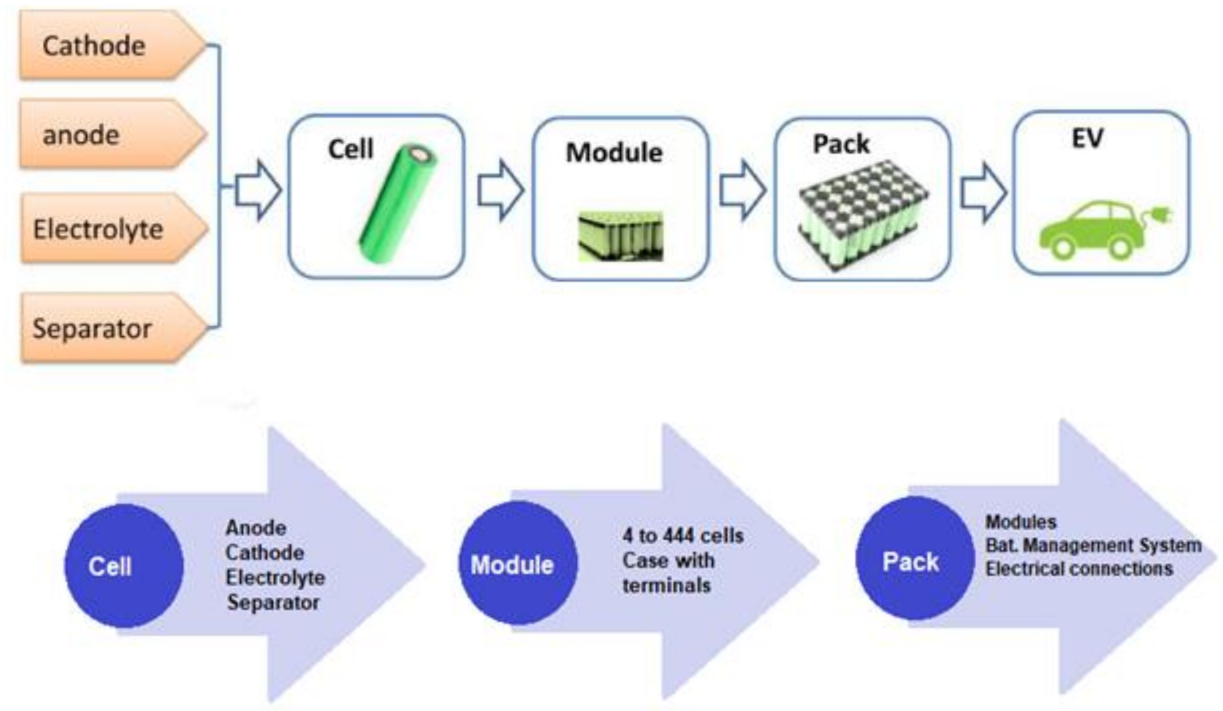
LMO-NCA	Graphite	AESC	3.75	167	375	30	172	Nissan Leaf
LFP	Graphite	A123	3.3	131	247	21	130	Chevrolet spark
LFP	Graphite	BYD	3.3	120	220	61	300	BYD e6

Source: Automotive Li-ion Batteries: Current Status and Future Perspectives, Waterloo Institute

6 Chapter - 6: BATTERY CELLS, MODULES & PACKS

The battery manufacturing supply chain has three main parts:

a. Cell manufacturing
b. Module manufacturing and
c. Pack assembly



Three Stages in making of an EV Battery Pack

The process of making batteries begins with the construction of a set number of cells into "modules," which are then integrated into packs. These three stages can be carried out in the same place or broken up into two or (theoretically) three sites. Tesla, for example, manufactures its own modules and packs at its car assembly factory in Fremont, California, while Panasonic manufactures cells for these in Japan (Model S and Model X). In 2017, Tesla inaugurated its new "Gigafactory" in Nevada, where cells and modules for the Model 3 are built, and packs are manufactured at its Fremont, California car assembly plant.

Pack assembly usually takes place near the vehicle assembly location because of the high cost of transporting battery packs, which are larger and heavier than cells or modules.

6.1 Battery Cell Construction

The electrochemical cell is the smallest but most critical component in Li-ion batteries. At a basic level, all Li-ion battery cells have three functional layers: the positive electrode (cathode), the negative electrode (anode), and the separator. These thin layers are either rolled or stacked to increase the effective surface area available for energy storage and then packaged in an outer cell housing.

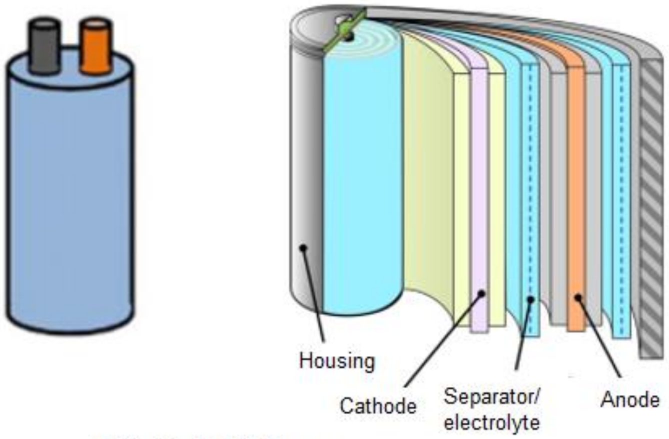
The three standard Li-ion cell configurations are Cylindrical, Prismatic, and Pouch.

Both prismatic and pouch cells are flat and rectangular, but prismatic has a hard case whereas pouch has a soft pack.

Cylindrical cells are less expensive than rectangular cells, have a high specific energy, and are commonly employed in portable devices. These cells are mechanically stable and can sustain high internal pressures without deforming.

