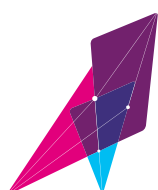
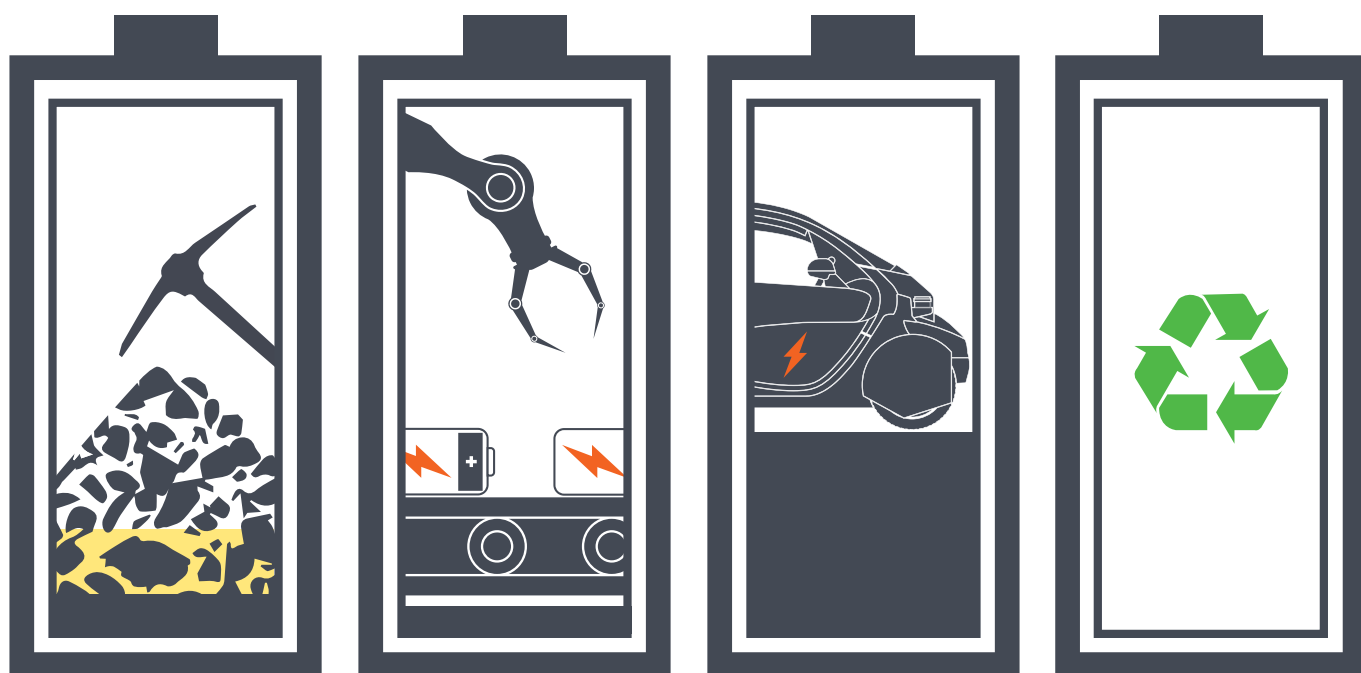


Safe and sustainable lithium-ion batteries

March 2022

An Energy Futures Lab and IMSE White Paper



Institute for
Molecular Science
and Engineering

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Acknowledgments

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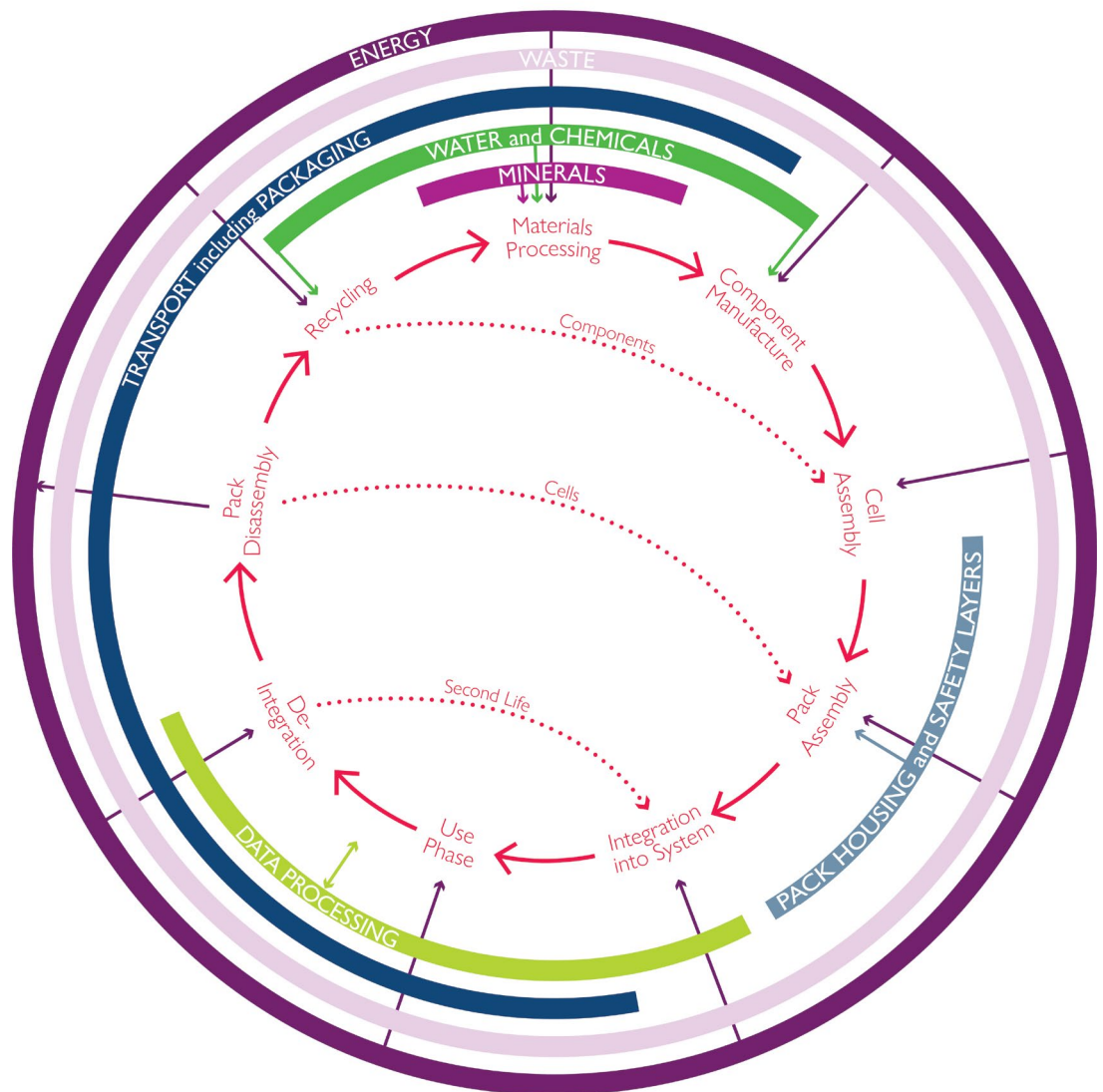
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List of acronyms

