

A Review on Lithiumion battery

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ABSTRACT-A lithium-ion battery is a type of rechargeable battery that stores energy by the reversible reduction of lithium ions. Graphite typically serves as the anode or negative electrode, while silicon-carbon is now being utilized more frequently. Lithium polymer batteries (with polymer gel as the electrolyte) are the main materials used in handheld electronics. Akira Yoshino created the first modern Li ion battery prototype in 1985, and a team lead by Yoshio Nishi commercialized it in 1991. Batteries that are not properly recycled can catch fire and produce dangerous waste, particularly when they include poisonous metals such as cobalt and nickel. Graphite formed of carbon serves as the negative electrode in a typical lithium-ion

cell. Electrodes made of graphene are another type of experimental material. Lithium and water react violently to produce hydrogen gas and lithium hydroxide (Li OH). As a result, a non-aqueous electrolyte is commonly employed. A lithium-ion cell's voltage, energy density, life, and safety can all significantly vary depending on the materials used. Nanoscale electrode materials and different electrode structures are of interest. Lithium salts such as lithium tetrafluoroborate (LiBF₄) are extensively employed in research.

KEYWORDS - Lithium-ion battery, Reversible reduction, Negative electrode , Positive electrode, Electrolyte , Energy density .

I. INTRODUCTION

The reversible reduction of lithium ions creates a lithium-ion battery, also referred to as a Li-ion battery, which is a form of rechargeable battery. In portable electronics and electric vehicles, it is the most typical type of battery utilized. It is also widely used in grid-scale energy storage, as well as military and aerospace applications. Li-ion batteries outperform other rechargeable battery technologies in terms of energy density, self-discharge, and memory effect.

The different varieties of lithium-ion batteries have different chemistry, performance, cost, and safety properties. As the active

components, intercalation chemicals are used in the majority of commercial Li ion batteries. Graphite typically serves as the anode or negative electrode, while silicon-carbon is now being utilized more frequently. It is possible to construct cells that emphasize power density or energy. With a high energy density, lithium polymer batteries (with polymer gel as the electrolyte), lithium cobalt oxide (LiCoO₂) cathode material, and graphite anode are the main materials used in handheld electronics. Lithium-based compounds such as lithium iron phosphate (LiFePO₄), lithium manganese oxide (LiMn₂O₄ spinel, or Li₂MnO₃-based lithium rich layered materials, LMR-NMC), and lithium nickel manganese cobalt oxide (LiNiMnCoO₂ or NMC) may have longer lifetimes and/or higher rate capabilities. One of the key technologies (in conjunction with renewable energy) for lowering greenhouse gas emissions from cars is the electrification of transportation, which makes extensive use of NMC and its derivatives.



M. Stanley Whittingham developed the first rechargeable lithium-ion battery in the 1970s based on a lithium-aluminum anode and a titanium disulfide cathode, but it had safety problems and was never commercialized. Whittingham also devised the idea of intercalation electrodes. By utilizing lithium cobalt oxide as a cathode, John Good enough improved upon this work in 1980. Akira Yoshino created the first modern Li-ion battery prototype in 1985, and a team lead by Yoshio Nishi from Sony and Asahi Kasei commercialized it in 1991. This battery employs a

carbonaceous anode rather than lithium metal. Since cells in lithium-ion batteries have volatile electrolytes and can catch fire or explode if broken or improperly charged, these batteries can provide a safety risk if improperly designed and manufactured.

The production of secure lithium-ion batteries has advanced significantly. Battery Ion The flammable electrolyte is being removed from all solid state batteries. Batteries that are not properly recycled can catch fire and produce dangerous waste, particularly when they include poisonous metals. Additionally, lithium mining presents substantial challenges due to its water-intensive nature in frequently dry places and the fact that other important minerals needed in batteries, like cobalt, are frequently conflict minerals. Researchers have been prompted by both environmental concerns to increase the effectiveness of minerals and find substitutes like iron-air batteries.

In order to promote safety, research has been conducted on non-flammable electrolytes. Lithium-ion battery research focuses on prolonging lifespan, boosting energy density, cutting costs, and quickening charging. Aqueous batteries, ceramic solid electrolytes, polymer electrolytes, and systems with a lot of fluorine are a few examples of techniques.

II. DESIGN

Generally, graphite formed of carbon serves as the negative electrode in a typical lithium-ion cell. A metal oxide is frequently used as the positive electrode. A lithium salt in an organic solvent serves as the electrolyte. A separator keeps the anode and cathode from shorting. Depending on the direction of current flow through the cell, the electrochemical functions of the electrodes switch between anode and cathode.



Graphite is the most widely utilized anode (negative electrode) in industry, and when it is fully lithigated, it has a maximum capacity of 1339 C/g

(372 mAh/g). The positive electrode is often made of one of three substances: a layered oxide (like lithium cobalt oxide), a polyanion (like lithium iron phosphate), or a spinel (such as lithium manganese oxide). Electrodes made of graphene are another type of experimental material, however due to their high cost, they are still not commercially practical.

Lithium and water react violently to produce hydrogen gas and lithium hydroxide (Li OH). As a result, a non-aqueous electrolyte is commonly employed, and the battery pack is strictly protected from moisture by a sealed container. The non-aqueous electrolyte is often a combination of organic carbonates containing complexes of lithium ions, such as ethylene carbonate and propylene carbonate. Since ethylene carbonate is solid at ambient temperature, a propylene carbonate solvent is added in order to create the solid electrolyte interphase on the negative carbon anode.



Lithium hexafluorophosphate (LiPF₆), which combines strong ionic conductivity with chemical and electrochemical stability, is virtually always used as the electrolyte salt. Passivating the aluminium current collector, which serves as the positive electrode, requires hexafluorophosphate (cathode). The aluminium current collector is ultrasonically fused to the titanium tab. Lithium salts such as lithium perchlorate (LiClO₄), lithium tetrafluoroborate (LiBF₄), and lithium bis(trifluoromethanesulfonyl)imide (LiC₂F₆NO₄S₂) are extensively employed in research but are incompatible with larger format cells. frequently as a result of their incompatibility with the aluminium current collector. The anode (negative) current collector is a copper current collector with a spot-welded nickel tab.

To increase electrical characteristics, current collector designs and surface treatments can take many different shapes, including foil, mesh, dealloyed foam, fully or selectively etched

surfaces, and surfaces coated with different materials.

A lithium-ion cells voltage, energy density, life, and safety can all significantly vary depending on the materials used. The usage of innovative architectures with nanotechnology is now being investigated to boost performance. Nanoscale electrode materials and different electrode structures are among the topics of interest.

Vendors and researchers are concentrating on enhancing the energy density, operating temperature, safety, durability, charging time, output power, eliminating the need for cobalt, and cost of lithium-ion battery technology as a result of the rising demand for batteries.