6.1.1 Cylindrical Cells

Cells with a cylindrical shape are made in a characteristic "swiss roll" manner (known as a "jelly roll" in the US), which means rolling long strips of cathode foil, separator, and anode foil together and inserted into a rigid stainless steel or aluminum cell housing or “can”. The can is filled with liquid electrolyte, safety disks are inserted into the top, and the electrodes are welded to the outer battery terminals (in this case, the top and bottom of the cell). The cell is hermetically sealed by crimping the top disk assembly closed.



Cylindrical Cell Format

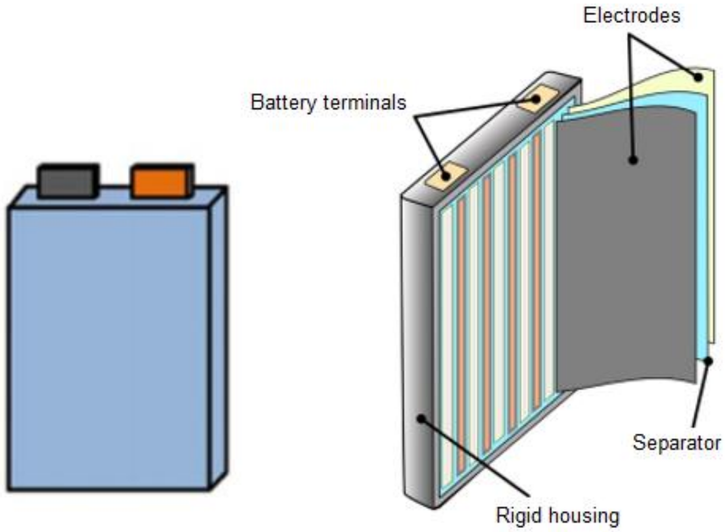
Cylindrical cells are designated by a five-digit number describing their size. For example, the most used Li-ion cylindrical cell in EV applications (and laptops) in the recent past was the 18650, which holds about 10 Wh of energy. The numbering indicates that it is 18 mm diameter x 65 mm height cell. The first two numerals represent the diameter of the battery in millimeters, while the last three digits represent the height of the battery in tenths of millimeters.

There has been a recent push to use the 21700 cells in EVs, as manufacturers claim that the cell has higher specific energy and lower cost than the 18650. Tesla, for example, has recently switched from the 18650 to the 21700-battery configuration. The size of these 21700 cells is 21 x 70 mm.

One advantage of cylindrical cells compared to cells with stacked electrodes is faster production speed. A disadvantage can be a large radial temperature gradient inside the cells may develop at high discharge currents.

6.1.2 Prismatic Cells

Prismatic cells are flat or rectangular-shaped batteries that are commonly used for powering electronic gadgets. Individual electrodes can be stacked in a flat spiral or rectangular stack in the electrode/separator assembly (like a deck of cards). The battery connections can be mounted on the top or side of the enclosure as contact pads. The prismatic cell thin form factor is ideal for consumer devices, particularly when ease of battery replacement is desirable.



Prismatic Cell Format

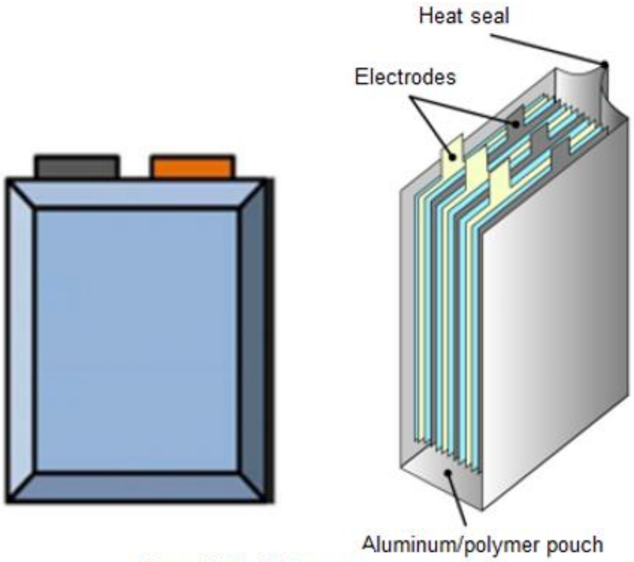
Prismatic cells can be made in practically all sizes and aspect ratios necessary for their intended use. The most common sizes are 5 x 34 x 50 mm and 10 x 34 x 50 mm, however as with other types, vendor-specific sizes and made-to-order sizes are also available.

Prismatic cells are more space-efficient than cylindrical cells, but they are more expensive to construct, less efficient in heat management, and have a shorter cycle life.

Nissan used prismatic cells for its Leaf EV for the first several model years of that vehicle.

6.1.3 Pouch Cells (sometimes called “lithium polymer” cells)

Pouch cells are a newer technology that resemble prismatic cells in design but employ a thin laminated polymer/aluminum "bag" instead of a hard metal container. Pouch cells save money, weight, and thickness by eliminating the rigid housing, but they may not provide the same level of safety and durability as prismatic cells. The flexible pouch is prone to swelling and this can pose problems with lifetime, capacity loss, and safety.



Pouch Cell Format

The absence of a case gives pouch cells the highest gravimetric energy density; however, for many practical applications they still require an external means of containment to prevent expansion when their SOC level is high, and for general structural stability of the battery pack of which they are part. The pouch-style cells are sometimes also referred to as prismatic cells due to their rectangular shapes.

6.2 Lithium-Polymer Batteries

Pouch cells are often labeled as “lithium polymer” or” Li-Po cells”.