A h	Ampere hours (a unit of battery charge capacity)	μm	Micrometre
BMS	Battery Management System	MnSO₄	Manganese(II) Sulfate
CF	Carbon Footprint	NaOH	Sodium Hydroxide
CO₂eq (kW h)⁻¹	CO ₂ equivalent per kilowatt-hour	NH₄OH	Ammonium Hydroxide
CoSO₄	Cobalt(II) Sulfate	NiSO₄	Nickel(II) Sulfate
DRC	Democratic Republic of Congo	NCA	Lithium Nickel Cobalt Aluminium oxide (LiNi _{0.84} Co _{0.12} Al _{0.04} O ₂)
EC	European Commission	NIB	Sodium-ion Battery
EMAS	EC's Eco-Management and Audit Scheme	NMC	Lithium Nickel Manganese Cobalt Oxide (LiNi _{1-x-y} Mn _x Co _y O ₂)
EMS	Environmental Management System	NMP	N-methyl-2-pyrrolidone
EnMS	Energy Management System	NOx	Nitrogen Oxides
EV	Electric Vehicle	PHES	Pumped Hydro Energy Storage
GHG	Greenhouse Gas	PM10	Particulate matter of 10 micrometres or less
GW h	Gigawatt hours (a unit of energy)	PVDF	Polyvinylidene Difluoride
GWP	Global Warming Potential	QMS	Quality Management System
HF	Hydrofluoric acid	SEI	Solid Electrolyte Interphase
ICEV	Internal Combustion Engine Vehicle	SiGr	Silicon-Graphite Composite
ISO	International Organization for Standardization	SoC	State of Charge (of a battery)
kW h	Kilowatt hours (a unit of energy)	SoH	State of Health (of a battery)
LCA	Life Cycle Assessment	SOx	Sulfur Oxides
LCI	Life Cycle Inventory	TW h	Terawatt hours (a unit of energy)
LCO	Lithium Cobalt Oxide (LiCoO ₂)	W	Watts (a unit of power)
LFP	Lithium Iron Phosphate (LiFePO ₄)	W h	Watt hours (a unit of energy)
LMO	Lithium Iron Phosphate (LiMn ₂ O ₄)		
LTO	Lithium Titanate (Li ₄ Ti ₅ O ₁₂)		
LiPF₆	Lithium Hexafluorophosphate		
LiPo	Lithium Polymer Battery		
Li-Air	Lithium-air Battery		
LIB	Lithium-ion Battery		
Li-ion	Lithium-ion		
LiM	Lithium Metal Battery		
Li-S	Lithium-Sulfur Battery		

Executive summary

The transition to clean energy and electric mobility is driving unprecedented demand for lithium-ion batteries (LIBs). This paper investigates the safety and sustainability of LIBs, exploring ways of reducing their impact on the environment and ensuring they do not pose a danger to health of workers or users. The battery life cycle, shown below, is a complex web of inputs and outputs, from initial mineral processing through to end-of-life recycling. Key measures that would increase life cycle sustainability are shown, including 1) the recycling of components to bypass materials processing and component manufacture stages, 2) identifying usable cells for reuse, and 3) providing second life options during de-integration. Implementing these measures would reduce energy, water, chemical and resource usage, ultimately accelerating product sustainability. Each step in the value chain also bears safety risks either from the use of harmful chemicals during materials mining, processing and recycling, unsafe working conditions or through inherent battery features. Continuous battery research and improved engineering are crucial to reduce the severity and likelihood of safety incidents. The use of non-toxic materials, safety engineering using thermally stable battery components, and the replacement of liquid organic electrolytes by solid-state electrolytes are promising routes towards enhanced battery safety.



Prospective battery life cycle, showing major input and outputs for each step.

Introduction

Following the recommendations by the Committee on Climate Change, the UK government elected to decrease its greenhouse gas emissions (GHG) to net-zero by 2050, taking decisive action to mitigate the current global warming trend, with a transition away from fossil fuels towards electrification in the transport sector being essential to achieve this.^{1,2}

With a contribution of 23 %³ to the annual UK GHG emissions, the decarbonisation of the transport sector is paramount if net zero emissions are to be achieved by 2050. The recent announcement of the ban on new petrol- and diesel-powered car sales by 2030 in the UK⁴ accelerates the need for clean, energy-efficient, safe and cost-effective solutions in the automotive industry. Presently, a promising solution to decrease transport-related emissions is the shift from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs), although the ability of EVs to decrease emissions depends strongly on the energy source used to manufacture, charge and recycle them. This solution is considered necessary, alongside a redesign of transportation systems in the post-Covid 19 recovery plans involving increased use of forms of active travel⁵ and working from home that can achieve substantial reductions in per-capita km travelled by private vehicles.⁶ Achieving climate goals in the transport sector requires ambitious EV adoption, resulting in a global battery demand expected to increase by a factor of 14 within the next decade.⁷ In the UK, CO₂ emissions from all major modes of transport decreased by 1.3 % in 2018 and, with EV cost decreases (18 % between 2017 and 2018 alone) and significant expansion of the EV charging infrastructure, this trend can be accelerated.³ Lithium-ion batteries (LIBs) are an integral part of an EV, offering high performance at an increasingly more affordable cost. Moreover, LIBs have emerged as one of the most promising options to leverage the enhanced penetration of renewable energy sources required for electrical grids.³ Energy storage technologies, such as batteries, can act as a buffer, accommodating the intermittency of renewable energy sources by absorbing excess energy and providing stored energy on demand. This paper focuses specifically on LIBs for the transport sector.

Why lithium-ion batteries?

Compared with other energy storage options (e.g. lead-acid batteries, redox-flow batteries), presently LIBs provide an attractive combination of affordability, high energy and power densities, high cycling efficiencies and lifetimes.^{8–10} LIBs are also versatile and modular, able to be used for a range of application scales, from small portable electronics up to large grid storage systems. Since the commercialisation of the first LIBs in 1991,¹¹ battery chemistry and performance have been optimised for different requirements, resulting in a large variety of LIB systems, each with different advantages, drawbacks and suitable applications. The differences in their chemical compositions not only influence battery performance characteristics, such as specific energies, power densities and lifetimes, but also result in varying manufacturing processes and costs. In the past decade, LIB pack costs have decreased dramatically due to economies of scale and improved manufacturing; these were reported to be around \$100·(kW h)⁻¹ by mid-2020^{12,13}, with certain designs already reported at a cost less than \$85·(kW h)⁻¹.¹⁴

Safeguarding the future

Global EV battery capacity demand is on track to increase from 0.17 TW h per year in 2019 to 1.5 TW h per year in 2030, which will contribute towards added concerns over the negative environmental impacts associated with EV batteries (Figure 1).¹⁵ Sustainable production, use and end-of-life (EoL) management of those batteries is imperative to ensuring a truly clean transformation of the transport sector. Researchers, manufacturers and consumers have questioned the economic benefits, pressure on raw materials (e.g. lithium and cobalt compounds) and sustainability of a battery economy.^{10,16} This has led to expanding research on the environmental impact of LIBs via life cycle assessment (LCA),^{17–21} battery waste management,^{22,23} second life applications^{24,25} and energy efficient and environmentally

benign recycling of EoL EV batteries,^{26,27} to further decrease environmental impacts and minimise primary raw material requirements.^{28–31}

Safety of LIBs throughout their life cycle, including the production, usage and recycling phases, is also critical, especially exposure to hazardous chemicals when handling damaged cells or thermal runaway reactions during usage that could lead to battery fires and explosions (Figure 1). Disposal of EoL batteries into landfills should be prohibited by law, as the cells may ignite or leak toxic chemicals into the environment. Fires caused by batteries may lead to public rejection, so it is important to ensure that the risks are well understood and managed.

