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Green and Sustainable Batteries



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Synonyms

Green materials and sustainable; Long-life batteries; Recycling

Definition

To provide eco and sustainable systems, green batteries require designed and maintained, including materials, processing, efficiency, cost, and recycling. Green battery development requires the use of improved components and established recycling technologies.

Introduction

The urgent need to expand green batteries has led to in-depth insights into their concerns. Anode and cathode materials, modifications, and innovative design are essential areas for expanding green energy.

Generalized Principles for Green Devices

First, we will explore the rules that can be streamlined for green energy storage devices.

Based on the green principles, the development of the green principles is determined by three primary components, including the grid electricity source (hydro, nuclear, fossil fuels, renewables), vehicles, and battery type (e.g., lead-acid, metal-air, sodium-ion, Li-ion, Li-S, Li-CO₂). Several stages are involved in the battery life cycle, including generation, assembling, employment, and end-of-life (EOL). During the employment step, the battery is operated and charged via local utility's electricity. A battery's chemistry, for instance, affects its thermal stability and lifespan, therefore, concerning its sustainability. As batteries are utilized, their capacity diminishes, reducing efficiency and environmental performance.

Enhancing Life Cycle Battery Efficiency Using Appropriate Material Chemistry

Chemistry of battery refers to developing and selecting effective strategies enhancing operational and life cycle efficiency in mobile batteries. This subject directly influences the sustainability and also technical performances of the battery systems. For instance, the cell voltage and energy capacity of each mobile battery which define the amount of deliverable electrical energy (per mass and/or per volume) are affected by chemistry (Armand and Tarascon 2008). Moreover, the power of a battery as well as the cycle life of different battery types, which are significant parameters also depend mostly on battery chemistry like material and compositions used in electrodes and electrolyte. For example, lithium-ion batteries which are recognized by their large power/weight ratio and good energy density, and now are commercially available, use LiFePO_4 (LFP), LiMn_2O_4 (LMO), and $\text{LiNi}_x\text{Co}_y\text{Mn}_{1-x-y}\text{O}_2$ (NCM) materials as cathode and $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO) and graphite (C) materials as anode (Han et al. 2014). Interestingly, although novel advanced porous materials like metal-organic framework (MOFs) and covalent-organic frameworks (COFs) have been extensively studied for application in Li-ion batteries in the past decades, their commercialization in rechargeable batteries is still hindered by many issues, such as costly production, low stability, weak conductivity, and low tap density. Nonetheless, LMO has caught more extensive attention among others thanks to its higher energy density, lower price, and more importantly its nontoxicity and also because of the rarity of some commonly used materials like cobalt, used in NMC materials. Currently, cobalt is not attractive to manufacturers due to its high cost, relatively low performance, and some safety issues associated with that. Therefore, finding novel cobalt-free materials for use in electrodes are under more attention and will be more cost-competitive for commercialization. The above explanations clearly demonstrate the effect of the selected materials and chemicals as well as their compositions on the batteries' performances and environmental sustainability.

Reduce Burden Rate per Delivered Energy

The production burden cost associated with material production, manufacturing, and infrastructure, which is defined per energy service provided and delivered by the battery systems, should be reduced. It should be noted that material production and manufacturing steps in the battery system possess a significant environmental burden and consequently increase production burden rate in electrical vehicles. Nonetheless, Dominic A. Notter et al. believed that the emissions originating from vehicle production areas (industrial areas) are less harmful owing to a smaller population density, compared to ICEV emitting NO_x in urban areas (Notter et al. 2010).

Based on cradle-to-gate total energy analysis used in NCM batteries provided by Dai et al. (2019), and also by Ambrose and Kendall (2016), metal supply and process energy are top two most important factors affecting environmental burden (global warming potential) for Li batteries production. Copper, aluminum, steel, and gold and tin are the most used metals in the production of the anode, cathode, battery container, and battery management system, respectively. Based on these research results, active cathode material, aluminum, is responsible for around 40% of material production global warming. Furthermore, their results demonstrated that energy used for cell production is the major contributor to the energy and environmental impacts of NMC batteries. However, they pointed out a very important note that the impacts could be significantly changed upon the location of battery produced as well as the location of the source materials. Although there are no studies on production burden rate in MOF- and COF-based materials used in the battery systems, several research and review works have explored the application of these types of materials for energy storage in batteries and supercapacitors (Dai et al. 2019; Ajdari et al. 2021).