Li-Po refers to a Li-ion battery with a polymer electrolyte (gel-based) rather than a liquid electrolyte and a microporous separator rather than the more common porous separator found in standard varieties. Electrolyte does not leak from the laminate bag because of the gel electrolyte. Gel electrolyte is made from the following materials:

a. Polyethylene oxide (PEO)
b. Polyacrylonitrile (PAN)

c. Poly vinylidene fluoride (PVDF)
d. Poly methyl methacrylate (PMMA)

The lithium polymer batteries have a foil type casing with laminated sheets within. This allows the batteries to be made much lighter - in fact, weight savings of up to 20% or more are common.

The gel-based electrolyte allows for the creation of pouch cells in a variety of shapes and sizes, which is attractive to many manufacturers who are continually seeking to have slimmer equipment, laptops, and phones etc.

Compared to more traditional lithium-ion battery technology, lithium polymer batteries have a few advantages.

a. Can be made with a very slim outline.
b. Can be made in a variety of shapes and outlines.
c. Low weight
d. Higher energy density for given weight (WH/kg)
e. Cost of manufacture now becoming lower.
f. Bendable batteries available.
g. Slightly higher top usage temperature.

In most respects, the polymer version of a battery gives a slight improvement in performance, but also the cost is slightly more.

6.2.1 Applications of LIPO

All types of battery formats (cylindrical, prismatic, and pouch) are installed in today’s electric cars. So far, cylindrical cells lead the field in terms of energy density (e.g., Tesla), prismatic pouch (e.g., from LG), and prismatic can cells (e.g., from LG, Samsung, Panasonic, and others).

However, the move from conventional to solid-state batteries could rob cylindrical batteries of their advantage over pouch or prismatic cells, especially if the use of solid electrolytes requires stacking the electrodes, making cylindrical winding impossible.

6.3 Battery Modules

Multiple cells are typically grouped together in a casing with terminals attached to form a module. The number of cells per module varies depending on the manufacturer and type of cell. AESC, for example, utilizes four cells in its modules for Nissan Leaf battery packs, but Samsung SDI employs 12 cells in its modules.

Refer to the picture below showing how the cells are connected to create a battery.

Lithium Ion Battery Module
Source: USABC

6.4 Battery Packs

Battery packs are the final stage of EV battery production and consist of a group of modules into one unit along with electrical connections, cooling equipment, and battery management system (BMS). The BMS is responsible for ensuring that these hundreds or thousands of battery cells are safe and functional. The BMS is composed of electronics and software that monitor the health and safety of the battery pack and control charging and discharging at a cell level.

Battery manufacturers design EV battery packs for specific vehicle models and tend to assemble them near the vehicle assembly plant.

Nissan Leaf Battery Pack

Battery packs tend to be custom designed for each application, meaning different EV models likely have drastically different battery packs. The Tesla Model 3's battery pack, for example, includes 7,104 cylindrical cells, whereas the Chevy Bolt's battery pack contains 288 prismatic cells and the Nissan Leaf's battery pack contains 192 pouch cells.

6.5 Value Chain – Manufacturers

Traditional electrical appliance manufacturers such as Panasonic, BYD, PEVE (a joint venture between Panasonic and Toyota), AESC (a joint venture between NEC and Nissan), LG Chem, and Samsung SDI are among the leading lithium battery makers. Here are some facts:

a. In 2018, the industry's four behemoths - Panasonic, CATL, BYD, and LG Chem - brought in a combined $100 billion in revenue.
b. The Tesla and Panasonic Gigafactory in Nevada is the world's largest lithium-ion battery factory, capable of producing 35 gigawatt hours of batteries each year.
c. China's CATL is the world's second-largest battery maker and China's number-one battery manufacturer. BYD Co. is another leading Chinese battery manufacturer.
d. Panasonic is the world's fourth-largest lithium battery manufacturer. In Japan, it is ranked first.

Top Li-ion Battery Manufacturers

Company	**Capacity (GWh)**	**Headquarters Location**	**Manufacturing Locations (2019)**
Tesla-Panasonic	35	USA	Nevada, US
LG Chem	17	South Korea	South Korea, Poland, US, China
BYD	16	China	China
Panasonic	8.5	Japan	US, Japan, China
Envision Group (formerly AESC)	8.5	China (formerly Japan)	US, Japan, UK
CATL	7.8	China	China
Guoxuan High-Tech	6	China	China
Samsung SDI	6	South Korea	South Korea, Hungary, China
Lishen	3	China	China

CBAK	2.8	China	China
CALB	2.8	China	China
LEJ	2.5	Japan	Japan
Wanxiang (formerly A123)	2	China (formerly US)	China, US

Source IDA.org

6.5.1 Battery Raw Materials

Most Li-ion batteries rely on a mix of Lithium, cobalt, carbon (graphite form), manganese, and nickel. These elements are extracted from natural mines deep within the earth's crust. Some of these materials are harder to find than others, though none should be classified as "rare earth metals." According to current data,

a. The terrestrial lithium reserves amount to 14 million tonnes based on Li metal equivalent.
b. The terrestrial cobalt reserves are estimated at around 25 million tonnes, while the economically extractable cobalt reserves are estimated to be 7.1 million tonnes in 2016. A drop in the demand for cobalt can be expected in the longer term.
c. The terrestrial nickel reserves are estimated at 89 million tonnes.

From 2020 to 2050, demand for lithium, cobalt, nickel, and cobalt manganese oxide is expected to increase by factors of 18–20 for lithium, 17–19 for cobalt, 28–31 for nickel, and 15–20 for most other materials, requiring a massive expansion of lithium, cobalt, and nickel supply chains and likely additional resource discovery.