III. ELECTROCHEMISTRY

Anode and cathode materials, which are both composed of compounds containing lithium atoms, are the reactants in the electrochemical reactions in a lithium-ion cell. Positively charged lithium ions and negatively charged electrons are produced via an oxidation half-reaction at the anode during discharge. It's possible for the oxidation half-reaction to leave behind uncharged material at the anode. After travelling through the electrolyte and the external circuit, lithium ions and electrons recombine at the cathode (together with the cathode material) in a reduction half-reaction. While the external circuit and electrolyte both serve as conductive media for lithium ions and electrons, respectively, they are not involved in the electrochemical reaction. Electrons go via the external circuit during discharge from the negative electrode (anode) to the positive electrode (cathode). Because the chemical potential of the cell is lowered during discharge, energy is transferred from the cell to wherever the electric current loses energy, which is usually in the external circuit. Electrons pass via the external circuit from the positive electrode to the negative electrode during charging, reversing these reactions and transportation. The external circuit must supply electrical energy in order to charge the cell. The cell uses this energy to store it as chemical energy (with some loss, e. g. due to coulombic efficiency lower than 1).

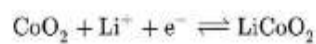
Lithium ions can enter and exit each electrode's structure through a process known as insertion (intercalation) or extraction (deintercalation), respectively.



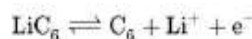
These batteries are also called “rocking-chair batteries” or “swing batteries” because the lithium ions “swing” back and forth between the two electrodes (a term given by some European industries). smaller than 1).

The chemistry is demonstrated by the following equations.

In the lithium-doped cobalt oxide substrate, the positive electrode (cathode) half-reaction is



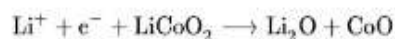
The graphite's negative electrode (anode) half-reaction is



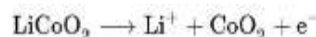
The complete reaction (right to left: charging, left to right: discharging)



The total response has its bounds. Lithium oxide is produced as a result of over discharging supersaturating lithium cobalt oxide, which may happen as a result of the following irreversible reaction:



X-ray diffraction shows that overcharging to 5.2 volts causes the production of cobalt (IV) oxide:



In a lithium-ion cell, the transition metal cobalt (Co) in $\text{Li}_{1-x}\text{CoO}_2$ is oxidized from Co^{3+} to Co^{4+} during charge and reduced from Co^{4+} to Co^{3+} during discharge to transport lithium ions to and from the positive or negative electrodes. The permitted depth of discharge is constrained by the fact that the cobalt electrode reaction is only reversible for $x < 0.5$ (x in mole units). Sony created the Li-ion cells in 1990

using this chemistry.

The voltage multiplied by the charge equals the energy of the cell. Lithium has a density of 13,901 coulombs per gramme, or Faraday's constant/6.941. This results in 41.7 kJ or 11.6 kWh per kilograms of lithium at 3 V. The extra elements that go into a lithium battery, which make lithium batteries several times heavier per unit of energy, are not taken into account, therefore this is a little bit higher than the heat of combustion of gasoline.

Aqueous solutions will electrolyze at potentials higher than the cell voltages listed in the Electrochemistry section.

Lithium salts like LiPF₆, LiBF₄, or LiClO₄ are dissolved in organic solvents like ethylene carbonate, dimethyl carbonate, and diethyl carbonate to form the liquid electrolytes of lithium-ion batteries. Cations that are moving from the negative to the positive electrodes during discharge use a liquid electrolyte as a conductor. At 20 °C (68 °F), liquid electrolyte conductivities are typically in the range of 10 mS/cm, increasing by roughly 30–40% at 40 °C (104 °F), and slightly decreasing at 0 °C (32 °F). High conductivity and the ability to produce solid electrolyte interphase (SEI) are provided by the combination of linear and cyclic carbonates, such as ethylene carbonate (EC) and dimethyl carbonate (DMC).

During charge, organic liquids conveniently disintegrate on the negative electrodes. When the proper organic solvents are employed as the electrolyte, the solvent decomposes at initial charging and forms a solid layer known as the solid electrolyte interphase, which is electrically insulating yet offers high ionic conductivity. When the electrolyte receives a second charge, the interphase stops it from further decomposing. Ethylene carbonate, for instance, creates a dense and stable interface when it decomposes at a relatively high voltage of 0.7 V vs. lithium. An interface that is reasonably stable is offered by composite electrolytes based on POE (poly (oxyethylene)). It can be applied as a liquid (low molecular weight) in standard Li-ion cells or as a solid (high molecular weight) in dry Li-polymer cells. A different strategy for reducing the flammability and volatility of organic electrolytes is to use room-temperature ionic liquids (RTILs).

The electrolyte substance in batteries nowadays is a solid thanks to recent advancements in battery technology. Ceramics are the most promising of these. Lithium metal oxides make up the majority of solid ceramic electrolytes, and because they naturally contain lithium, they facilitate easier lithium-ion transfer through the

solid. The key advantage of solid electrolytes is the lack of leakage danger, which is a significant safety concern for batteries using liquid electrolytes. Ceramic and glassy electrolytes are the two primary divisions of solid ceramic electrolytes. Ceramic solid electrolytes feature crystal structures that are highly organised and typically have ion transport channels. Lithium super ion conductors (LISICON) and perovskites are typical ceramic electrolytes. Similar to ceramic solid electrolytes in composition, glassy solid electrolytes are amorphous atomic structures, but they have higher conductivities generally because of higher conductivities at grain boundaries. Sulfur can be used in place of oxygen to increase the ionic conductivity of both glassy and ceramic electrolytes. Increased polarisation potential and a greater radius of sulphur allow for higher conductivity of lithium. As a result, solid electrolytes conductivities are getting close to matching those of their liquid counterparts, with the best ones having conductivities of 10 mS/cm. Adding a third substance, called as an additive, in modest quantities is an effective and affordable technique to adjust the properties of particular electrolytes. The bulk properties of the electrolyte system won't be impacted while the targeted property can be greatly enhanced by sparingly adding the addition.

These three main categories can be used to categorise the numerous additives that have been tested:

- (1) those used to modify SEI chemistry;
- (2) those used to improve ion conduction characteristics;
- (3) those used to increase cell safety (e.g. prevent overcharging).

IV. CHARGING AND DISCHARGING

Lithium ions (Li⁺), through the non-aqueous electrolyte and separator diaphragm, transport the current in the battery cell during discharge from the negative to the positive electrode.

When a battery is being charged, an external power source (the charging circuit) applies an over-voltage (a higher voltage than the battery produces, with the same polarity), which forces a charging current to flow within each cell from the positive to the negative electrode, or in the opposite direction from how a discharge current would normally flow. The lithium ions then move from the positive to the negative electrode, where they undergo a process called intercalation in which they embed themselves in the porous

electrode material.

Under typical operating circumstances, energy losses due to electrical contact resistance at interfaces between electrode layers and at contacts with current collectors can reach up to 20% of the total energy flow of batteries.

Single Li-ion cells and whole Li-ion batteries require slightly different.