Minimizing Scarce Chemicals

The utilization of scarce and critical materials used in the production of batteries should be minimized due to limitation of existing source of these materials. Indeed, the excessive use of scarce and

critical materials such as lithium, nickel, cobalt, copper, manganese, and tantalum will change them in such a way that they would not be available for future battery generations (Greim et al. 2020). Because the system of battery is inherently material intensive, the abovementioned materials are usually utilized in large quantities and are known as critical substances. According to the US Department of Energy (DOE) assessment, two significant parameters of “supply risk” and “importance to clean energy” are considered for evaluation of the materials criticality.

To ensure successful performance of vehicle battery systems, it is crucial to consider the materials as part of the material selection process. This aspect of material selection for energy storage systems also has a direct influence on the final cost of battery systems so that the biggest part of their costs comes from materials costs. Although, on the basis of the US geological survey, there are enough worldwide reserves for lithium to produce around 33 billion EVs, vehicles equipped with today’s lithium-ion batteries, both abundant and low-cost materials, are still crucial to be investigated in energy storage devices (National Research Council 2012). It should be noted that some options like the use of organic materials to fabricate electrodes have been proposed; nonetheless, these materials show some disadvantages, like low thermal stability and intensive solubility in electrolytes, leading to limitations in their commercialization (Armand and Tarascon 2008). As a result, the utilization of scarce and critical materials should be minimized as much as possible; otherwise, depletion of materials can make strong limitations in future battery system deployment.

Maximizing Round-Trip Efficiency

Round-trip efficiency of a battery system is mostly defined as the percentage of electricity put into storage that is later delivered. So, higher the round-trip efficiency will result in less energy lost stored in the battery. This efficiency also is known as one of the key parameters affecting performances of battery systems varying from 75% to 90% and also 98% for zinc-bromine, Li-ion, and Li-air batteries, respectively (Safanama et al. 2020). It should be noted that

an increase in the round-trip efficiency will result in fewer adverse environmental effects during the operation of the EVs, which is a crucial parameter in use stage emissions. For instance, the influence of round-trip efficiency on emissions released in the use stage of a plug-in hybrid vehicle (PHEV) was evaluated by Zackrisson et al. (2010). Their results unveiled that the impact of round-trip efficiency on the environment was relatively two to six times larger than that of environmental impacts related to battery weight. Moreover, Schram et al. (2020) determined the vehicle-to-grid (V2G) round-trip efficiency of electric vehicles. They found that different operating factors like temperature can influence the round-trip efficiency ranging from 79.1% to 87.8%. Their results also demonstrated charging at lower ambient temperatures will lead to significant adverse impact on the round-trip efficiency. This adverse effect of temperature was also observed by Yuksel et al. (Yuksel and Michalek 2015) where they mentioned, at cold temperatures, discharge ability and consequently, round-trip efficiency of battery systems decreases. Hence, this is very important to find the optimal operating temperature to reach the optimum point of battery systems with the highest round-trip efficiency.

Maximize Service Life of Battery System and Limit Its Degradation

In order to maximize the lifetime of battery systems, employing some strategies to prevent their aging and degradation is vital. In addition to the active materials in a battery system that would be influenced by degradation or aging, whole parts of a battery, even inactive components such as binder, separator, and collectors would be affected by the time and use.

There are many processes and key variables affecting the degradation of battery systems. Indeed, precise understanding of the degradation mechanism of battery systems is so complicated because of a variety of variables from environmental conditions to product utilization affecting the aging process. From those variables temperature, frequency of charge-discharge cycling, change in state of charge (SoC), charge-discharge cycle depth, charge and discharge current

magnitude, used maximum voltage, and also mechanical vibrations have been extensively studied by different research groups. For instance, the results of research of Hoke et al. showed that by minimizing time spent at high SoC, the degradation rate is decreased at a constant charge-discharge cycling as well as battery temperature. It should be noted the type of anode and cathode materials also have an impact on the aging and degradation of battery systems and degradation can also take place during rest periods. Generally, two key forms of degradation in battery systems, including capacity fade and power fade, occur. These forms of degradation can be found individually or simultaneously. Capacity fading is related to the depletion of the amount of energy that can be stored in a battery, while power fading ascribes a reduction in the amount of power in a battery. Worthwhile to mention, almost all battery products consider 20% capacity fade of the battery's end of life (Spotnitz 2003). Very beneficial recommendations from different battery manufacturers regarding the use and maintenance of LIBs to maximizing lifetime of battery systems as well as minimizing their degradation rate could be found elsewhere.