Studies conducted between 2009 and 2015 found that there are adequate raw materials for batteries, and that global reserves exceed predicted demand, including for electric vehicles and consumer gadgets. The temporary shortages or price increases for individual resources cannot be ruled out in the future if the demand for other applications such as drones/air taxis come into play.

6.5.2 Supply Risks

In the future years, the production of electric vehicles and the use of lithium-ion batteries will grow fast, resulting in an increased demand for raw materials such as lithium, cobalt, graphite, copper, aluminum, nickel, and manganese. Nickel, manganese, aluminum, and copper all have acceptable production levels and no apparent supply issues. Three critical minerals for battery manufacture — lithium, cobalt, and graphite – may face supply constraints.

6.5.2.1 Lithium

Lithium is largely concentrated in Argentina, Peru, Bolivia, and Chile. The mining of Lithium has a huge environmental impact due to toxic chemicals, which are used in processing lithium, and problems with waste disposal at the mines. With respect to refining, about half the lithium refining capacity is concentrated in China, followed by Chile and Argentina.

6.5.2.2 Cobalt

Over 60% of the global supply for Cobalt comes from the Democratic Republic of Congo (DRC), which has a poor human rights track record; international organizations have denounced for years the exploitative labor practices involved in cobalt production. In 2018, China accounted for more than 85% of the DRC's cobalt ore and concentrate exports, by value.

6.5.2.3 Graphite

About two-thirds of the graphite used in Li-ion batteries are synthetic, and the remainder is mined and refined. China accounts for over half of the mined graphite worldwide and all the commercial-scale graphite refining. Synthetic graphite, which is roughly twice the cost of natural mined/refined graphite, is produced mostly in Asia.

To make lithium-ion batteries practical for mass-produced EVs, access to affordable raw materials and components for batteries will be decisive. The risks are due to high geopolitical concentrations of cobalt and social and environmental impacts associated with lithium mining.

6.5.3 Transportation

One of the major risks associated with battery-powered equipment is the short-circuit of the battery because of battery terminals coming into contact with other batteries, metal objects, or conductive surfaces. Short circuits and terminal damage can occur if batteries or cells are not separated and packaged properly. Unless the battery is provided with similar protection by the device in which it is contained, they must be packaged in a strong rigid outer container.

The International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO) have established international laws that limit the shipment of lithium-ion batteries by air. Several UN regulations govern the shipment of Li-ion batteries (specifically UN3480, UN 3481 and UN3090).

6.5.3.1 Prohibitions (UN 3480)

Lithium ion batteries are not allowed to be carried as cargo on passenger aircrafts. All packages prepared in accordance with Packing Instruction 965, Section IA, IB and II, must bear a Cargo Aircraft Only label, in addition to other required marks and/or labels.

6.5.3.2 Restrictions (UN 3480 only)

The state of charge (SoC) of lithium ion batteries must not exceed 30% of their rated capacity when shipped. Only with the agreement of the State of Origin and the State of the Operator, and under the written conditions imposed by those authorities, may cells and/or batteries with a SoC more than 30% be exported.

Small batteries that are integrated into equipment face fewer constraints than large batteries or batteries that are packed separately from the equipment. EV battery packs are often above 1000 pounds in weight. These products are classified as "dangerous goods" and are prohibited from being transported by air. Due to these transportation constraints, battery pack assembly operations are typically placed next to or near car assembly plants. For example, the early models of the Chevy Bolt, which is assembled in Michigan, used batteries produced by LG Chem that were shipped from its South Korea factories and then assembled into packs in a factory in Michigan. Beginning in 2018, LG Chem began producing batteries for the Chevy Bolt in Michigan as well, so that cell, pack, and vehicle assembly operations for the Chevy Bolt are all co-located.

7 CHATPER - 7 LITHIUM-ION BATTERY CHARGING EQUIPMENT

The procedure of charging an electric vehicle battery is simple: you simply plug your car into a charger that is connected to the power grid. However, not all EV charging stations are created equally. Some can be installed simply by plugging into a standard wall outlet, while others require a custom installation. The amount of time it takes to charge your car depends on the charger you choose.

EV Charging Connector

Li-ion batteries require suitable charge control and protection circuitry. Overcharging a Li-ion battery can cause a fire or explosion, and over-discharging can permanently damage the battery.

7.1 Conditions for Lithium-ion Battery Charging

Charging Li-ion batteries differs significantly from charging Ni-MH batteries. Li-ion battery charging is voltage-dependent rather than current-dependent.

Li-ion batteries charge in a similar way as lead-acid batteries.

One of the distinctions in charging Li-ion batteries is that they have a greater voltage per cell, ranging from 3.7 to 4 volts as opposed to 1.2 volts for Ni-MH and 2 volts for lead-acid batteries.

Lithium-ion cells also require much tighter voltage tolerance on detecting full charge, and once fully charged, they do not allow or require to be trickle or float charged. It is particularly important to be able to detect the full charge state accurately because lithium-ion batteries do not tolerate overcharging. They over-heat and this reduces their life but in extreme circumstances, it can lead to them catching fire or even exploding.

Most consumer-orientated Li-ion batteries charge to a voltage of 4.2 volts per cell and this has a tolerance of around ± 50 mV per cell. Charging beyond this causes stress to the cell and results in oxidation that reduces service life and capacity. It can also cause safety issues as well.

7.1.1 Charging Steps

Li-ion batteries are usually charged in two steps. Constant Current (CC) and Constant Voltage (CV).

<u>Step -1: Constant current</u>

The first step is a constant-current charge at 0.5-1.0 C until the battery reaches its maximum voltage, usually 4.1-4.2 V/cell.

<u>Step -2: Constant voltage</u>

The voltage eventually rises to 4.2 Volts/cell after a while. The cell or battery must now enter a second charging stage known as the saturation charge. During the constant voltage phase, the charger applies a voltage to the battery equal to the maximum cell voltage multiplied by the number of cells in series, and the current steadily decreases.