- An individual Li-ion cell is charged twice:
 1. Constant current (CC)
 2. Constant voltage (CV)
- Three phases of charging are used for Li-ion batteries (a series of Li-ion cells):
 1. Constant current
 2. Balance (only required when cell groups become unbalanced during use)
 3. Constant voltage

Until the top-of-charge voltage limit per cell is achieved, the charger maintains a constant current to the battery while gradually increasing the voltage.

A balancing circuit equalises the state of charge of each cell during the balance phase, which lasts until the battery is balanced. During this phase, the charger/battery lowers the charging current (or cycles the charging on and off to lower the average current). As it is usually erroneous to do so during other phases of the charge cycle, balancing normally happens whenever one or more cells reach their top- of-charge voltage before the other(s). Passive balancing, which temporarily connects resistors across the cell or cells to be balanced, is the most popular method for accomplishing this. Active balancing, which distributes extra energy to other cells (or the full pack) via a DC-DC converter or other circuitry, is less frequent, more expensive, but more effective. This step is skipped by some rapid chargers. Some chargers achieve balance by independently charging each battery. The charger, which normally simply supplies the bulk charge current and does not interact with the pack at the cell- group level, frequently performs this. Examples of such devices are e-bike and hoverboard chargers. In this approach, the BPC/BMS will make a request for a lower charge current (such as for EV batteries) or will turn off the charging input (common in portable gadgets) while balancing is taking place. When charging at constant voltage and cycling back and forth between charge modes, balancing most frequently takes place. The pack is often only fully charged once balancing is finished because even one cell group that is less charged than the

others will reduce the total battery's useful capacity to that of the group in question. Depending on the severity of the imbalance in the battery, balancing may take hours or even days.

As the current gradually decreases towards 0, the charger applies a voltage to the battery during the constant voltage phase that is equal to the maximum cell voltage times the number of cells in series. This continues until the current falls below a predetermined threshold of about 3% of the initial constant charge current. approximately once per 500 hours, periodic topping charge. When the voltage drops below 4.05 V/cell, it is advised to start top charging.

Li-ion batteries have stricter working and charging temperature restrictions. High temperatures are where lithium-ion chemistry shines, but extended heat exposure shortens battery life. In the temperature range of 5 to 45 °C (41 to 113 °F), Li-ion batteries have good charging performance and may even permit "fast-charging" Needs a better source This temperature range is appropriate for charging. Charging is allowed between 0 and 5 °C, but the charge current should be decreased. The little temperature increase over ambient that occurs during a low-temperature charge as a result of the internal cell resistance is advantageous. At lower temperatures, the internal resistance of the battery may increase, resulting in slower charging and longer charging times. High temperatures during charging may cause battery degradation, and charging at temperatures above 45 °C will decrease battery performance. Lithium-ion batteries made for consumer use shouldn't be charged at temperatures lower than 0 °C (32 °F). Despite the fact that a battery pack could seem to be charging normally, metallic lithium electroplating might happen at the negative electrode during a subfreezing charge and may not be removable even with frequent cycles. Except for mobile phones, which may permit some degree of charging when they detect an emergency call in progress, the majority of devices outfitted with Li-ion batteries do not allow charging outside of 0-45 °C for safety concerns. Batteries slowly self-discharge even when they are not linked to a source of current. Manufacturers commonly estimate the self-discharge rate of lithium-ion rechargeable batteries to be 1.5 to 2% each month.

Temperature and charge status both affect the rate. According to a 2004 study, self-discharge was mainly time-dependent under normal cycle situations, but after several months of standing on an open circuit or floating charge, state-of-charge dependent losses started to become considerable. At intermediate stages of charge, the self-discharge

rate actually decreased rather than monotonically rising with state of charge.

As batteries get older, self-discharge rates could rise. Self-discharge was measured in 1999 at 8% at 21 °C, 15% at 40 °C, and 31% at 60 °C each month. The anticipated monthly self-discharge rate as of 2016 was 2[7]-3%, up from an estimate of 2% to 3% in 2007. Comparatively, as of 2017, the self-discharge rate for NiMH batteries decreased from up to 30% per month for formerly common cells to approximately 0.08–0.33% per month for low self-discharge.

V. CATHODE

LiCoO₂ or LiMn₂O₄ are typically used to make cathode materials. A pseudo-tetrahedral structure that supports two-dimensional lithium-ion diffusion emerges in the cobalt-based material. Due to their high theoretical specific heat capacity, high volumetric capacity, low self-discharge, high discharge voltage, and good cycle performance, cobalt-based cathodes are the best choice. The material's high price and poor thermal stability are limitations. The cubic crystal lattice system used by the manganese-based materials enables three-dimensional lithium-ion diffusion. Because manganese is less expensive than other metals, manganese cathodes are appealing. If its drawbacks could be resolved, they might be used to create a battery that is more effective and lasts longer. Some restrictions include the cathode's poor cycling stability caused by manganese's propensity to dissolve into the electrolyte during cycling. Although cobalt-based cathodes are the most popular, additional materials are being investigated in an effort to reduce prices and prolong cell life.

As of 2017, LiFePO₄ is a candidate for large-scale manufacture of lithium-ion batteries for use in electric car applications because of its low cost, great safety, and high cycle durability. For instance, after 8000 cycles of 100% drain, Sony Fortelion batteries still had 74% of their original capacity. To compensate for its poor electrical conductivity, a carbon conductive agent is needed.

It is important to note that conventional NCM layered cathode materials can be cycled to voltages/charges greater than those corresponding to Li:M=1 to form so-called "lithium-rich" cathodes. A novel semi-reversible redox transition with around 0.4–0.8 electrons/metal site charge and a greater voltage emerges under such circumstances. Non-binding electron orbitals mostly focused on O atoms are involved in this transition. Although there was a lot of initial attention, this phenomenon did not lead to commercially viable goods since such "lithium-

rich" phases quickly structurally degraded (O₂ evolution and lattice rearrangements).

VI. ANODE

Graphite and other carbon compounds are often utilized to make negative electrode materials, however newer silicon-based materials are increasingly being used (see Nanowire battery). 89% of lithium-ion batteries in 2016 contained graphite (43% synthetic and 46% natural), 7% amorphous carbon (either soft carbon or hard carbon), 2% lithium titanate (LTO), and 2% materials made of silicon or tin. These substances are utilised due to their availability, electrical conductivity, and ability to intercalate lithium ions to retain electrical charge with only a 10% volume expansion. Due to its superior performance and low intercalation voltage, graphite is the predominant material. It has been suggested that there are a number of other materials with higher capacities, however they typically have higher voltages, which reduces low energy density. Anodes must operate at low voltage in order to maximise energy density; otherwise, the excess capacity is useless.