Minimize Hazardous Material Exposure and Emissions

A novel and attractive strategy for capturing CO₂ and converting and storing energy, metal-CO₂ batteries are a promising strategy. Li-CO₂ and Na-CO₂ batteries, in particular, provide high specific energy density. Despite these benefits, some issues and challenges remain, including current challenges in reaction mechanisms on cathodes modifying reaction pathways, catalysts, stabilities, and electrolyte compositions. In order to minimize the adverse environmental effects of battery systems during their production, use, and at the end-of-life stages, the utilization and emission of hazardous and toxic chemicals and materials should be minimized. Because of the presence of combustible material in lithium-ion batteries, the risk of fires or explosions is always possible. Larsson et al. (2017) illustrated that a substantial amount of hydrogen fluoride (HF) is emitted in the case of fire occurrence in various

types of commercial Li-ion batteries. They also found HF and phosphoryl fluoride (POF₃) toxic gases may be generated. In addition, due to the existence of some metals like lead, cobalt, copper, and nickel in high levels, the Li-ion batteries are categorized as hazardous wastes (Kang et al. 2013).

For instance, according to World Health Organization (WHO) data, China is ranked as the first country in the world facing serious public health issues where millions of children in China are currently at the risk of heavy metals like lead poisoning. This problem, besides high blood lead levels in China, is significant because of the rapid increase in production and the use of lead-acid batteries. Therefore, a reduction in the use of hazardous materials is necessary for keeping our environments cleaner.

Minimizing Adverse Environmental Effects

By increasing vehicle electrification, adverse environmental impacts of battery production such as GHG emissions increase. Dillman et al. (2020) used Monte Carlo simulation to investigate and compare the environmental effects of EVs and ICEVs. Their results from the meta-analysis showed that EVs can result in greater life cycle GHG emissions compared to ICEVs for European Union countries. Gan et al. also recently investigated the GHG emission intensities of EVs with those of gasoline vehicles in 2017 in China. They showed that the GHG emission intensities of EVs are much higher than those of gasoline ICEVs in some northern provinces in China (Gan et al. 2021). Nonetheless, some researchers believe that the GHG emissions would be considerably reduced when EVs are operated especially in urban regions facing with intensive traffic issues. Based on their findings, driving behavior and traffic intensity are two significant parameters affecting fuel and energy consumption in ICEVs. Therefore, EVs or generally transportation using electric powertrains are better choices especially in congested traffics where energy recovery through braking systems is activated at a low speed and will lead to a reduction in tailpipe emissions.

Considering the whole battery life cycle provides a complete view of the battery's environmental impact. Along with utilization, it is needed to consider raw material extraction, battery material generation, transportation, packing and cell design, charging energy, condition regulating, and recycling batteries. Figure 1 shows the schematic of required steps to get the green materials for batteries.

Green Materials and Outlooks for LIBs

Since the commercialization of Sony's LIB in 1991, the electrochemical energy storage system has become the most critical market. With the market's emphasis on higher energy content and affordability, materials and components of LIB cells have evolved to achieve more performance-optimized configurations within technical, chemical, and physical limitations. There are serious concerns regarding sustainability and environmental aspects (Fig. 2), which might be shown to be debilitating, especially when the demand for lithium-ion batteries continues to grow. The majority of green and eco-friendly challenges of the LIB are fluorinated and toxic compounds (metal oxides, cathode binder, and electrolyte), energy-intensive material production (metal oxides, graphite, and current collectors), energy-intensive cell production, high-priced electrode processing (cathode processing by nonaqueous solvents), and recycling limitations.

Cathode Materials

$\text{Li}_{1-x}\text{M}_{1-x}\text{O}_2$ as a Li/Mn-rich layered oxide cathodes, in which M represents Co, Mn, Ni, and x defines 0.15–0.20, (termed as LMR-NMC) give relatively high initial practical capacities (200–300 mAh g⁻¹) (Qiu et al. 2016) while having poor rate capability and cycling life. Furthermore, material density and lower redox potential are extra challenges.