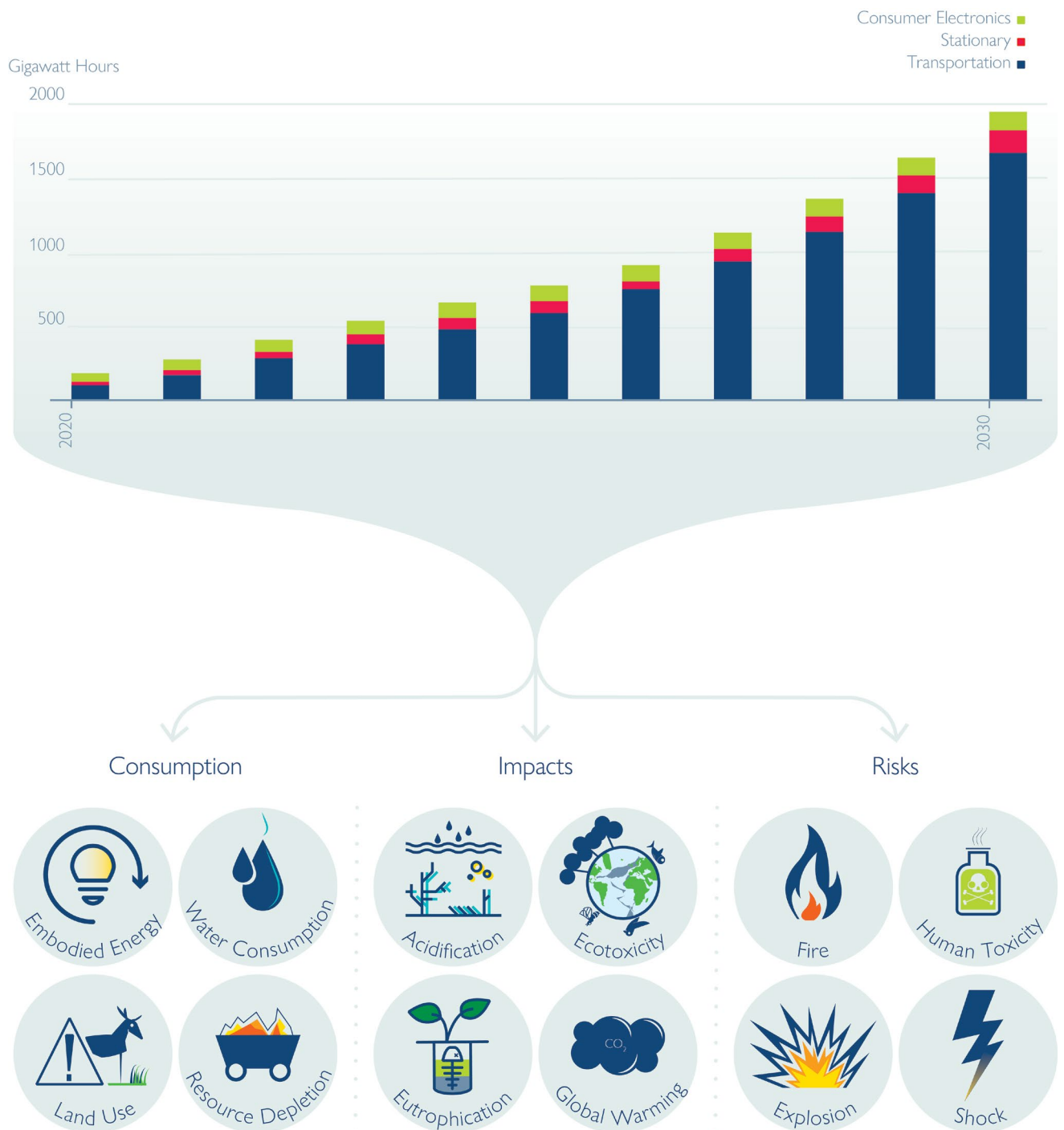


Figure 1. Growth of LIB demand by application projected until 2030³² and challenges related to the increasing amount of LIBs.

BOX 1.

Energy (in Joules or Watt hours, W h) is defined as the amount of work a system can do, while power (in Watts) relates to the rate at which that work can be done. High-energy systems can do a large amount of work, but over a long period of time, while high-power systems can do work more rapidly. For energy storage devices, energy and power are often given as energy/power density (in units of W h dm⁻³ or W dm⁻³; also called volumetric energy / power density) or as specific energy/power (given in W h or W kg⁻¹; also called gravimetric energy / power density). LIBs are suitable for many applications (e.g. EVs or grid-storage) as they provide both: relatively high power and energy densities, in both volumetric and gravimetric terms.

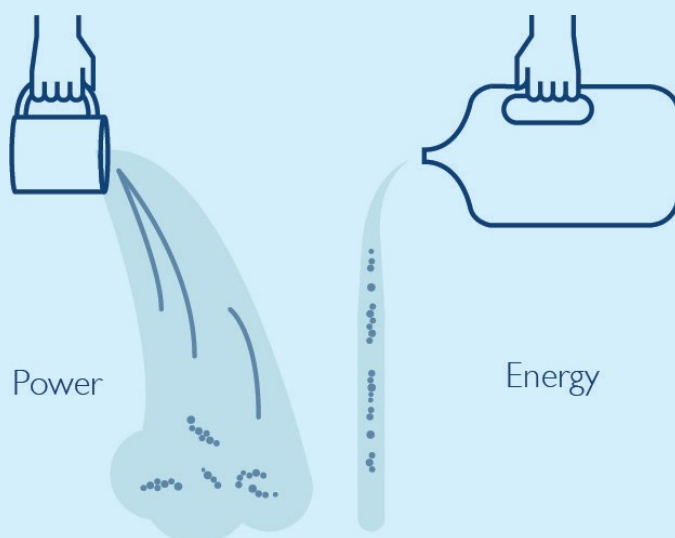


Figure 2. Power versus energy

Battery fundamentals

Rechargeable batteries consist typically of one or more electrochemical cells, each containing a positive (cathode during discharge, anode during charge) and negative (anode during discharge, cathode during charge) electrode, separated by a micro-porous membrane and all immersed in an organic electrolyte solution containing lithium salts dissolved in organic carbonate solvents. Oxidation (loss of electrons) and reduction (gain of electrons) reactions occur at the interfaces between the electrolyte and each of the electrodes; oxidation occurs at anodes and reduction at cathodes. By arbitrary convention, oxidation currents and overpotentials ($E_a - E_{a,eqm}$) are defined as positive, and reduction currents and overpotentials ($E_c - E_{c,eqm}$) as negative.