The end of the charge cycle is reached when the current falls to around 10% of the rated current. The charge duration for this step may be roughly two hours, depending on the type of cell and the manufacturer, among other factors.

A typical electric car (60 kWh battery) takes just under eight hours to charge from discharged to fully charged with a 7-kW charging point. For many electric cars, up to 100 miles of range can be added in about 35 minutes with a 50-kW rapid charger.

7.2 EV Battery Charging Stations

Charging equipment, usually termed as “Electric Vehicle Supply Equipment” (EVSE) come in two basic varieties.

The first, comprising of “Level 1” and “Level 2” EVSE, operates using alternating current (AC), and can draw electricity directly from the local distribution system. All BEVs and PHEVs carry an on-board inverter with limited capacity, to convert AC power to direct current (DC), which is required to charge the battery.

The second variety, “Level 3” and above, uses DC charging, which bypasses the need for an inverter by charging the battery directly and can therefore deliver much more power. There is otherwise no relevant difference in the AC and DC charging process. Chargers in public or commercial locations, typically Level 2 and above are the “commercial chargers”, which may be standalone devices, or stations comprised of multiple chargers.

7.2.1 Level 1 EVSE

A level 1 charger is like plugging into a standard, 120-volt outlet and does not require special equipment or installation. This type of charging is also known as trickle charging. L1 chargers are the least expensive option and are most often used at home.

Level -1 Charging (EVSE)

L1 charger (120V, 16A, 1.9kW) will add approximately 5-8 km of travel range per hour, and a full charge can take between 8 and 20 hours, depending on the battery capacity of the vehicle.

Manufacturers: AeroVironment, Duosida, Leviton, and Orion.

7.2.2 Level 2 EVSE

Level 2 chargers are used for both residential and commercial charging stations. They use a 240 V (for residential) or 208 V (for commercial) plug, and unlike Level 1 chargers, they can’t be plugged into a standard wall outlet. Instead, they are usually installed by a professional electrician.

Level -2 Charging (EVSE)

L2 charger (240V, 15A, 2.5/3.0 kW) will add up to 25-40 km of travel range in one hour, and can take between 2 and 6 hours, depending on the battery capacity of the vehicle.

Manufacturers: Nissan, Clipper Creek, Charge point, Juice Box, and Siemens.

7.2.3 DC Fast Chargers (also known as Level 3 EVSE or CHAdeMO EV charging stations)

DC Fast Chargers, also known as Level 3 (L3) or CHAdeMO charging stations, use as high as 600V and are installed only in commercial locations along heavy traffic corridors and at public stations. These require highly specialized 3rd party services for operation and maintenance.

The DC fast charges can deliver much higher levels of electrical power ranging between 10 to 50 kW. A DC fast charger with an output voltage of 480V and 600V can provide about 150 km of range per 20-30 minutes of charging.

Not all EVs can be charged with the use of DC Fast Chargers. The Mitsubishi “i” and Nissan Leaf are two examples of electric cars that are DC Fast Charger enabled.

Caution: Various studies demonstrate that consistent high DC fast charger usage can accelerate deterioration in battery capacity over time and capacity degradation.

7.2.4 Ultra-Rapid Charging Points or Superchargers

Ultra-Rapid Charging points or superchargers can recharge up to 80% SoC in a battery in about 10 -15 minutes.

Tesla’s proprietary network of Superchargers, with a typical power output of 120 kW, is designed to serve Tesla vehicles exclusively and corresponds most closely to Level 4. These super-fast charging stations can charge a Tesla battery in about 30 minutes. Tesla superchargers are designed exclusively for Tesla vehicles, which means that if you own a non-Tesla EV, your car isn't compatible with Supercharger stations. Tesla owners receive 400 kWh of free Supercharger credits each year, which is enough to drive about 1,000 miles.

Caution: 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 the monitoring and control of cell temperature.

The EV is typically charged through a standard connector and receptacle that works with any Level 1 (120 V AC) or Level 2 (240 V for residential/208 V for commercial) plug. Some rapid charging stations use different receptors (known as SAE receptors or CHAdeMO) which are not standardized.

7.3 Charging Regulations & Standards

The Society of Automotive Engineers (SAE) in North America is at the forefront of efforts to standardize charging. The standard SAE J1772 is for electrical connections for electric vehicles. It details the physical and electric characteristics of both the charge system and coupler. The standard was adapted on January 14, 2010.

This Standard defines a five-pin configuration for the connector used for Level 1 and Level 2 charging. The connector is designed to survive more than 10,000 connection and disconnection cycles. Level 3 configurations are currently under development, as is a Direct Current fast charging configuration.

All major vehicle and charging system manufacturers support this standard, which should eliminate drivers' concerns about whether their vehicle is compatible with the infrastructure.

Manufacturers such as Coulomb Technologies of the United States have already introduced charging stations that is compliant with SAE J1772 Standard.

The Underwriters Laboratories has verified the safety and durability of the SAE J1772 standard.

7.3.1 Power Connectors

a. Type 1 (SAE J1772), a single-phase connector used in the US and Asia.
b. Type 2 (IEC 618515), a 3-phase connector used in Europe.
c. A Combined Charging System (CCS) is available for fast charging (DC) and slow charging (AC).
d. DC fast chargers, CHAdeMO is the most common connector standard.

Type-1 Connector (1-ph AC)

Type-2 Connector (3-ph AC)

Combo Charging System (AC/DC)

CHAdeMO Connector (DC)

The latest in EV charging is wireless (or Induction) charging. Unlike conduction charging, which requires a conductor to feed electricity, energy in wireless charging is transmitted through electro-magnetic induction. The energy flows from a transmitter coil housed in a pad that sits on the pavement to a receiver coil in a pad underneath the vehicle. Wireless chargers are in the early stages of development and are currently very expensive.