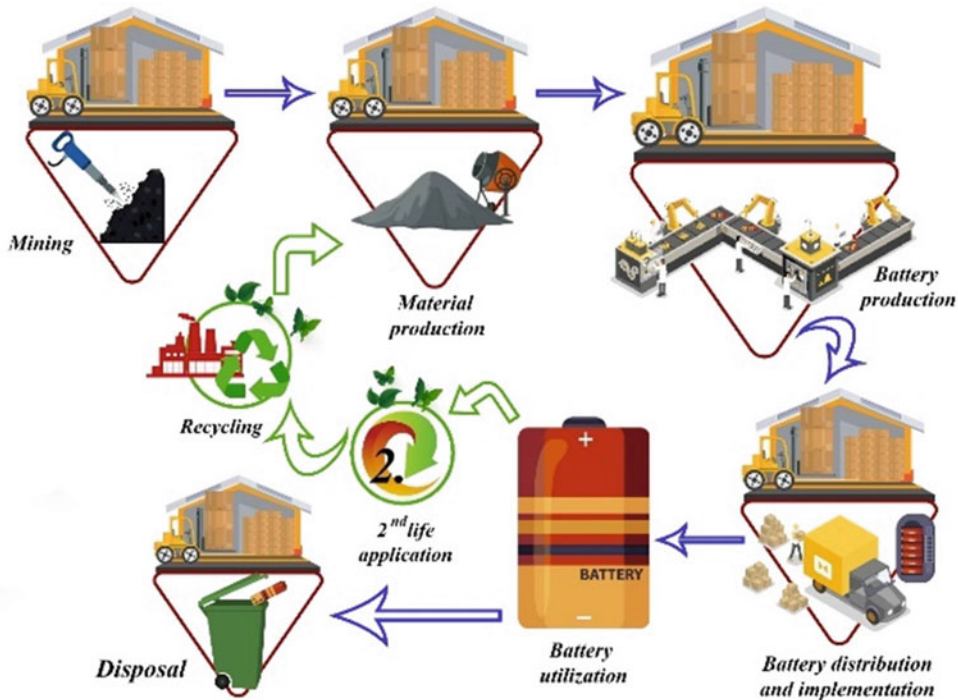
The prevailing state-of-the-art cathode materials of most LIBs hold commercial NMC or NCA. They are made from layered metal oxides (MOs), called LiMO_2 typically ($M = \text{Mn, Ni, Al, Co, i.e., LiMn}_x\text{Ni}_{1-x-y-z}\text{Al}_z\text{Co}_y\text{O}_2$). Compared to other

possible cathodes, they provide a couple of benefits, such as rate capability, material density (4.5–5.1 g cm⁻³), redox potential (≈ 3.7 V vs. Li|Li⁺), and high practical specific capacity (140–210 mAh g⁻¹), making them an undisputed competitor (Arinicheva et al. 2020). Also, the redox-active transition metal in LiCoO_2 (LCO) is purely stemmed from cobalt, intensifying the Co-related concerns while reducing prices due to low-consumed Co materials. The concerns would be most profound when statistics stated portable consumer electronics and small-sized batteries are a place to showcase LCO-based batteries, which offer desirable life span, rate capability, and high material density (5.1 g cm⁻³) (Noh et al. 2013).

Due to the high cost of Co and the need for LIBs with higher energy density, Ni content in layered cathodes has steadily increased, where $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$ (NMC-811) substituted for $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ (NMC-111) (Busà et al. 2021).

NMC-811 and NCA with Ni contents >90% are currently being introduced into batteries by first-cell manufacturers, and NMC cathode formulations with Ni contents >80% are currently under investigation. Although high Ni approaches have led to lower costs and higher energy contents, they simultaneously reduce cathodes' cycle life and safety (Wangda et al. 2020).

Regarding the oxide-based cathode materials, obstacles arising from the instability of the lattice oxygen in oxide-based intercalation cathodes, including gas generation, thermal runaway, and capacity degradation, highlight the significance of shed lighting on the critical factors for lattice oxygen stability. Lattice oxygen stability in layered rock-salt $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_{2-\delta}$ (NCM-111) with studying the behavior of oxygen release and related crystal and electronic structure changes was carried out by Hou et al. (2021). The release of oxygen destroys the structure and changes the amount of Li and Ni in the structure. When oxygen is released, the amount of transfer metals decreases, and consequently, the ability to maintain charge balance decreases. Studies have shown that Ni³⁺ is initially reduced, and then Co³⁺ is reduced, while the amount of Mn³⁺ was constant during the release of 5% oxygen. These studies show that the presence of Ni³⁺ significantly



Green and Sustainable Batteries, Fig. 1 Schematic production and recycling steps for LIB (materials)

increases the amount of oxygen release. Based on this charge behavior, the lattice oxygen stability degrades by high-valent Ni. It is compatible with the accepted principles that charged cathodes with high-valent transition metals are much more unstable than the pristine and discharged cathodes.


A recently evolving literature indicates that single-crystal materials are an increasingly promising strategy for improving the long-term cycling stability of layered cathodes. Single crystal cathodes typically consist of larger particles with lower specific surface areas than polycrystalline cathodes, typically synthesized by a coprecipitation process (Kimijima et al. 2016). These monocrystalline compounds have a much lower tendency to suffer from parasitic reactions, such as gas release from an oxidizing electrolyte that generally occurs in crystalline compounds, which may be due to the reduced area of the material/electrolyte interphase. The single-crystal cathodes could offer advantages to long-life battery applications despite having lower capacities (Li et al. 2017).