Since graphite can only store a maximum of 372 mAh/g of energy, significant research has gone into creating materials with larger theoretical capacities and overcoming the technical obstacles that currently prevent their use. An detailed review of earlier studies on silicon-based anodes for lithium-ion secondary cells may be found in the 2007 Review Article by Kasavajjula et al. In example, Hong Li et al. demonstrated in 2000 that an amorphous Li-Si alloy is created when lithium ions are electrochemically inserted into silicon nanoparticles and silicon nanowires. The cycling of electrochemical cells with anodes made of silicon nanowires, with a reversible capacity ranging from at least roughly 900 to 1500 mAh/g, was described by Bo Gao and Professor Otto Zhou the same year. Several methods of adding a protective layer have been proposed in order to increase the stability of the lithium anode. Since silicon can hold up to 10 times the amount of lithium ions, it is starting to be considered as an anode material. However, the alloying of silicon with lithium results in a substantial volume expansion (about 400%), which leads to catastrophic failure of the cell. The insertion and extraction of Li⁺ can cause fissures in silicon, which has been employed as an anode material. Due to the electrolyte exposure brought on by these fissures, the Si surface decomposes and a solid electrolyte interphase (SEI) forms on the newly formed Si surface (crumpled graphene encapsulated Si nanoparticles). The anode's capacity and cycling stability will decline as this

SEI continues to thicken, consume the available Li^+ , and deteriorate.

POSITIVE ELECTRODE

Technology	Company	Target application	Benefit
Lithium Nickel Manganese Cobalt Oxide NMC, $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$	Imara Corporation, Nissan Motor, Microvast Inc., LG Chem, Northvolt	Electric vehicles, power tools, grid energy storage	good specific energy and specific power density
Lithium Nickel Cobalt Aluminium Oxide NCA, LiNiCoAlO_2	Panasonic, Saft Groupe S.A. Samsung	Electric vehicles	High specific energy, good life span
Lithium Manganese Oxide LMO, LiMn_2O_4	LG Chem, NEC, Samsung, Hitachi, Nissan/AESC, EnerDel	Hybrid electric vehicle, cell phone, laptop	
Lithium Iron Phosphate LFP, LiFePO_4	University of Texas/Hydro-Québec, Phostech Lithium Inc., Valence Technology, A123Systems/MIT	Segway Personal Transporter, power tools, aviation products, automotive hybrid systems, PHEV conversions	moderate density (2 A·h outputs 70 amperes) High safety compared to Cobalt / Manganese systems. Operating temperature $>60^\circ\text{C}$ (140°F)
Lithium Cobalt Oxide LCO, LiCoO_2	Sony first commercial production	broad use, laptop	High specific energy

NEGATIVE ELECTRODE

Technology	Density	Company	Target application
Graphite	Weight: 260 Wh/kg	Tesla	The dominant negative electrode material used in lithium ion batteries, limited to a capacity of 372 mAh/g.
Lithium Titanate LTO, $\text{Li}_4\text{Ti}_5\text{O}_{12}$		Toshiba, Altairnano	Automotive (Phoenix Motorcars), electrical grid (PJM Interconnection Regional Transmission Organization control area, United States Department of Defense), bus (Proterra)
Hard Carbon		Energ2	Home electronics
Tin/Cobalt Alloy		Sony	Consumer electronics (Sony Nexelion battery)
Silicon/Carbon	Volumetric: 730 Wh/L Weight: 450 Wh/kg	Amprius	Smartphones, providing 5000 mAh capacity

VII. ELECTROLYTE

Alternatives to electrolytes, such as the lithium polymer battery, have also been crucial. Polymer electrolytes show promise in reducing lithium dendrite development.

The purpose of polymers is to maintain conductivity and prevent short circuits. Because of slight variations in the electrolyte concentration, the ions in the electrolyte

disperse. Here, only linear diffusion is taken into account. As a function of time t and distance x , the concentration change, c , is

$$\frac{\partial c}{\partial t} = \frac{D}{\varepsilon} \frac{\partial^2 c}{\partial x^2}$$

D stands for the lithium ion's diffusion coefficient in this equation. Its value in the LiPF₆ electrolyte is 7.5 10⁻¹⁰ m²/s. The porosity of the electrolyte has a value of 0.724.

VIII. FORMATS

5.1 Cells

As opposed to whole batteries, Li-ion cells come in a variety of geometries that can be broadly categorized into four groups:

- Small cylindrical (solid body, no terminals) batteries are commonly used in older laptop batteries, most e- bike batteries, and most electric car batteries. There are numerous typical lithium-ion cylinder sizes.
- large cylindrical (solid body with large threaded terminals)
- Flat or pouch-shaped batteries with a soft, flat body are commonly seen in contemporary laptops and cell phones; these are lithium-ion polymer batteries.
- plastic case that is rigid and has big threaded terminals (such as electric vehicle traction packs)

The typical "swiss roll" method (also known as a "jelly roll" in the US) is used to create cylindrical cells. This method involves rolling together a single long "sandwich" made up of the positive electrode, separator, negative electrode, and separator. An Archimedean spiral can represent the jelly roll in cylindrical cells as a rough shape. The faster manufacturing rate of cylindrical cells over cells with stacked electrodes is one benefit. A significant radial temperature differential that forms inside cylindrical cells at high discharge currents can be one drawback.

Although pouch cells have the highest gravimetric energy density due to the lack of a case, for many practical applications they still need an external containment system to prevent expansion when their state of charge (SOC) level is high and to ensure the structural stability of the battery pack they are a part of. As a result of their rectangular geometries, rigid plastic and pouch-style cells are also occasionally referred to as prismatic cells. Modern (by 2020) electric vehicle batteries will primarily use three types of Li-ion batteries: cylindrical cells (like those made by Tesla), prismatic pouch (like those made by LG), and prismatic can cells. According to battery technology analyst Mark Ellis of Munro & Associates, these battery types will be used at scale (e.g., from LG, Samsung, Panasonic, and others). The advantages and drawbacks of each form factor for EV use are distinctive.

Since 2011, a number of research teams

have announced the development of lithium-ion flow batteries in which the cathode or anode materials are suspended in an organic or aqueous solution.

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5.2 Batteries



A battery is made up of numerous connected lithium-ion cells, often known as a battery pack. Temperature sensors, voltage regulator circuits, voltage taps, and charge-state monitors are also found in battery packs for big consumer electronics like laptop computers. Overheating and short circuiting dangers are reduced by these components. It is more effective and efficient to link multiple tiny batteries in a parallel circuit to power larger equipment, such as electric cars, than it is to connect a single huge battery.

IX. USES

Commercial Li-ion batteries are mostly employed in electric vehicles and consumer devices. Such gadgets consist of:

- Mobile phones and smartphones, computers and tablets, digital cameras and camcorders, electronic cigarettes, handheld game consoles, and torches are examples of portable gadgets (flashlights).
- Power tools: Li-ion batteries are used in a range of garden tools, including whipper-snippers and hedge trimmers, as well as cordless drills, sanders, and saws.
- Electric vehicles: Advanced electric wheelchairs, electric motorbikes and scooters, electric bicycles, personal transports, and hybrid vehicles all employ electric vehicle batteries. Aside from that, there are radio-controlled toys, model planes, aircraft, and the Mars Curiosity rover.