Summarizing, the Table below presents each EVSE level, connector type, maximum voltage, and power.

Level	**Connector**	**AC/DC**	**Max. V & I**	**Power (kW)**
Level 1	Type 1	1 phase AC	120 V/16 A	1.9
Level 2	Type 1	1/3 ph. AC	240 V/80 A	14 - 19
Level 3	Type 2	3 phase AC	480 V/63 A	43 - 52
Level 3	CHAdeMO	DC	500 V/125 A	63
Combo	Type 3	AC and DC	1 kV/400 A	36 - 200+

8 CHAPTER - 8: ISSUES & CHALLENGES WITH LITHIUM-ION BATTERIES

For EVs to perform at their best, many technical hurdles and safety concerns related to Li-ion batteries must be addressed. Capacity fading, limited cycle life, charge/discharge rate, charging method, and hysteresis are all major issues with Li-ion batteries. Material recyclability, environmental impacts, and excessive cost are also the considerations.

8.1 Capacity Fading

The irreversible loss of usable energy and power capacity of a rechargeable battery with time and usage is referred to as capacity fading. A vehicle's travel range is limited by its energy capacity, and its acceleration rate and regenerative brake power are limited by its power capacity.

The degradation of the anode, cathode, electrolyte, separator, and current collectors are the main causes of performance degradation in Li-ion batteries. Generally, a battery is considered functional until it reaches 80% of its initial capacity. Currently, the issue of capacity fading is addressed by using bigger batteries to achieve sufficient performance until the battery life expires, which is approximately 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 suffers two types of losses:

a. Calendar life loss due to storage
b. Cycle life loss due charge/ discharge cycling

Calendar fade refers to the battery's performance decline over time, regardless of whether it is used or not, while cycle fade refers to the battery's performance deterioration as it is used.

8.1.1 Cycle Life

The amount of Li ions that can be shuttled back and forth between the cathode and anode while the battery is cycled determines the battery's capacity. Some of those ions are removed off the cathode and end up at the anode during the charge/discharge process. 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.

8.1.2 Calendar Life

When a Li-ion battery is idle and not subject to charging/discharging, the Li-ions begin to react with the electrode material and the electrolyte and form a layer of chemical compound at the electrode-electrolyte interface. This thin layer called the Solid Electrolyte Interface (SEI) protects the electrode but also grows thicker over time resulting in increased internal resistance and gradual wearing of the electrodes. 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.

Other reasons for battery capacity fade include:

a. Increase in ambient and cell temperatures
b. Increase in internal impedance
c. High discharge rate, very high DOD, etc.

A 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.

8.2 Safety Issues

The Li-ion battery cells are not tolerant of mistreatment. A Li-ion battery stores a large amount of energy in rather small packing. When this 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.

Overcharge, over-discharge, thermal runaway, dendritic growth, and gas evolution are all factors that can cause safety hazards in Li-ion batteries.

8.2.1 Overcharging

Li-ion cells have a narrow range of operating voltage and temperature. The safe voltage range is between 2.3 V (min. discharge) to 4.2 V (max. charge). Working outside of the parameters will quickly result in a dead battery or, in the worst-case scenario, a fire and explosion.

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 into the battery in the form of a 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 increased cell voltage. When the cell voltage reaches around 4.7 V, the electrolyte and solvents breakdown and form flammable gasses. Pressurization of these gases results in battery swelling along with high cell temperature, which, in the worst condition, may lead to explosion and fire. Another problem of overcharging is lithium plating and subsequent dendrite growth. The consequence is a loss of capacity, potential internal short-circuit, battery explosions or fire.

Overcharging can be avoided by switching off the charger after the cell voltage has reached the desired level. When the charger is switched off, the cell voltage drops and stabilizes at roughly 3.7 to 3.9 V.

8.2.2 Over-discharge (Current-Collector Dissolution)

The cell voltage of most Li-ion batteries is between 2.5 and 4.2 volts. A phenomenon known as over-discharge happens when a cell is discharged below the designated lower voltage limit. This occurs in battery packs that use series-parallel cell combinations to achieve high voltage and current. Because it is difficult to have all of the cells in a pack at the same charge level, the cells with lower capacity are required to release the same amount of energy as the other cells while discharging.

Over-discharge of Li-ion cell results in the dissolution of copper current collector at the anode. Over a period, this copper can get deposited on other components and leads to an internal short. This also results in permanent capacity fade or failure.

8.2.3 Thermal Runaway

The safe working temperature range of a typical Li-ion cell is around 15°C to 50°C. The cycle life of the battery reduces significantly at temperatures below 15ºC and slightly above 50ºC. Cells should not be subject to high-temperature charging (>50°C) or low temperature charging (<0°C).

The internal resistance of Li-ion cells varies between 80 - 100 mΩ. During charge/discharge cycles, a 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 ºC due to any reason, it will accelerate into further chain reactions leading to more heat release. This is known as thermal runaway.

The temperature of the cell rises rapidly to 300-400°C or more in a short period of time under these conditions, causing the melting or vaporization of numerous compounds in the cell. A gassing, leaking, or burning battery will result, which may explode or catch fire quickly. The thermal runaway was one of the key factors in the majority of recorded EV battery fires.

An increase in cell temperature reduces the battery’s 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.

8.2.4 Lithium Dendrite Formation

When Li-ion batteries are unintentionally overcharged, the chemical structure of the anode and cathode is destroyed, and some lithium ions form snowflake-shaped lithium metal deposits known as "dendrites," which can result in capacity fading, internal short-circuits, high temperature generation, and battery explosions or fire. Impurities in the lithium metal can also contaminate the batteries and cause the formation of dendrites.