Considering the availability of raw materials, cobalt-free cathode chemistries such as disordered rock salt phases such as $\text{Li}_4\text{Mn}_2\text{O}_5$, certain Li/Mn-rich oxide compositions, e.g., $\text{Li}_{1.2}\text{Ni}_{0.2}\text{Mn}_{0.6}\text{O}_2$, and the high-voltage spinel $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ (LNMO), show promises for cathode development (Yao et al. 2018). In cases where large amounts of raw materials are required for one battery pack, such as electromobility or grid storage (20–100 kWh), availability is crucial. $\text{LiFe}_{1-x}\text{Mn}_x\text{PO}_4$ (LFMP) with $0 \leq x \leq 1$ or LiFePO_4 (LFP) cathode materials like phospho-olivine-type are deemed environmental friendly and consist of abundant elements (Tian et al. 2021; Vivo-Vilches et al. 2021).

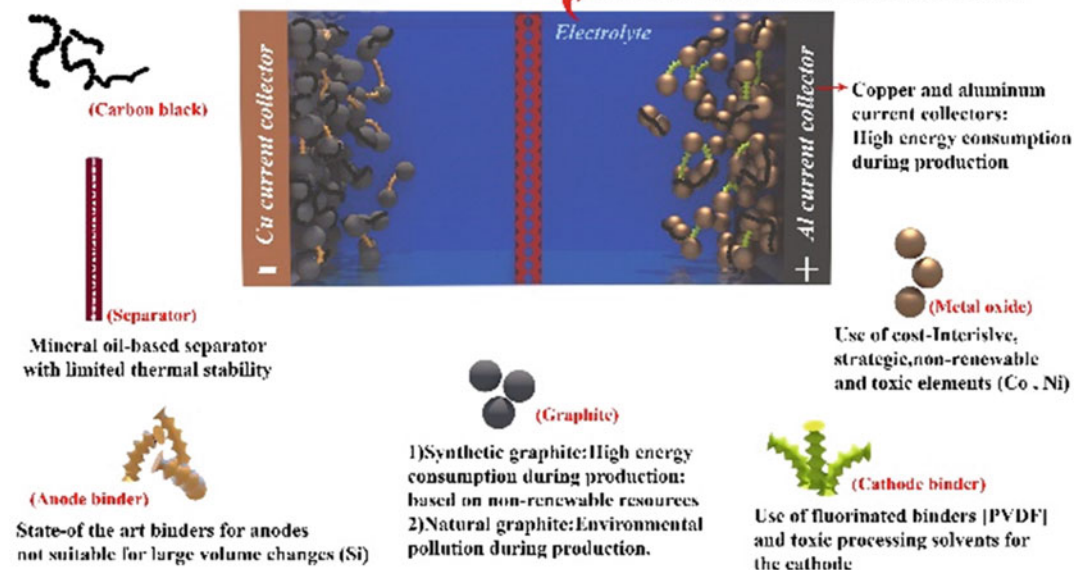
Durable shelf and cycle life LFP-based LIBs can be derived from preventing undesired electrolytes' parasitic reactions, which is in direct agreement with a comparatively low window of operational voltage and high structural stability of the polyanionic phosphate network.

Beyond existing phosphates frameworks, there are various other polyanionic structures, like those own various redox-active central atoms (e.g., Co,

* The move toward higher operating voltages necessitates the employment of sophisticated but frequently hazardous electrolyte additives and surface coatings.

 Challenging concerns over recycling process and efficiency

Using a toxic and poisonous electrolyte as an electrolyte fluorinated salts (LiPF_6): extremely hazardous decomposition of breakdown



Green and Sustainable Batteries, Fig. 2 Environmental challenges of current materials and components in LIB cells

Fe, V, Mn, Mo, Ni), silicates, sulfates, and borates (Ling et al. 2021; Singh et al. 2021).

A cathode's theoretical redox potential depends on the chemical reaction between its anion and cation. For instance, in fluorosulfates (SO_4F^{3-}) and fluorophosphates (PO_4F^{4-}), a small amount of electron-withdrawing anions may increase the potential (e.g., F^- or OH^-) (Lander et al. 2014). The cathode material's attainable capacity depends first and foremost on the extractable Li content per formula mass (i.e., molecular weight).

Compared with layered LiMO_2 , polyanionic host structures possess a more inclusive formula mass, translating to lower theoretical capacities for compounds comprising only one Li^+ ion as a weakness compensated by the presence of multiple Li^+ ions in each formula unit.

Although Li_2MSiO_4 ($M = \text{Fe, Mn}$) as Li metal silicates have low electronic conductivities like polyanionic materials, which are usually compensated for by nanosized active particles coated with

relatively high carbon contents, they provide benefits of low environmental risks, affordability, abounding, and holding two Li ions in their unit, which offer improved theoretical capacities (330 mAh g^{-1}).