Backup power in telecommunications applications is one of the more specialised uses. Although they are not yet

cost-competitive at scale, lithium-ion batteries are also frequently mentioned as a potential solution

for grid energy storage.

X. PERFORMANCE

The energy density and voltage of lithium-ion batteries vary because different positive and negative electrode materials are possible.

When compared to aqueous batteries, the open-circuit voltage is higher (such as lead–acid, nickel– metal hydride and nickel-cadmium). Although this is significantly influenced by the voltage and temperature the batteries are maintained at, internal resistance increases with both cycling and age. The voltage at the terminals decreases under load as a result of rising internal resistance, which limits the maximum current draw. The battery will eventually reach a point where it can no longer withstand the typical discharge currents that are required of it without causing an undesirable voltage drop or overheating. This happens as the resistance of the battery increases.

The nominal open-circuit voltage and typical charging voltage of batteries with lithium iron phosphate positive and graphite negative electrodes are 3.2 V and 3.6 V, respectively. The nominal voltage of lithium nickel manganese cobalt (NMC) oxide positives with graphite negatives is 3.7 V, and the maximum charging voltage is 4.2 V. Current-limiting circuitry is used during the charging process, which is carried out at constant voltage (i.e., charging with constant current until a voltage of 4.2 V is reached in the cell and continuing with a constant voltage applied until the current drops close to zero). At 3% of the initial charge current, the charge usually comes to an end. It used to take at least two hours to fully charge lithium-ion batteries because they couldn't be fast-charged. In 45 minutes or less, current generation cells can be fully charged. A small 600 mAh battery charged to 68 percent of its capacity in two minutes, and a larger 3,000 mAh battery charged to 48 percent of its capacity in five minutes, according to study done in 2015. An energy density of 620 Wh/L is present in the latter battery. Heteroatoms were used in the anode of the device, bound to molecules of graphite.

Over time, the performance of manufacturing batteries has increased. For instance, between 1991 and 2005, the energy density per dollar of lithium-ion batteries increased more than tenfold, from 0.3 Wh to over 3 Wh. The average yearly rate of progress from 2011 to 2017 was 7.5%. Overall, the cost of lithium ion batteries (measured in dollars per kWh) decreased by about 97% between 1991 and 2018. Energy density increased by more than three times in the same

time frame. Cost-cutting measures included large increases in energy density.

Different energy densities can also exist in cells of various sizes and chemistries. Compared to the 18650 cell, the 21700 cell has 50% more energy, and because of its larger size, less heat is transferred to its surroundings.

XI. LIFESPAN

The number of complete charge-discharge cycles necessary to attain a capacity loss or impedance rise failure threshold is generally used to determine the life of a lithium-ion battery. The phrase “cycle life” is frequently used in manufacturer datasheets to describe longevity in terms of the quantity of cycles required to attain 80% of the rated battery capacity. Lithium-ion batteries capacity (the amount of cyclable Li⁺) and cell resistance (mainly because of the continual expansion of the solid electrolyte interface on the anode) are both decreased by simply storing them in the charged state. The term “calendar life” refers to the entire battery life cycle, including both active and passive storage operations. Temperature, discharge current, charge current, state of charge ranges, among other stress factors, have an impact on battery cycle life (depth of discharge). Therefore, quantifying battery life by complete discharge cycles might be deceptive because batteries are not fully charged and discharged in practical applications like smartphones, laptops, and electric vehicles. Researchers occasionally utilize cumulative discharge, which is the total charge (in Ah) given by the battery over the course of its lifetime or equivalent full cycles, which reflects the accumulation of partial cycles as fractions of a full charge – discharge cycle, to avoid this error. Temperature and battery state of charge (SOC) both affect how well batteries hold a charge during storage, and a full charge (100% SOC) combined with a high temperature (often > 50 °C) can cause a significant capacity decline and gas generation. The total energy delivered over the battery's lifespan can be calculated by multiplying the battery's cumulative discharge by the rated nominal Voltage. From this, one can compute the cost of energy per kWh (including the cost of charging).

Batteries gradually degrade throughout the course of their lives, resulting in reduced capacity (and, in some circumstances, lower operating cell voltage), as a result of several chemical and mechanical changes to the electrodes.

In lithium-ion batteries, a number of degradation processes take place, some during cycling, some during storage, and some constantly:

The rate of degradation increases when batteries are used or stored in hot or cold conditions, although it is modest at room temperature. Capacity loss is also accelerated by high charge levels. Among the most well-known mechanisms are:

- (1) The loss of lithium inventory due to the reduction of the organic carbonate electrolyte at the anode, which causes the expansion of the Solid Electrolyte Interface (SEI), where Li^+ ions become irreversibly imprisoned. This manifests as a rise in ohmic impedance and a fall in Ah charge. The SEI layer thickness at constant temperature increases as a square root of the time in the charged state does the SEI resistance and the loss in cyclable Li^+ . A suitable statistic for describing this key deterioration process is not the number of cycles. The electrolyte reduction process can proceed explosively in high temperatures or when there is mechanical damage.
- (2) Lithium metal plating also causes internal short-circuiting, fire, and a loss of lithium inventory (cyclable Ah charge). Li plating causes greater slopes of capacity loss every cycle and resistance rise per cycle once it starts during cycling.
- (3) Loss of the (negative or positive) electroactive substances as a result of dissolution (for example, $\text{Mn}(3+)$ species), cracking, exfoliation, detachment, or even a regular volume change during cycle. Both charge and power decline are symptoms of it (increased resistance). The volumetric strain of repeated (de)lithiation cycles can fracture both positive and negative electrode materials.
- (4) Cathode material structural deterioration, including $\text{Li}^+/\text{Ni}^{2+}$ cation mixing in nickel-rich materials This shows up as “voltage fading,” “electrode saturation,” and loss of cyclable Ah charge.
- (5) Additional material deterioration. At low cell voltages, the negative copper current collector is particularly susceptible to corrosion and/or disintegration. The electroactive elements separate from the PVDF binder, which results in the loss of cyclable Ah charge.

The figure displays these. The capacity vs. cycle number figure shows a knee (slope change) as one principal degradation mechanism changes to another.



Below is a more thorough explanation of a few of these mechanisms: 1] Li^+ ion conduction is only possible with the help of the negative (anode) SEI layer, which is a passivation coating created by electrolyte (such as ethylenecarbonate) reduction products (and, thus, further solvent reduction). After the first few charges (formation cycles), the negative SEI layer achieves a constant thickness under normal operating circumstances, allowing the device to function for years. However, this exothermic electrolyte reduction might proceed vehemently and result in an explosion via a number of reactions at high temperatures or due to mechanical separation of the negative SEI. Over hundreds to thousands of cycles, the capacity of lithium-ion batteries is susceptible to deterioration. Lithium ions are used up during the SEI's formation, which lowers the electrode material's total charge and discharge efficiency. In order to encourage the production of a more stable SEI that continues to be selective for lithium ions to flow through while blocking electrons, a variety of SEI-forming chemicals can be introduced to the electrolyte as a breakdown product. Due in part to the deterioration of the SEI or lithium plating, cycling cells at high temperatures or rapid rates can accelerate the deterioration of Li-ion batteries. Li-ion battery degradation can be significantly accelerated when they are charged past 80%.