Li-ion batteries must be sold as battery packs with very accurate battery management circuitry to prevent overcharging. During charging, the protective circuit limits the peak voltage of each cell. The protective circuitry also keeps the cell voltage from falling too low during discharge.

The use of solid electrolytes, alloying Li anodes with other metals, and using additives to increase uniformity at the solid electrolyte interface are all novel ways to prevent dendrite development.

8.2.5 Gas Evolution

The degradation of electrolyte and their reactions with the positive/negative electrodes are the primary causes of gas generation in Li-ion batteries. Depending on the state of the battery, the amount of gas produced will vary. Gas liberation will be minimal during regular charge/discharge cycles.

Gas generation will grow during abnormal conditions such as overcharge, over-discharge, thermal runaway, and so on, and this could lead to pressurization and an explosion. A safety valve is supplied in some high-power Li-ion battery systems to expel the gas.

8.3 Safety with Battery Management System (BMS)

Cells used in battery packs should be individually monitored and controlled by a Battery Management System (BMS). The BMS is required and essential for Li-ion batteries since the cells are particularly sensitive to overcharging, shorting, and deep discharge.

The following are the most important functions:

a. BMS tracks the level of charge, the temperature, voltage, and several other factors.
b. BMS monitors almost everything that the battery does, ensuring that temperature is regulated, power output is kept even, and battery pressure does not exceed advisable limits.
c. BMS terminates the charging process when the battery or cell is fully charged (normally when voltage per cell rises above 4.2 volts). Similarly, over-discharge protection is

provided to prevent the battery voltage falling below about 2.3 volts dependent upon the manufacturer.

d. BMS also provides the battery charge status – the state of charge (SoC). It is just like providing the fuel status.

8.4 Li-ion Batteries Safety & Usage Guidelines

Lithium-ion batteries or Li-ion batteries can be relatively expensive. It, therefore, pays to follow simple guidelines that can help ensure the maximum life is obtained from them.

8.4.1 Don’t Totally Discharge

Before a lithium-ion battery is totally discharged, it should be charged. In general usage, this is most likely the most crucial aspect. Allowing them to become completely discharged significantly reduces their lifespan. For example, it is recommended that cellphones (which use Li-ion batteries) be charged when they reach 10 to 20% charge. Li-ion batteries should never be discharged below their minimum voltage, which is between 2.4 and 3.0 volts per cell.

8.4.2 Charge Current

The charging current can't go over the set limitations. The maximum value is typically 0.8C, however lower values are more commonly used to provide some margin. There is an effect on the lifetime of batteries or cells that can handle higher current charges. If it is possible to keep the charge rate low and avoid using fast charging, the cell's usable life will be extended.

8.4.3 Non-use Care

If a Li-ion battery is not going to be used for an extended period of time, it should be stored partially depleted, usually between 40% and 60% of full charge. To counteract the consequences of self-discharge, it should be charged on a regular basis (around 2 percent per month).

8.4.4 Follow Manufacturer’s Instructions

Lithium-ion batteries should always be charged according to the manufacturer's instructions. Always use the manufacturer's charger because the charger and battery pack may have various levels of protection depending on the design.

Cells should never be subject to mechanical abuse or stress. Test batteries, chargers, and associated equipment in accordance with an appropriate test standard (e.g., UL 2054), NRTL certification (where applicable), help identify defects in design, manufacturing, and material quality.

8.5 Safety Testing

The United Nations (UN), Underwriters Laboratories (UL), and the International Electrotechnical Commission (IEC) have published standards for safety testing of Li-ion batteries. Most shipments of Li-ion batteries must be tested according to the UN Manual of Tests and Criteria, Part III, Subsection 38.3 (UN 38.3).

UN38.3, UL 1642, and IEC 62133 (among others) define a series of tests, including but not limited to overcharge, short circuit (both internal and external), crush, impact, altitude, and heating tests. Batteries must not catch fire or explode, and they must not leak or overheat to pass.

The Institute of Electrical and Electronics Engineers (IEEE) has established standards for batteries in portable computers (IEEE 1625) and cellular phones (IEEE 1725), which specify extra design and production criteria, many of which are intended to avoid internal short-circuiting.

8.6 Disposal

Cobalt, nickel, manganese, iron, and aluminum, among other metals in Li-ion batteries, are not as poisonous as lead or cadmium in lead acid or Ni-Cd batteries. They can be disposed of in landfills in many countries. While Li-ion batteries can be recycled to recover metals, recycling is expensive, and the recycling infrastructure is not as widespread as that for lead-acid batteries. Charged lithium-ion batteries pose a fire or explosion hazard if crushed, punctured, or incinerated; batteries should be fully discharged before disposal.

9 CHAPTER - 9: TECHNOLOGY, CHALLENGES & THE FUTURE

Next-generation technologies are enabling increased performance in consumer electronics as well as the advent of new applications like drones and electric vehicles. Future batteries must be smaller, lighter, less expensive, and have a longer lifespan.

NMC -111 is currently the dominating cathode material for EVs. Each digit in the number NMC-111 denotes the proportion of nickel, manganese, and cobalt in the blend. That is nickel, manganese, and cobalt are in ratio of 33.33% each. This material is pricey due to the high percentage of cobalt.

NMC-442 and NMC-532 are two novel chemistries that have been developed and are now being used commercially. Efforts are on to reduce the cobalt content still further and develop nickel-rich chemistries such as NMC-622 and NMC -811.

NMC-811 is the most energy-dense cathode material. It's not quite ready for commercial use yet. The biggest problem is that it can only tolerate a limited number of charge-discharge life cycles before failing. This problem is currently being researched.