Chemistry of non-ceramic cathode compounds, such as organic cathode materials, is a broad field of study with assorted potential competitors (e.g., dilithium rhodizonate or benzoquinone), free of critical transition metals. Because of their relatively low redox potentials, low electronic conductivity, and being more of a stationary application, organic cathodes are not ideal for mobile use but can be considered for stationary applications if cycling stability is adequate (Kumar et al. 2021).

Anode Materials for Green Batteries

Carbon-based materials, especially graphitic carbons, are becoming the anode materials of choice for Li-ion batteries (Li et al. 2021). Although they share many electrochemical characteristics with

Li, they also possess some prominent electrochemical properties. They offer a high cell voltage, high energy efficiency, a flat and low working potential, high persistence in commercial carbonate-involved electrolytes, high voltage efficiency or low voltage hysteresis, and a relatively high specific capacity (372 mAh g^{-1}). From coke-based (soft carbon) anodes to graphite-based anodes, the anode of LIBs has undergone continuous development in advanced materials over the past decades.

Synthetic graphite (SG) and natural graphite (NGs) can be recognized as models of graphitic carbons. As a result of the significant cost distinctions between graphite and cathodes, NGs are replacing SGs significantly. For instance, in China, SG production and NG production both require significant amounts of energy. It is one reason for the cost differences. Despite the presence of other anode materials such as lithium titanate (LTO, $\approx 3\%$), amorphous Si-based anode materials ($\approx 3\%$), and carbon ($\approx 2\%$), the anodes utilized in the commercial LIBs presently consist primarily of SG ($\approx 56\%$) and NG ($\approx 35\%$).

There can be a distinction between primary and secondary materials based on SG. The by-product of the electrode production for aluminum or steel is called secondary type ("scrap"). Materials' character is considerably altered by the batch features (e.g., crystallite size, ash content, density) used for manufacturing. Alternatively, the primary type of prepared SG is more specific in its properties and composition and deserves more for critical applications.

There are two main methods of making graphitic carbons, i.e., SGs and NGs. Three steps are involved in each of the production processes (Kamal et al. 2020):

- (1) The graphite ore treating and mining for NGs or carbon precursors pretreating for SGs.
- (2) Extra material processing for NGs and the graphitization scheme for SGs, or graphite ore treating and mining for NGs and the graphitization procedure for SGs.
- (3) Fine-tuning and refinement particles.

The process usually involves heating petroleum coke and coal-tar pitch to high temperatures ($\sim 3000 \text{ }^\circ\text{C}$), combined with SG precursors. An intermediate material is formed by calcining the precursor at $800\text{--}1200 \text{ }^\circ\text{C}$, that is, soft carbon. An additional mechanical round involves crushing, smashing, milling, and grinding the particles to achieve the desired morphology, specific surface area, particle size, and shape before particle size analysis (weighing and grading). It is also possible to convert the obtained soft carbon into graphitic carbon for immediate application in batteries.

The worth of metal additives can degrade the graphitization temperature and, consequently, the manufacturing process's related expenses and energy consumption (e.g., $\text{Ni}(\text{NO}_3)_2$ or FeCl_3). Adding iron (Fe) catalysts to biomass-derived carbons remarkably increased the graphitization degree. A significant reduction in pyrolysis temperature can further lead to a high reversible specific capacity. The electrochemical performance of LIBs will need to be analyzed for the impact of different metal additives in further comprehensive studies.

Natural graphite (NG) is formed by heating and compressing organic deposits controlled by high pressing and warmth over an extended period. Graphite ratios of up to 20% are started in economically exploitable deposits.

Acid leaching is reported to be the most effective way to remove silicate impurities, which give high chemical pure NG over $2000 \text{ }^\circ\text{C}$. Besides, the roasting method is another promising strategy to remove sulfide impurities and eliminate silicate effectively, which comprises thermic processing (at $\approx 250\text{--}1000 \text{ }^\circ\text{C}$) in an alkali environment, with further processes of water washing and acid leaching (Rogozhnikov et al. 2016).

Particle refinement and carbon coating are part of the final step of producing NG. On the whole, insufficient monitoring and a lack of measures to prevent environmental and air pollution are seen as severe problems about NG production in countries invested in it.

To improve the material sustainability for LIB, heat treatment of biomass or industrial waste is considered an efficient method of achieving

synthetic carbonaceous anodes. Numerous publications in recent years have described how carbons can be prepared and used as anodes in LIBs.

According to the majority opinion, the most promising strategy to further improve anode material energy density will involve adding stepwise bits of silicon (Si) to the graphite anode, namely, Si oxide or SiO_x (nanoparticle) particles. However, contact losses, large volume changes, the instability of the solid electrolyte interphase (SEI), and mechanical electrode degradation are challenging terms and limited Si materials' utilization.