LIBs take their name from the lithium cations, Li⁺, which intercalate into the electrodes and migrate between them through the electrolyte during charge/discharge. As for Li⁺ ions, during battery discharge, electrons (e⁻) move from negative to positive electrodes, through an external circuit, as shown schematically in Figure 3. When current density j is drawn from a battery, positive and negative electrode reactants are consumed, causing the reaction zone to move away from the separator, through which ionic current path lengths are a minimum, towards the anode and cathode current collectors. Assuming very fast reactions, so overpotentials $|\eta| \rightarrow 0$, ohmic potential losses ($\sum j \cdot L_i / \sigma$) occur due to ionic current density flowing through electrolyte solution of ionic conductivity σ with increasing, time-dependent path lengths L_i in porous reacted layers, as well as through the microporous separator. As shown schematically in Figure 4, those ohmic potential losses at positive (cathode) and negative (anode) electrodes decrease discharge potential differences (U_d), so $U_d < \Delta E$ (open circuit (or equilibrium) potential difference). Conversely, on subsequent charging, the (reversed) applied current causes oxidation to occur at the positive electrode, which then operates as an anode, and reduction occurs at the negative electrode, operating as cathode; the potential losses then cause: $|U_c| > \Delta E > U_d$. This is in addition to the decrease of open circuit potentials (ΔE) with increasing conversion of positive and negative electrode materials (Figure 5); charging causes the reverse effect.

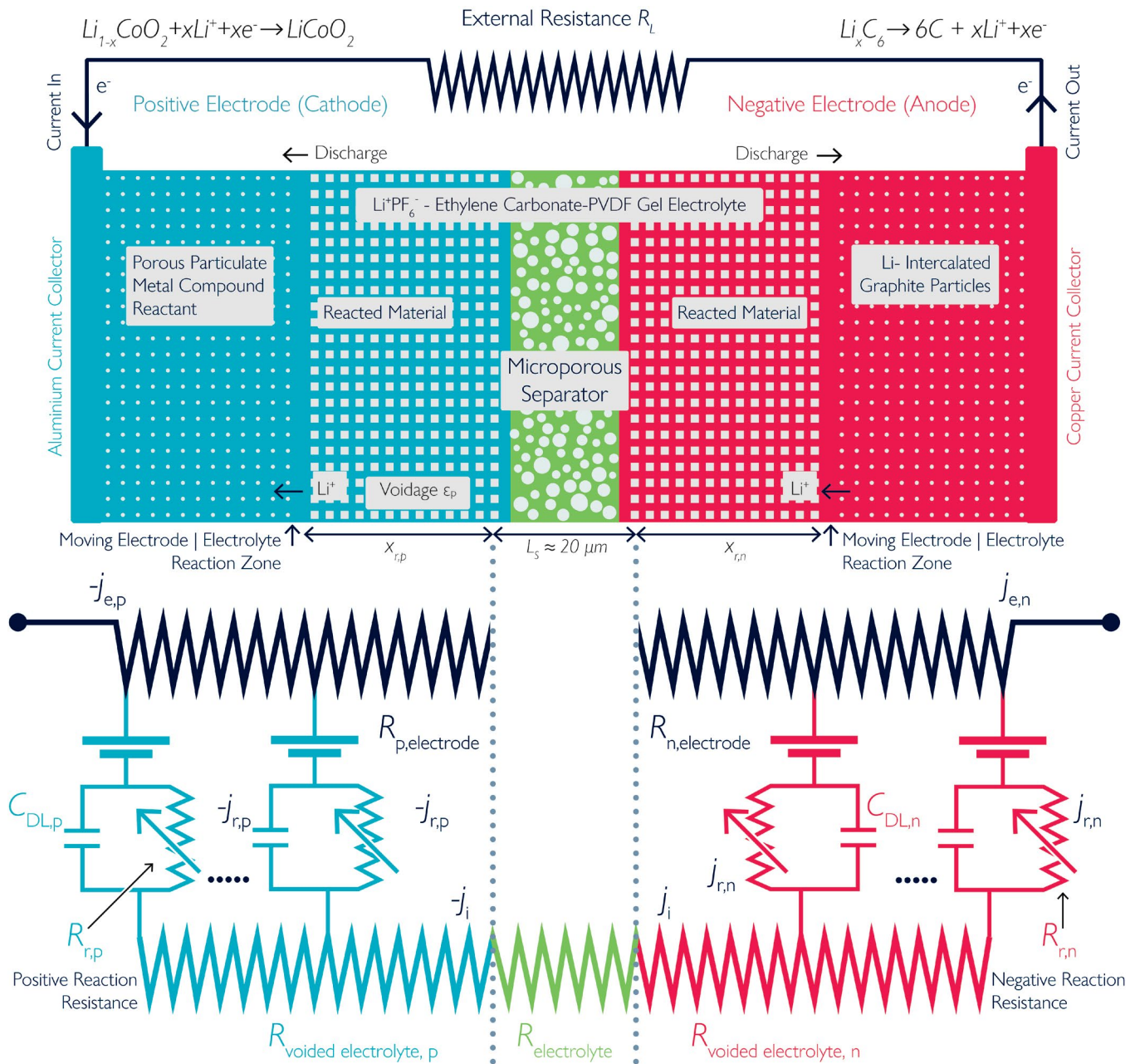


Figure 3. Schematic example of a partially discharged Li-ion battery and corresponding analogue electronic circuit.

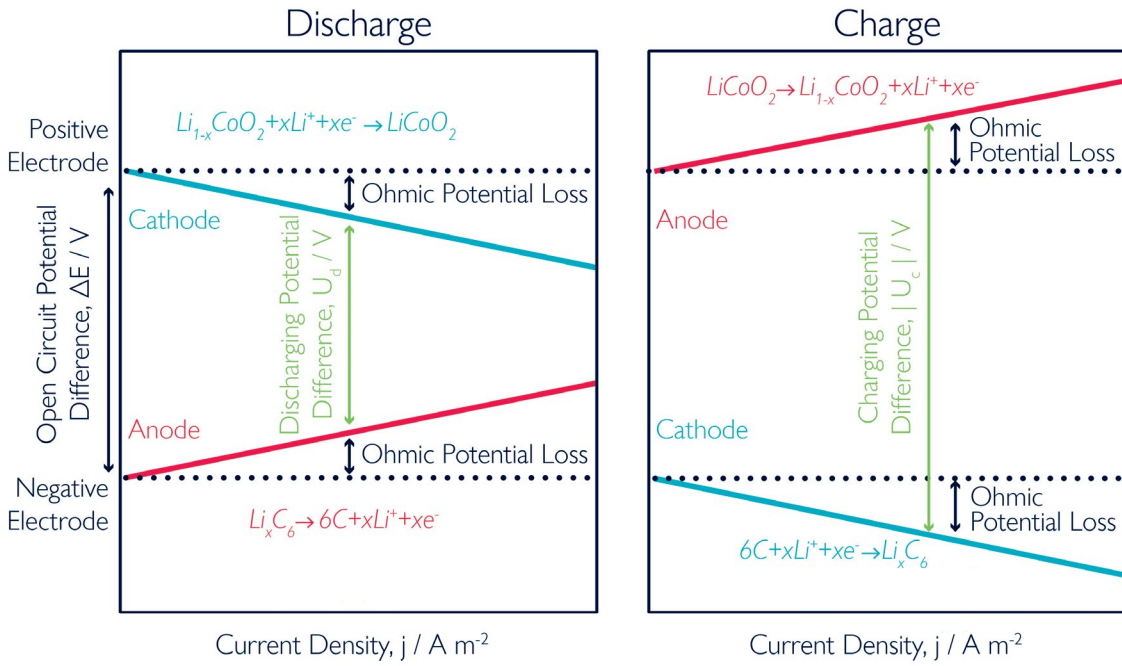


Figure 4. Schematic of potential distribution in example LIB with open circuit potential difference ΔE , and potential differences during discharging (U_d) and charging (U_c), at current density j .