Common elements of the SEI layer that forms on the anode include a combination of lithium oxide, lithium fluoride, and semicarbonates, depending on the electrolyte and additives (e.g., lithium alkyl carbonates).

Alkyl carbonates in the electrolyte breakdown at high temperatures into insoluble species like Li_2CO_3 , which thickens the layer. This lowers cycle capacity and raises cell impedance. In demanding situations like mobile devices, gases created by electrolyte dissolution can raise the cell's internal pressure and pose a possible safety risk. Under 25°C , cyclable lithium is being lost due to the plating of metallic lithium on the anodes and subsequent interaction with the electrolyte. A gradual increase in film thickness and capacity loss

may result from prolonged storage. [162] Li⁺ plating on the anode, which results in irreversible capacity loss, can be started by charging at a voltage higher than 4.2 V.

Hydrolysis and thermal decomposition are two processes that electrolyte deterioration. Water starts catalysing a variety of breakdown products at concentrations as low as 10 ppm, which might have an impact on the electrolyte, anode, and cathode. Together with LiF and PF₅, LiPF₆ takes part in an equilibrium reaction. Typically, the equilibrium is located far to the left. Water, however, produces a significant amount of LiF, an insoluble, electrically insulating substance. LiF adheres to the anode surface, thickening the coating. When LiPF₆ is hydrolyzed, PF₅, a potent Lewis acid, is produced. This acid reacts with electron-rich species like water. Phosphorus oxyfluoride and hydrofluoric acid (HF) are produced when PF₅ interacts with water. In turn, phosphorus oxyfluoride interacts to produce difluorohydroxy phosphoric acid and more HF. The SEI film becomes more brittle when exposed to HF. The carbonate solvent on the cathode can then gradually seep onto the cathode oxide, generating heat and perhaps leading to thermal runaway. As low as 70 °C is the minimum temperature at which electrolyte salt decomposition and solvent interactions begin. At higher temperatures, there is noticeable breakdown. At 85 °C, the reaction of EC with DMC results in the formation of transesterification products like dimethyl-2, 5-dioxahexane carboxylate (DMDOHC).

When a battery is charged or drained, particularly at high currents, heat is produced. Large battery packs, such those seen in electric cars, are frequently fitted with thermal management systems that keep their internal temperatures within the range of 15 °C (59 °F) and 35 °C (95 °F). Temperatures in cylindrical and pouch cells vary linearly with discharge current. Temperatures may rise as a result of poor internal ventilation. Non-uniform temperatures can cause non-uniform and rapid breakdown in large batteries with numerous cells. In contrast, high charge states have no impact on the calendar life of LiFePO₄ cells.

Much less is known about the positive SEI layer in lithium-ion batteries than the negative SEI. It is thought to have a low ionic conductivity and manifests during cycling and calendar ageing as a rise in the cathode's interfacial resistance.

2] The production of dendrites is caused by the metallic lithium's unpredictability during intercalation in the anode. Dendrites can build up over time and puncture the separator, creating a short circuit that can result in heat, fire, or

explosion. Thermal runaway is the term used to describe this process. The biggest issue while charging Li-ion batteries in freezing temperatures is lithium plating.

3] The Hunter degradation mechanism can cause manganese dissolution and reduction on the anode in certain manganese-containing cathodes. By disproportionating a surface trivalent manganese to create a tetravalent manganese and a soluble divalent manganese, hydrofluoric acid catalyses the loss of manganese in LiMn₂O₄ according to the Hunter mechanism:



Capacity fade is caused by spinel material loss. Mn²⁺ begins to deposit on the anode as metallic manganese at temperatures as low as 50 °C, with the same consequences as lithium and copper plating. The crystal lattice is destroyed by cycling across the predicted maximum and minimum voltage plateaus due to Jahn-Teller distortion, which happens when Mn⁴⁺ is converted to Mn³⁺ during discharge. When a battery is stored with a charge higher than 3.6 V, electrolyte oxidation by the cathode begins, which causes the cathode to produce an SEI layer. Like the anode, capacity fade and uneven current distribution are caused by excessive SEI production, which creates an insulator. LiCoO₂ and LiMn₂O₄ cathodes slowly deteriorate at storage voltages below 2 V, releasing oxygen in the process, and their capacity is irreversibly lost.

4] The primary cause of the declining capacity of the Ni-rich cathode materials is cation mixing. Increasing the Ni content causes a significant amount of mixing of the Ni²⁺ and Li⁺ cations due to their close proximity in the ionic radius (Li⁺ = 0.076 nm and Ni²⁺ = 0.069 nm), which is the result of the two-electron Ni²⁺/Ni⁴⁺ redox reaction, which increases the capacity as the Ni content in the NCM layered material rises. Li⁺ in the cathode is difficult to extract during charge/discharge cycling, and the presence of Ni²⁺ in the Li layer prevents Li⁺ from diffusing, leading to capacity loss and an increase in ohmic resistance.

5] The copper anode current collector may dissolve as a result of discharge below 2 V, which could cause a catastrophic internal short-circuit upon recharge.

When lithium-ion batteries in an electric car lose 80% of their nominal charge capacity, it is advised to replace them, according to IEEE standard 1188-1996. The 20% capacity loss will be used as a benchmark for comparison in the sections

that follow. We should still point out that the linear model of degradation—which assumes a constant percentage of charge loss per cycle or per period of time—is not always applicable and that a “knee point”—a change in the slope indicative of a shift in the primary mechanism of degradation—is frequently noticed.

In order to complete the experiments more quickly, the majority of investigations on lithium-ion battery ageing have been conducted at high temperatures (50–60 °C). Fully charged nickel-cobalt-aluminum and lithium-iron phosphate cells lose about 20% of their cyclable charge after being stored under these circumstances for a period of one to two years. The most significant deterioration mechanisms in these circumstances are thought to be the aforementioned anode ageing processes. The extra mechanism of Mn ion dissolution, however, may explain why manganese-based cathodes degrade (by around 20 to 50 percent) more quickly under these circumstances. Lithium-ion battery degradation appears to follow the same pathway(s) at 25 °C as it does at 50 °C, although at a slower rate. In other words, it is anticipated that lithium-ion batteries will irreversibly lose 20% of their cyclable charge in 3-5 years, or 1000–2000 cycles at 25 °C, based on the limited extrapolated experimental evidence. Titanate anodes in lithium-ion batteries prevent SEI formation and have a longer lifespan (> 5000 cycles) than graphite anodes. Although the inclusion of a titanate anode theoretically increases entire cell lifetime, in actual use other degradation mechanisms (such as the dissolution of Mn³⁺ and the Ni³⁺/Li⁺ place exchange, the disintegration of PVDF binder, and particle separation) appear in complete cells after 1000–2000 days.