While certain precursor materials for the manufacture of Si-based materials have an abundant supply, such as SiO/SiO₂ precursors, waste products or bio-based alternatives are becoming more attractive as research developments (Ou et al. 2015).

Many research strategies are being considered to increase the Si content of LIB cells (>10 wt%) and still enable good cycle life. Among various approaches, the most promising ones include developing advanced silicon/graphite blends, which possess low specific surface areas and high tap densities, combined with electrode formulations and more competent binder theories. Furthermore, there must be a more satisfying electrolyte formulation for effective SEI formation and adequately pre-lithiated and pretreated solutions.

Electrolyte

Among electrochemical energy storage's key components are electrolytes. Over decades, liquid electrolytes have demonstrated excellent Li-ion battery properties, including ionic conductivity ($\sim 10^{-3}$ S cm⁻¹) and good electrode porosity. Liquid electrolyte use often involves risks such as leakage and combustion of organic electrolyte molecules. As a consequence, polymer electrolyte systems become potential replacements for liquid electrolyte systems. Although solid polymer counterparts (SPEs) contribute to more desirable mechanical and safety than liquid electrolytes, most of them own poor contact with electrodes and pass low ionic conductivities ($\sim 10^{-8}$ S cm⁻¹),

giving low electrical capacity and poor cycle performance (Zhang et al. 2021).

Solid-state batteries have been promised portable electronics to grid-scale systems, where many companies have announced breakthroughs in solid-state batteries. One of the significant advantages of solid-state batteries, along with being more compact and lighter, is safety. A solid-state battery is a promising approach to reducing environmental impacts, weight, and size while improving efficiency and safety.

With Samsung's solid-state battery prototype, the anode is produced by silver-carbon (AgC), allowing for batteries that are just five micrometers thick as a result. Thanks to the ultrathin layer of Ag-C nanocomposite, it is possible to promote the device's energy density by 900 Wh L⁻¹ compared to commercial counterparts (~ 100 Wh L⁻¹) (Lee et al. 2020).

Gel polymer electrolytes (GPEs), which act similar to liquid electrolytes but differ in their characteristics, have also received growing consideration from researchers.

The good mechanical properties and high ionic conductivity of GPEs (over 10^{-4} S cm⁻¹), thermal stability, wide electrochemical window, and adaptability with electrodes have drawn much attention. High cationic transference number, good ionic conductivity, electrochemical stability, chemical and thermal stability, mechanical properties, porosity, and electrolyte uptake are fancied requirements toward LIBs.

Alternative polymers have been considered to enhance the eco-friendliness and electrochemical performance of LIBs, such as biodegradable polymers, hydrogen bonding, and polyaromatics. Polyaromatic polymers' rigid framework contributes good mechanical qualities and can partially solvate the Li⁺ through aryl groups, hindering concentration polarization. Furthermore, the incompatibility of aliphatic and aromatic polymers between a GPE and electrolyte could be overcome by creating one with a porous structure. For utilization of GPEs, hydrogen-bonding polymers exhibit unique properties. Electrolytes and polymer chains interact in hydrogen-bonding networks to inhibit leakage and present further channels for Li⁺-ion delivery when a GPE is held

adjacent to the liquid electrolyte. Due to the mass production interests, the rising environmental challenges have drawn substantial curiosity to the biodegradable counterpart. After their handling and environmental disposal, LIBs are supposed to possess a diminished shock on the environment, where biodegradable polymers are fabricated. It is also reasonable to establish a molecular-level architectural formulation based on the GPE-type's polymer to facilitate incorporating specific inherent and demands, which is in direct line with enhancing the stability and performance GPEs for LIBs.

Recycling

The anode material can be either natural or synthetic graphite, while the cathode possesses electrical properties regarding the battery's components. They also have thin plastic films of separators and electrolytes, critical for stability and safety. Recycling LIB from consumer electronics scratches has been done commercially using cryo-milling, pyrometallurgy, and mechanical processes. Direct recycling is a reliable approach for recycling anodes and cathodes using supercritical carbon dioxide (CO₂) as an extraction solvent. Figure 3 schematically indicates recycling process for LIB.