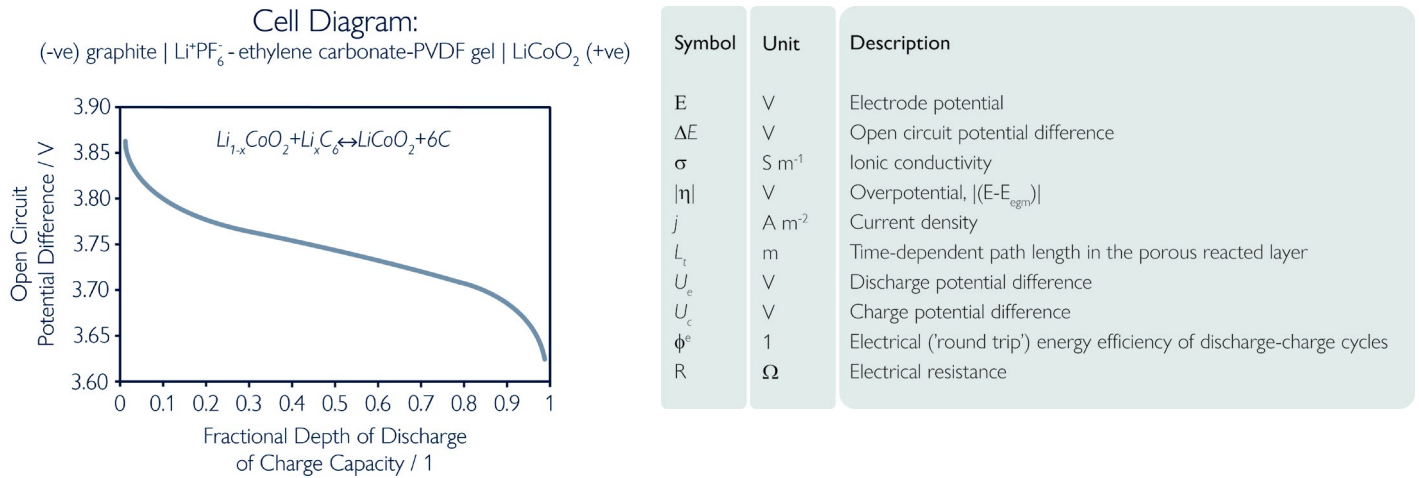


Figure 5 . Schematic example of effect of fractional depth of discharge (x) on battery open circuit potential difference, ΔE .

Assuming there are no charge losses to parasitic reactions, such as solvent decomposition or secondary electrode reactions, charge yields at cathode and anode are unity, so the electrical ('round trip') energy efficiency of discharge-charge cycles can be defined by:

$$\Phi^e = \frac{U_d}{U_c}$$

Hence, to maximise energy efficiencies, ohmic potential losses and the resulting thermal energy dissipation should be minimised, enabling chemical energy conversion efficiencies to be maximised. However, the then infinitely small current densities would result in infinite long charging times, so current densities need to be optimised to optimise capital and operating costs.

Technology mix

LIB technologies are often categorised based on the positive electrode materials used. Figure 6 shows the family of electrode materials presently used commercially. The most common negative electrode material is (lithiated) graphite, but other materials such as silicon and lithium titanate (LTO) are also deployed. Lithium nickel-manganese-cobalt (NMC) and lithium nickel cobalt-aluminium (NCA) oxide positive electrodes (cathodes) are combined either with graphite, or more recently, with silicon for increased energy density / specific energy and decreased costs. For long lifetimes and high power, lithium iron phosphate (LFP) cathodes can be combined with LTO anodes, but this decreases energy densities. Liquid electrolytes used at present include the salt, lithium hexafluorophosphate (LiPF_6), dissolved in organic solvents such as ethylene carbonate, dimethyl carbonate and propylene carbonate.

While lithium cobalt oxide (LCO) cathodes are still used widely in portable electronics, their structural instability makes it difficult to extract their theoretically high energy densities without compromising lifetime.³³ One mitigation strategy is to change the composition of LCO, adding Ni^{II} and Mn^{II} to form composites with higher structural integrity and capacity, enabling overall enhanced performances.^{33–36}

Since their introduction, NMC formulations have emerged as the dominant choice in the battery industry, predicted to account for more than 70 % of battery capacity to be produced by 2025. In order to further decrease cost and increase performance of NMC LIBs, the standard formulation of NMC333 – the numbers meaning that it consists of one-third each of Ni, Mn and Co metal atoms – for automotive applications is modified to transition gradually from expensive cobalt