XII. SAFETY

5.3 Fire hazard

Since they contain a flammable electrolyte and may pressurize if they sustain damage, lithium-ion batteries can be a safety risk. An explosion or fire could result from a short circuit in a battery cell that was charged too quickly. A Li-ion battery fire can be caused by one of four different types of abuse: thermal abuse, such as inadequate cooling or an external fire; electrical abuse, such as overcharging or an external short circuit; mechanical abuse, such as penetration or crash; or internal short circuit, such as one brought on by ageing or manufacturing flaws. Due to these dangers, testing requirements are stricter than for acid-electrolyte batteries, requiring a wider range of testing conditions as well as additional battery-specific tests. Additionally, safety regulators have

placed shipping restrictions. Some firms have issued battery-related recalls, such as the 2016 Samsung Galaxy Note 7.

A flammable liquid electrolyte is present in lithium-ion batteries. A major fire can be started by a bad battery. The battery’s protection circuit can be destroyed by faulty charges, which can compromise the battery’s safety. The safety of the entire pack may be jeopardised because when charging occurs below 0 °C, pure lithium is deposited on the negative electrode of the batteries. Lithium while charging at temperatures below 0 °C, which jeopardises the safety of the entire pack.

A battery cell that has been short-circuited will likely overheat and possibly catch fire. Li-ion battery thermal runaway produces poisonous and combustible smoke. Cobalt-oxide batteries contain between 100 and 150 kJ/(Ah) of fire energy, the majority of which is chemical. In order to power some aircraft’s systems, large lithium-ion batteries were substituted for other chemistries around 2010. As of January 2014, there had been at least four significant lithium-ion battery fires or smokes on the 2011-introduced Boeing 787 passenger aircraft, which did not result in crashes but had the potential to. UPS Airlines Flight 6 lost control and crashed near Dubai after its battery payload caught fire. Research initiatives aim to create non-flammable electrolytes to lessen fire risks.

5.4 Damaging and overloading

A lithium-ion battery may experience issues if it is crushed, damaged, or exposed to a higher electrical load without any overcharge protection. A battery explosion may result from an external short circuit.

Li-ion batteries are susceptible to thermal runaway and cell rupture if overheated or overcharged. In dire circumstances, this could result in a leak, an explosion, or a fire. Many lithium-ion cells (and battery packs) have fail-safe circuitry that disconnects the battery when the voltage exceeds the safe range of 3- 4.2 V per cell, or when the battery is overcharged or drained, in order to lessen these dangers. Without efficient battery management circuits, lithium battery packs made by a vendor or an end user are prone to these problems. It is difficult to know for sure whether any specific battery management circuitry is effectively implemented. Poorly designed or implemented battery management circuits may potentially cause issues.

5.5 Voltage limits

Voltage ranges outside of the safe range between 2.5 and 3.65/4.1/4.2 or 4.35V can damage

lithium-ion batteries (depending on the components of the cell). Due to the reactive components in the cells, exceeding this voltage range causes premature ageing and safety issues. Long-term storage may cause the protective circuitry's tiny current demand to drain the battery below its shutdown voltage, rendering regular chargers ineffective since the battery management system (BMS) may keep track of this charger or battery "failure." Many different kinds of lithium-ion cells cannot be properly charged below 0 °C due to the risk of lithium plating on the cell's anode, which could lead to issues including internal short-circuit routes.

Additional security measures are mandated[by whom?] in each cell, including:

- Separator for shutdowns (for overheating) • rip-off tab (for internal pressure relief)
- Vent (pressure relief in case of significant outgassing) (pressure relief in case of severe outgassing)
- Thermal interruption (overcurrent, overcharging, exposure to the environment)

These characteristics are necessary because, while the positive electrode may not produce oxygen during usage, the negative electrode generates heat. However, when activated, these extra devices take up room inside the cells, increase the risk of failure, and might permanently disable the cell. Furthermore, compared to nickel metal hydride batteries, which merely need a hydrogen/oxygen recombination device and a backup pressure valve, these characteristics raise expenses. These safety measures can be defeated by contaminants inside the cells. Additionally, not all types of cells can have these characteristics installed on them; for example, prismatic high current cells cannot have a vent or a thermal interrupt. High current cells must not generate an excessive amount of heat or oxygen in order to avoid a failure that could be violent. Instead, inbuilt thermal fuses that activate before the anode and cathode reach their thermal limits must be included.

Lithium iron phosphate (LFP) replaces the lithium cobalt oxide positive electrode material in lithium-ion batteries, increasing cycle counts, shelf life, and safety but decreasing capacity. As of 2006, these safer lithium-ion batteries were mostly utilised in large-capacity battery applications such as electric vehicles and other large-capacity battery applications.

5.6 Recalls

- To spot fake batteries, Kyocera Wireless recalled

about 1 million cell phone batteries in October 2004.

- About 22,000 laptop batteries were recalled by Dell in December 2005, and 4.1 million were in August 2006.

- About 10 million Sony batteries that were used in laptops by Dell, Sony, Apple, Lenovo, Panasonic, Toshiba, Hitachi, Fujitsu, and Sharp were recalled in 2006. The batteries were discovered to be vulnerable to internal metal contamination during manufacturing. These particles have the potential to puncture the separator in specific situations, leading to a dangerous short circuit.

- Lenovo, a computer manufacturer, recalled about 205,000 potentially explosive batteries in March 2007.

- Nokia, a producer of mobile phones, recalled more than 46 million batteries in August 2007 because they posed an explosion and overheating danger. One such instance with a Nokia N91 that used a BL-5C battery happened in the Philippines.

- Following 35 confirmed fires in September 2016, Samsung recalled almost 2.5 million Galaxy Note 7 devices. The internal positive and negative poles of Samsung batteries touched during the recall because to a manufacturing design flaw.

5.7 Transport restrictions

Over a billion lithium metal and lithium-ion cells are reportedly carried annually, according to IATA. Due to the potential for fire, several types of lithium batteries may not be allowed inside the aircraft. Lithium and lithium-ion batteries, whether shipped separately or integrated into equipment, are prohibited from being shipped by air (including EMS) by some postal administrations.

XIII. ENVIRONMENTAL IMPACT

Lithium, nickel, and cobalt extraction, solvent production, and mining byproducts all pose serious environmental and health risks. Due to water pollution, lithium extraction can be harmful to aquatic life. It is well recognised to contaminate drinking water, surface water, and cause respiratory issues, ecosystem degradation, and landscape destruction. Additionally, it causes arid areas to consume water in an unsustainable manner (1.9 million litres per tonne of lithium). Massive waste production of lime and magnesium as a result of the extraction of lithium also poses unresolved issues.

South Africa, Australia, China, North and South America, Asia, and South Africa are all places where lithium is mined.