The mechanical method has good efficiency for the recovery of Li₂CO₃. It enhances the leaching efficiency of valuable metal, has lower energy consumption, and can be utilized in any battery configuration and chemistry. This process requires to be coupled with other systems to recover most materials (mainly hydrometallurgy). Hydrometallurgy approach is also compatible with different battery systems to recover copper, aluminum, cobalt, and Li₂CO₃. However, the anode may be damaged and is cost-effective for cells comprising Ni and Co. While the pyrometallurgy (smelting) method can be applied to any configuration and recovery of copper, cobalt, some iron, and nickel, direct recycling (supercritical CO₂) is applicable approximately

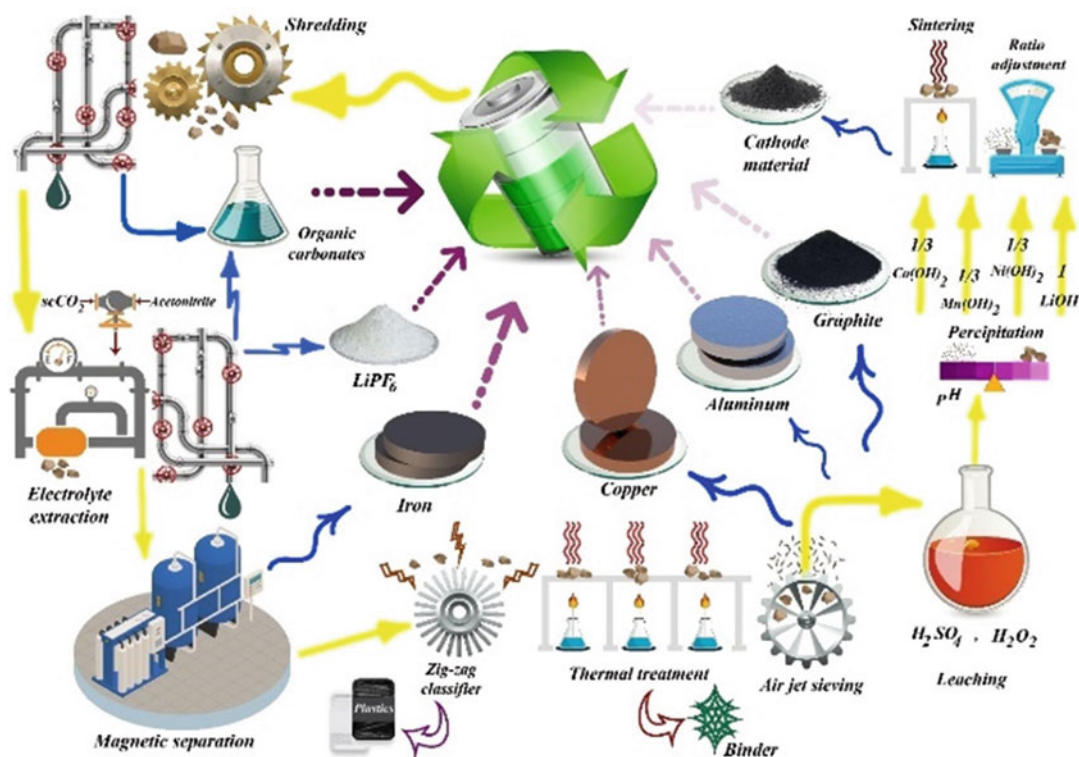
for all battery materials and all components (excluding separators). Concerning the direct recycling approach, recycled substances could damage their operational work rather than pure analogs, and mixing cathodes addresses cost concerns, diminishing the recycled product's value.

In comparison with lead-acid batteries, the end-of-life LIB recycling effort does not compare. Taking a lead-acid battery and recycling it can be profitable with high-purity recycled lead, which can undergo a chemical process after the electrolyte solution is drained.

Recycling end-of-life LIB is expected to be driven primarily by the lower cost of recycled materials. There could also be social and environmental reasons to recycle batteries at the end of their working lives. The three major areas include expenses, greenhouse gas emissions, and energy, critical issues. Economies of scale are expected to reduce costs as a critical economic driver. In addition, recycling LIBs will likely result in significant energy savings and emission reductions. In comparison with hydrometallurgy or pyrometallurgy, direct recycling seems to require less energy and produce fewer emissions.

Conclusion

Demanding high efficiency has paved the way for overcoming environmental problems related to energy storage systems by expanding green batteries and finding a way to design and make cathodes, anodes, electrolytes, and separators or recycling processes. Enhancing life cycle battery efficiency using appropriate material chemistry, lessening the burden rate per delivered energy, minimizing scarce chemicals, adverse environmental effects, hazardous material exposure, and round-trip efficiency, and maximizing the service life of the battery system are crucial demands toward developing green batteries. Therefore, improving cobalt-free cathodes and child-labor issues, anode (graphite) preparing, promising alternatives batteries



Green and Sustainable Batteries, Fig. 3 Schematic illustration of the recycling process for LIB

(e.g., Li- CO_2 , Li-S), and recycling procedures are great approaches toward greener batteries.

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