Lithium-titanate and lithium-iron-phosphate batteries are gaining importance in the EV market because these are relatively cheap and don’t need cobalt. Many companies are developing cobalt-free lithium iron phosphate, lithium-sulphur, lithium air, and other chemistries that have the potential to outperform cobalt/nickel-based lithium-ion batteries in terms of energy density and cost.

The anode of a lithium-ion battery is typically made of graphite, which can only store a finite amount of energy. Amorphous silicon composites are being studied as a replacement for graphite anodes, which can quadruple storage capacity. Additional researchers are working on anodes made of lithium and two other metals, antimony mixed with copper, manganese, or indium. Such three-metal alloys should also increase storage capacity.

Solid-state batteries, Li-air batteries, and Li-Sulphur batteries are among the battery technologies being researched using alternative materials.

Solid-state batteries have a solid electrolyte instead of a liquid electrolyte. These can perform at super-capacitor levels since they can be fully charged or discharged in less than 8 minutes, making them perfect for electric vehicles. The problem is finding a solid substance that can carry lithium ions fast enough.

The lithium-air battery (Li-air for short) is a metal-air battery chemistry that induces current flow by oxidizing lithium at the anode and reducing oxygen at the cathode. The Li-air battery's main selling point is its extraordinarily high energy density. Li-air batteries have a theoretical capacity of 12 kWh per kg.

9.1 Next-Generation Technologies and Innovations

Next-generation technologies are essentially focusing on:

a. Cost, reliability and charging time for EVs
b. Cycle lifetime and cost for high-frequency stationary battery energy storage
c. Safety across multiple applications

The table below provides a summary of new innovations happening in the field of Battery Technology.

Technology	**Potential Advantages**	**Challenges and Limitations**
Novel anodes (e.g., Silicon based anodes, Li-metal)	Si has a higher energy capacity than graphite anodes. These can offer theoretical increases in energy density of up to 40 percent.	Anodes made of Si alone suffer from volume expansion and do not offer long cycle life. Ongoing innovations use only minor Si concentration additive to graphite, limiting potential density increases to 10–20 percent.
Low-Cobalt cathodes	Decreased dependence on critical materials, cost. Many advanced-cathode chemistries such as Nickel Manganese oxide (NMO) exist that have higher energy capacities and voltages.	Manufacturing, scale-up, safety, cycle life. These NMO cathode materials are currently facing issues with the liquid electrolyte used in common battery systems, which breaks down at voltages above 4.5 V.

Nanostructured electrodes	Power density, cycle life	Manufacturing, cost
Battery recycling	Decreased dependence on critical materials	Cost, business case
Novel separators	Safety	Cost
Novel liquid electrolytes	Safety, cycle life	Cost, manufacturing
Coatings and additives	Power density, cycle life	Cost
Sodium - ion	Sodium is a low cost, abundant material. Improved safety for battery transportation.	Issues of volumetric/ gravimetric energy density compared to Li-ion.
Li-Sulfur	Sulphur is a low cost, abundant material. High theoretical specific energy. Improved safety.	Poor energy density (volumetric). Issues with power density and discharge rate. Issues with cycle life stability.
Li-Air	Pure metal anode and ambient air/O2 cathode Very high theoretical capacity. Increased safety vs Li-ion. No use of heavy metals.	Short life cycle Issues with practical rechargeability Energy density reduces at high power
Solid-state electrolyte	Solid electrolyte and separator components. No concerns over ‘leakage’. Improved safety due to lack of liquid electrolyte. High operating voltages.	Poor conductivity. Power density, cycle life, and high-volume manufacturing.

	Increase potential energy density by 40%. Lighter and more space efficient. Less need for cooling.	
Battery-management systems and failure detection	Safety, cost savings, extending battery life Flexibility for different battery types and configurations, reliability.	Cost
Manufacturing methods	Cost, final battery performance or architecture	Requires substantial initial capital infusion
Source material extraction	Critical materials, cost	Competition

Sources: IDA.org.

Summary

The market for battery electric vehicles has grown significantly in recent years. Lithium batteries are now the most common alternative for energy storage due to their high energy density and low self-discharge rate. There are two types of lithium batteries: lithium metal batteries and lithium ion batteries.

Lithium metal batteries are generally non-rechargeable and contain metallic lithium. Lithium-ion batteries are rechargeable and contain lithium exclusively in an ionic state in the electrolyte. Because of its high energy density, decent power capabilities, longer life, safety, and low cost, Lithium-ion batteries are widely used in electronic devices and electric vehicles.

Within the Lithium-ion batteries there are many different chemistries available such as LCO, NCM, NCA, LFP, etc. depending on the cathode material. Graphite is commonly used as an anode material. In electric vehicles, NCM and NCA Li-ion batteries have the most market share. These batteries are an excellent alternative in this industry due to their moderate energy consumption (14.7 kWh/100 km), continuing cost drop, sophisticated production technology, increased cycle life, low weight, and great energy storage potential.

High operating temperatures are a drawback, as they may have negative consequences on their energetic performance and longevity. All of these pose a threat to the vehicle's safe operation.

References

a. A Guide to Understanding Battery Specifications and Electric Powertrains, MIT Electric Vehicle Team
b. Lithium-ion Batteries for Electric Vehicles: The US Value Chain: www.edf.org/home.cfm
c. “Lithium-ion Batteries,” Jeff Dahn, Linden’s Handbook of Batteries Technology, 4th edition, 2011.
d. Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale: National Renewable Energy Laboratory
e. Automotive Li-ion Batteries: Current Status and Future Perspectives, Waterloo Institute
f. Future of Batteries, Arthur D. Little report
g. Electrifying Insights, McKinsey’s 2017 report