Most cobalt used in Li-ion batteries is mined in the Congo (see also Mining industry of the Democratic

Republic of the Congo)

A kilogramme of Li-ion battery requires 67 megajoule (MJ) of energy to manufacture. It is challenging to assess the global warming potential of lithium-ion battery manufacture because it is highly dependent on the energy source utilised in mining and manufacturing activities. However, a 2019 study suggested 73 kg CO₂e/kWh. Recycling properly can drastically lower the production's carbon impact.

5.8 Solid waste and recycling

Li-ion batteries are typically regarded as non-hazardous trash since they contain fewer harmful metals than other types of batteries, which may contain lead or cadmium. Iron, copper, nickel, and cobalt—all components of lithium-ion batteries—are regarded as acceptable for landfills and incinerators. These metals can be recycled, usually by destroying the other components first, although mining is still typically less expensive than recycling; in 2019, less than 5% of lithium ion batteries were recycled. Since 2018, the recycling yield has greatly increased, and industrial-scale recovery of lithium, manganese, aluminium, the organic electrolyte solvents, and graphite is now achievable. Cobalt is the most expensive metal used in the cell's construction. Although lithium is less expensive than other commonly used metals and is infrequently recycled [225], recycling could help to avoid a scarcity in the future.

The buildup of battery waste poses both technical and health risks. The creation of lithium-ion batteries has a significant negative influence on the environment, which makes it essential to find effective solutions to reuse trash. Batteries must first be stored before being disposed of. Next, they must be manually tested, disassembled, and then the chemical components of the battery must be separated. Reusing the battery is preferred over completely recycling it because it uses less energy. There are serious concerns associated with keeping spent batteries in storage since they are far more reactive than traditional vehicle waste, such as Tyre rubber.

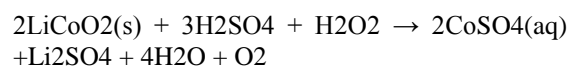
5.9 Pyrometallurgical recovery

The metal oxides in the batteries are broken down using the pyrometallurgical process into an alloy of Co, Cu, Fe, and Ni in a high-temperature furnace. This is the most typical and widely used technique for recycling, and it can be used in conjunction with other batteries of a similar design to boost smelting effectiveness and enhance thermodynamics. The metal current collectors facilitate the smelting procedure and enable the

simultaneous melting of entire cells or modules. The end result of this process is a mixture of gas, slag, and metallic alloy. The polymers that hold battery cells together burn off at high temperatures, allowing the metal alloy to be broken down into its constituent parts in a hydrometallurgical process. The slag can be further processed or utilized in the manufacture of cement. The procedure is comparatively risk-free, and the exothermic reaction caused by the combustion of the polymers lowers the amount of energy input needed. The polymers, electrolytes, and lithium salts will, however, be lost in the process.

5.10 Hydrometallurgical metals reclamation

In order to extract the necessary metals from the cathode using this technique, aqueous solutions are used. Sulfuric acid is the reagent used most frequently. The concentration of the acid, time, temperature, solid-to-liquid ratio, and reducing agent are variables that influence the leaching rate. It has been demonstrated through experimentation that H₂O₂ functions as a reducing agent to quicken the reaction's rate of leaching.



Once leached, the metals can be extracted through precipitation reactions controlled by changing the pH level of the solution. Cobalt, the most expensive metal, can then be recovered in the form of sulfate, oxalate, hydroxide, or carbonate. More recently recycling methods experiment with the direct reproduction of the cathode from the leached metals. In these procedures, concentrations of the various leached metals are premeasured to match the target cathode and then the cathodes are directly synthesized.

However, the main drawbacks of this approach are the high cost of neutralisation and the need for a sizable amount of solvent. Even if it's simple to tear up the battery, the cathode and anode must also be separated because putting them together in the beginning makes the procedure more difficult. In a closed-loop battery system, it is very challenging to separate the metals due to the complexity of the process and the existing architecture of batteries. Dissolving and shredding might take place in different places.

5.11 Direct recycling

The cathode or anode of an electrode is taken out, repaired, and then reused in a new battery. This process is known as direct recycling. With almost any modification to the crystal

morphology, mixed metal-oxides can be introduced to the new electrode. In order to replace the lithium that is being lost in the cathode owing to degradation from cycling, additional lithium is typically added during the process. The cathode strips are taken from the disassembled batteries, immersed in NMP, and then subjected to sonication to remove any extra deposits. Prior to annealing, it receives hydrothermal treatment with a LiOH/Li₂SO₄ solution.

Since the raw ingredients do not account for the majority of the cost, this technology is incredibly cost effective for batteries that are not cobalt-based. For low-cost cathodes like LiMn₂O₄ and LiFePO₄, direct recycling eliminates the time-consuming and costly purification processes. Most of the cost, embedded energy, and carbon footprint of these less expensive cathodes are related to manufacturing rather than the raw material. Experimental evidence suggests that direct recycling can replicate characteristics of pure graphite.

The method's disadvantage is the state of the retired battery. Direct recycling can affordably restore the battery's qualities in the event that it is still in reasonably good condition. However, direct recycling could not be cost-effective for batteries with low charge states. The procedure must be set up for one type of battery at a time since it must also be customized for the unique cathode composition. Finally, because battery technology is evolving quickly, a battery's design today might not be acceptable in ten years, making direct recycling inefficient.

XIV. CONCLUSION

Electrolyte interphase is electrically insulating yet offers high ionic conductivity. When the electrolyte receives a second charge, the interphase stops it from further decomposing. Different strategy for reducing flammability of organic electrolytes is to use room-temperature ionic liquids. Sulfur can be used in place of oxygen to increase the ionic conductivity of both glassy and ceramic electrolytes. Adding a third substance, called an additive, is an effective and affordable technique to adjust the properties of each particular electrolyte. LiFePO₄ is a candidate for large scale manufacture of lithium-ion batteries for use in electric car applications because of its low cost, great safety, and high cycle durability. Modern (by 2020) electric vehicle batteries will primarily use cylindrical cells, prismatic pouch, and prismatic can cells. In 45 minutes or less, current generation cells can be fully charged. Compared to the 18650 cell, the 21700 cell has 50% more energy.

Batteries gradually degrade throughout the course of their lives, resulting in reduced capacity. Lithium metal plating also causes internal short-circuiting, fire, and a loss of lithium inventory. LiCoO₂ and LiMn₂O₄ batteries slowly deteriorate at storage voltages below 2

When lithium-ion batteries in an electric car lose 80% of their nominal charge capacity, it is advised to replace them. Lithium-ion batteries contain a flammable electrolyte and may pressurize if they sustain damage. An explosion or fire could result from a short circuit in a battery cell that was charged too quickly. Testing requirements are stricter than for acid-electrolyte batteries. Many different kinds of lithium-ion cells cannot be properly charged below 0 °C due to the risk of lithium plating on the cell's anode. Lithium-ion batteries are considered non-hazardous trash since they contain fewer harmful metals (such as lead and cadmium) than other types of batteries. Recycling properly can drastically lower the production's carbon impact; less than 5% of lithium ion batteries were recycled in 2019. Direct recycling can affordably restore the battery's qualities in the event it is still in reasonably good condition.

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