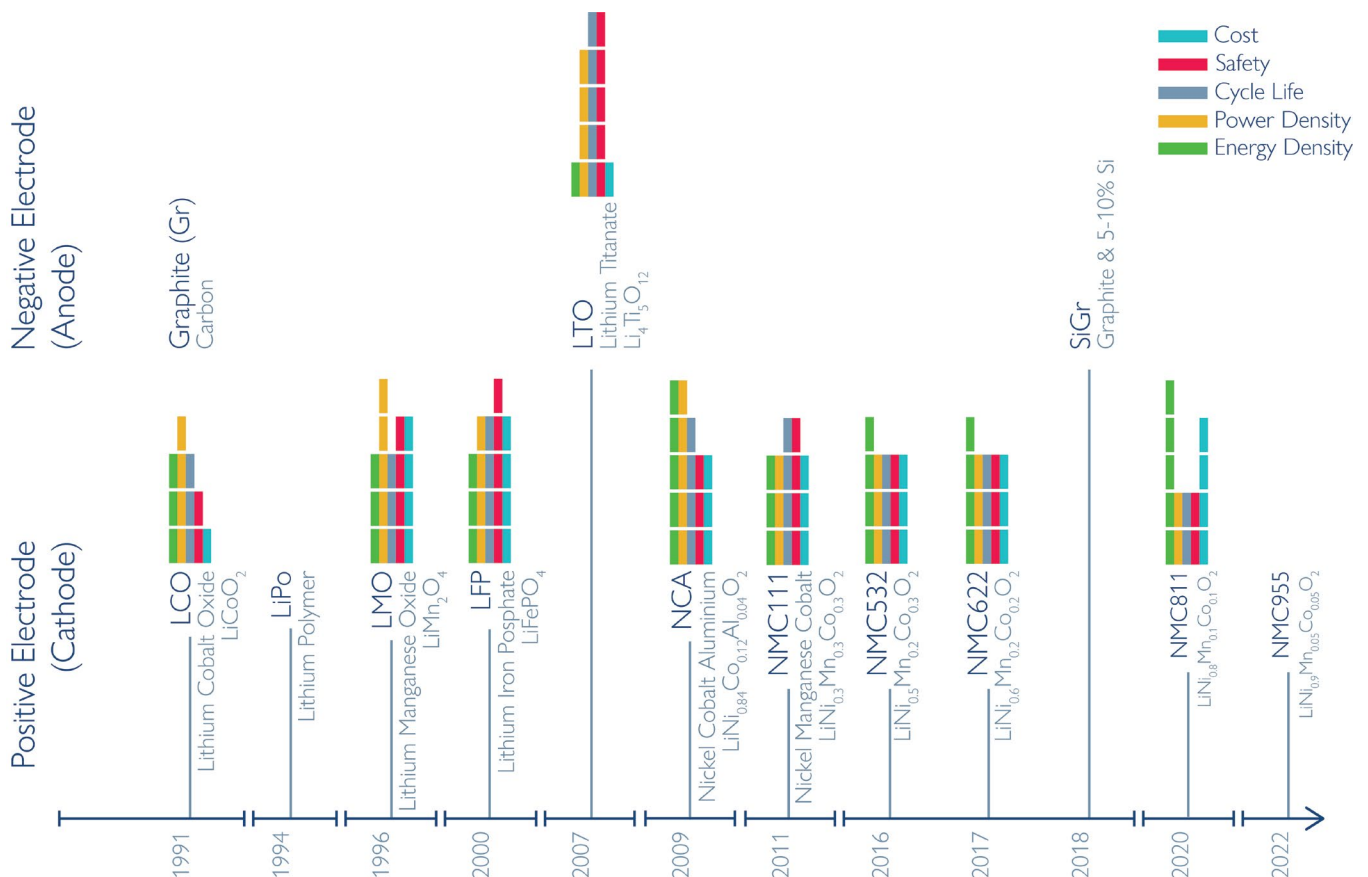


Figure 6. Timeline of the commercial history of LIB positive and negative materials. Where possible, the bars provide a comparison between materials, according to five key performance indicators, with 1 bar being the poorest and 5 bars the strongest (note: 1 bar for cost means highest price).^{41–43}

and increase the amount of nickel, providing higher capacity. NMC532, NMC622 and NMC811 were developed, with promising improvements in energy densities but, at the same time, decreased thermal stability and increased degradation rates.^{37–39} Another motivation for increasing the nickel content is to decrease concentrations of cobalt, which is associated with higher prices and socio-economic issues.⁴⁰

The development of NCA was another breakthrough, offering higher energy densities compared with LCO^{44–46} and deployed in Tesla EVs. However, thermal instability and capacity fade at elevated temperatures are still limiting its wider deployment.^{47,48}

In addition to the intensive research on layered oxide materials, Goodenough's group (Prof. John Goodenough received the Chemistry Nobel prize in 2019 together with Stanley Whittingham and Akira Yoshino for the invention of LIBs) developed so-called polyanionic cathode materials.^{49–52} They are named after the polyanion XO_4^{n-} (X = sulfur, phosphorous, silicon, boron, etc.) and occur in a myriad of structures, allowing greater flexibility to tune the material properties and electrochemical performance.^{53,54} The best known polyanion cathode material is lithium iron phosphate (LFP), which shows high structural and thermal stability as well as improved safety, material cost and sustainability, compared with NMC materials.^{55–58} However, its lower potential difference and energy density has prevented its dominance of the battery market. Nevertheless, LFP batteries are applied in electric buses and EVs, especially in China.

SiGr anodes are considered to be an effective way of increasing energy densities;^{59–61} however, Si suffers from large volume changes upon cycling, destabilising the battery components and resulting in short lifespans.^{60,62} Even though both nickel-rich positive electrodes and silicon-based negative electrodes still face severe challenges and short lifespans, the industry seems very optimistic that these novel materials will dominate the near- to medium-term future of LIBs.^{39,63,64}

Presently, carbon nanotubes (CNTs) and graphene are being studied intensively as replacements for graphite negative electrodes and carbon additives providing electronic conductivity for active materials in positive electrodes.^{65–67} Due to their unique morphology, CNTs and graphene can form long-range electron conduction networks, increasing power densities (cycling rate capabilities) and able to intercalate larger amounts of Li compared to graphite, leading to higher energy densities.^{65,68} They can also be used as free-standing electrodes, making Cu current collectors redundant and further increasing LIB energy densities. However, their manufacturing is still costly and difficult, as morphology and purity need to be controlled strictly to obtain optimal electrochemical performance.

Moving away from unstable liquid electrolyte solutions, prototypes of LIBs using polymer-based electrolytes - so-called lithium-polymer or LiPo batteries - were developed in the late 1970s.^{69,70} LiPo batteries consist of the same positive and negative materials as conventional LIBs, but the lithium salt is dissolved in a polymer matrix, such as (poly)ethylene oxide, instead of an organic solvent.⁷⁰ LiPos tend to be made as pouch cells, packaged in a foil-like bag, having the advantage of higher energy densities and form flexibility, in contrast to the solid metal casings of cylindrical or prismatic cells.

Next generation technologies

Solid-state batteries have gained widespread attention in and beyond the research community. Their name is derived from the solid-state electrolyte(s), which replaces the liquid organic electrolyte solution. Positive electrode materials are typically the same as in current LIBs and common negative electrodes are graphite, Si, LTO or Li-metal.^{69,71} It is only when using Li-metal or Li-Si alloy negative electrodes that theoretical energy densities are increased, making them an appealing alternative to present LIBs. However, present issues include poor lifetimes, unwanted side reactions, limited scalability of manufacturing processes for thin solid electrolytes and difficulty of ensuring intimate contact between the solid components during cycling and manufacture.^{72,73}

To achieve even higher energy densities, it is necessary to combine a lithium-metal (LiM) anode with a high energy density cathode^{74,75,76} such as Li-Air, in which oxygen is reduced at the cathode, or lithium-sulfur (Li-S),^{75,77} in which sulfur is reduced at the cathode. For Li-S cells, a major drawback is the so-called polysulfide shuttle effect, causing loss of active material, anode corrosion and limiting lifetime significantly⁷⁸, mitigation of which is the subject of intensive research.^{79,80} While the theoretically ultrahigh specific energy of Li-Air is attractive, in practice, this battery system suffers from limited performance and short cycle lifetimes.⁸¹ Further intensive research efforts are required to gain a more fundamental understanding of how to increase Li-Air performance and extend its usable life before a commercially viable prototype can be made.⁸²

Li-S and solid-state batteries have already been commercialised, finding applications, for instance, in small, unmanned aircrafts and scooters. However, their potential is not yet fully exploited and further research is required.¹⁶

Battery sustainability

Transformative technological developments for LIBs are required for their sustainability, not just for their cost and performance metrics such as energy and power densities. These improvements are required throughout their value chain, as shown in Figure 7. Firstly, a range of materials used in LIBs, including lithium, nickel, cobalt, manganese, aluminium, copper and graphite, are harvested mostly from primary raw materials (ores). Concentrates from their ores are processed, sometimes together with recycled secondary materials, to produce the compounds and cell components (anode, cathode, electrolyte and separator), which are then combined into battery cells. These are connected electrically to form battery modules and battery packs. The battery packs are then deployed for their first life use phase, during which they eventually degrade due to repeated charge/discharge and other processes. Once the performance level has reduced to 70-80 % of their initial capacity, they are considered to have reached the end of their first life use phase. At this stage, the batteries can either be repurposed for second life use, usually to provide grid storage, or recycled.

Each step in the battery value chain results in environmental impacts, including GHG emissions and various ecotoxicity and human health related impacts, described in the following sections. Environmental impact monitoring and assessment tools are also outlined and options to improve battery sustainability are discussed. These range from deploying substitute materials and alternative processes, to rethinking the supply chain from a whole systems perspective.

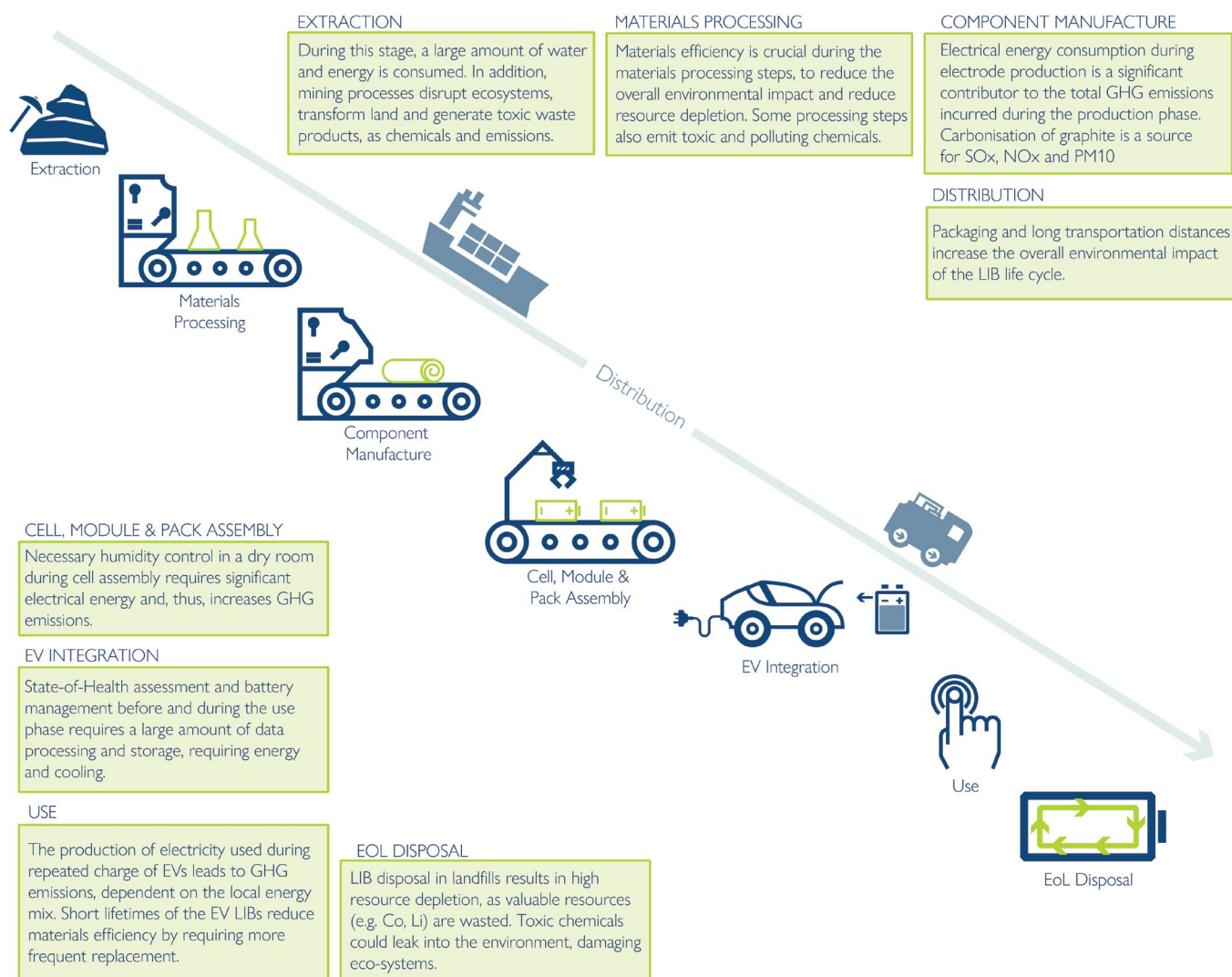


Figure 7. Current value chain of EV LIBs, from raw materials extraction to EoL disposal, with descriptions of the associated environmental impacts at each step.

Environmental monitoring tools and methodology

Knowing where the most detrimental environmental impacts arise in the LIB value chain and their extent is crucial for decision making and the development of mitigation strategies. Amongst the standardised tools used to provide international consistency in such assessments are the Environmental Management System (EMS), ISO 14001 / EMAS;⁸³ the Quality Management System (QMS), ISO 9001;⁸⁴ the Energy Management System (EnMS), ISO 50001⁸⁵ and Life Cycle Assessment (LCA), ISO 14040.^{86,87} LCA is a standardised methodology that can be used to determine the environmental impacts associated with a product, process or activity, widely used for comparing and benchmarking product alternatives, as well as marketing and regulatory decision making. Its principles and framework are described within the ISO 14040 standards.^{86,87}

The introduction of LCA and other environmental management tools support the move towards greater resource and energy efficiencies, less waste creation and assessment of alternative technologies and options. Implementing the circular economy principles of ‘reduce, re-use and recycle’ requires that primary extraction of raw materials be limited or bypassed altogether, increasing sustainability at the very start of product and resource life cycles. This can be achieved only by minimising waste and increasing the proportion of recycled materials in production processes.

Battery production

A growing body of literature has investigated the environmental impacts of battery production.^{17–21,31} The production of LIB packs is a multi-stage process chain, typically spreading across several countries and continents and including more than fifty individual raw materials. In a battery production plant, the major sources of environmental impact arise from the production of the positive electrode (cathode) material and the cell manufacturing process. The main steps of the battery production process are shown schematically in Figure 8.

Cathode production: The NMC cathode production starts with the co-precipitation of NiSO_4 , CoSO_4 and MnSO_4 as corresponding hydroxides with ammonium hydroxide (NH_4OH) and sodium hydroxide (NaOH), followed by calcination of the $\text{NMC}(\text{OH})_2$ product with Li_2CO_3 ,²⁰ forming the NMC powder. This is then mixed with a binder (polyacrylic acid and carboxymethyl cellulose) and the mixture is dispersed in N-methyl-2-pyrrolidone (NMP) solvent¹⁷ to produce the cathode paste. The paste is then deposited on Al current collectors and, after a series of compaction steps (calendering), the electrodes are dried under vacuum. Ammonia formed during the co-precipitation step at $\text{pH} > 10$, is removed from the wastewater in an ammonia stripping tower and sodium sulfate is removed through an evaporator. This requires substantial thermal energy, normally from natural gas, leading to high GHG emissions. Moreover, the roller hearth kilns used for calcination are designed with excess capacity, in order to achieve uniform temperature distribution and rapid firing. While this enables high material yields and improved product quality, kilns are very energy intensive to operate and contribute considerably to the overall GHG footprint of a battery.^{19,20}



Figure 8. Cell and pack assembly process. Cell assembly is usually conducted in a dry room, due to the sensitivity of Li compounds to humidity.

Cell manufacturing: Anodes and cathodes, separated by ca. 20 µm thick micro-porous polyethylene-polypropylene separators, are stacked or wound into cells and the current collector tabs are connected, before the cells are enclosed in Ni-coated steel cell containers or pouches and filled with electrolyte solution.³¹ The latter is prepared by dissolving a conducting salt (typically LiPF₆) in mixtures of cyclic and linear organic carbonate solvents.⁸⁸ Depending on the manufacturing plant, cell assembly processes are performed in a dry room, due to the sensitivity of Li compounds to humidity. This strict humidity control during the cell assembly process leads to high energy consumptions, resulting in increased GHG emissions.²⁰ Reported values of specific electrical energy consumptions for cell production are highly variable, but even the lower estimates constitute a large contribution to the overall GHG footprint of a battery.

The cells are connected to form a battery module including a Battery Management System (BMS). Finally, the battery modules are assembled into battery packs, and cooling and additional management systems are installed. A substantial amount of additional material is added at this stage, with the cells in a typical EV battery comprising just 50-60 % of the mass. After performance testing, the final battery packs are ready for testing and use.

Materials for lithium-ion batteries

The battery production processes have been shown to make the most substantial contribution to the cradle-to-gate GHG footprint of a battery.^{19,20} The stages of raw material extraction and processing and the production of the individual LIB components introduce additional environmental burdens via emissions that are major sources of toxicity, acidification and eutrophication impacts. The most important contributions are discussed below, together with the battery materials to which they relate.

Aluminium (Al) is used in the packaging surrounding the battery pack, the cathode current collector and the thermal management system.¹⁹ Its production relies on the exploitation of bauxite, Al^{III}-rich oxide ores, processed into aluminium oxide. Pure aluminium is produced using highly energy intensive electrolytic reduction.⁸⁹ Recycling of Al bypasses highly energy intensive smelting steps and is well established, with an estimated 75 % of global historical production still in use today.⁹⁰ While the Hall-Héroult process releases potent GHGs such as carbon tetrafluoride (CF₄) and hexafluoroethane (C₂F₆), these emissions are dwarfed by those which arise from electrical power consumptions.⁹¹ Al is the battery material with the greatest contribution to the GHG footprint of a battery pack.¹⁹

Copper (Cu), used in the negative electrode (anode) current collector, cell container and packaging, is extracted from either sulfide or oxide ores. The less abundant oxide ores are generally considered to be of higher quality, and require less costly processing. They are normally leached, purified by solvent extraction and electrowinning (SX-EW) followed by electrorefining. The commonly available sulfide ores incur higher processing costs, due to the energy intensive pyrometallurgical processes followed by smelting, converting, fire- and electrolytic refining, which are energy intensive, so causing significant GHG emissions overall. The process releases sulfur dioxide (SO₂), which is converted to sulfuric acid at additional cost, while unmitigated emissions induce a high acidification impact. Additionally, Cu ore concentration processes incur a series of ecotoxicity, human toxicity and eutrophication impacts,¹⁹ through acidification of aquifers and the release of heavy metals into freshwater environments.⁹²

Cathode materials: The preparation of the cathode precursors requires significant amounts of NiSO₄, MnSO₄ and CoSO₄. From the cathode materials, Ni production remains the most significant contributor to environmental impact. Ni ores are concentrated by crushing, grinding, froth flotation and magnetic separation; depending on the ore type, concentrates are treated by either hydrometallurgical or pyrometallurgical processing.⁹³ To achieve the purity required, the NiSO₄ used in batteries is produced by dissolution of Ni metal in sulfuric acid. NiSO₄ production incurs a series of environmental impacts resulting from the energy intensity of Ni processing, the disposal

of sulfidic tailings from mining operations and the sulfur dioxide emissions released during processing of nickel sulfide concentrates. Co is produced mainly as a by-product of mining and processing of the ores of Ni and Cu. Therefore, similar environmental impacts of lower magnitude are induced through Co extraction and processing, including acidification, eutrophication and global warming. For battery applications, MnSO_4 production starts with the electrolytic preparation of primary MnO_2 , including the reduction to MnO and consequent leaching with sulfuric acid to form MnSO_4 . The acidic solution is purified by oxidation with MnO_2 and neutralised with lime. The MnSO_4 solution is then filtered, its concentration adjusted and subjected to electrolysis, to yield the MnSO_4 powder grade required in the preparation of the battery cathode precursors.⁹³ Overall, NiSO_4 is the cathode material precursor having the greatest environmental impact, with lesser contributions coming from the preparation of MnSO_4 and CoSO_4 . This might become problematic in the future, as the current trend is for high Ni-content cathode materials. However, as a high share of cathode materials might come from recycled battery packs in the future, multi-product focused recycling operations can become more economical and sustainable.

Anode materials: The dominant anode material used in LIBs is synthetic graphite, produced through carbonisation of petroleum coke and coal tar pitch, followed by graphitisation.²⁰ The combustion of impurities during the carbonisation process is a significant source of NO_x , SO_x and PM_{10} .²⁰ Natural or coated natural graphite may be used as alternatives to synthetic graphite, but their use is associated with poor electrochemical performance.⁹⁴

Other materials: Another source of environmental impact arises from the production of the electronic components and printed circuit boards used in the BMS, as their associated production processes are highly energy intensive. However, the relative mass of these materials is very low, contributing little to the overall production impact of the battery. Due to the small amount of lithium used in LIBs, it does not constitute a large environmental burden. Li-rich brine resources and hard rock ores are processed to produce Li_2CO_3 and LiOH .⁹⁵ Li^+ extraction from salar brines extract large quantities of saline water with a significant ecological footprint, while the more expensive hard rock extraction produces more solid waste. The salars between Argentina, Bolivia and Chile contribute over 50 % of the world's lithium(I) production and account for almost 80 % of the world's LiI brine reserves. These hypersaline salars are unique environments that are host to several vulnerable species, such as the Andean flamingo. Continued expansion of lithium extraction and poor operational practices could result in significant challenges and threats for this unique ecosystem and its valuable biodiversity.⁹⁶

Use phase

Assembled LIB battery packs are transported to their application sites, e.g. car manufacturers, to be installed for their first life usage phase. In EV applications, the battery use phase might contribute substantially to the life cycle GHG emissions, due to continual charging of batteries over their lifetime. Depending on the local energy mix and production footprint of the electrical energy needed for EVs, the use phase environmental impact can vary significantly. In this respect, battery cycling efficiencies can become important during the use phase, since batteries with lower energy losses during cycling will use less energy and thereby incur fewer emissions.

During the use phase, battery lifetime is also a decisive performance parameter and can contribute significantly to the life cycle environmental footprint. As an extended battery lifetime allows for the footprint of the production phase to be spread over longer times or energy throughputs, its overall environmental impact is decreased.^{97,98} LIBs undergo complex electrochemical and mechanical degradation mechanisms, which are particularly pronounced in the highly demanding operating conditions imposed by EVs.⁹⁹ Battery aging can be divided into usage-dependent (cycle aging) and usage-independent (calendar aging) degradation.^{100,101} Cycle aging is a function of charge-discharge cycles and, consequently, is influenced by battery chemistry, pack design, operation mode¹⁰² (cycling rate, depth-of-discharge, temperature) and vehicle energy consumption. Calendar aging occurs even when the LIB is not in use, so even stored batteries may be subject to degradation, and is mainly a function of temperature and storage potential difference.¹⁰³

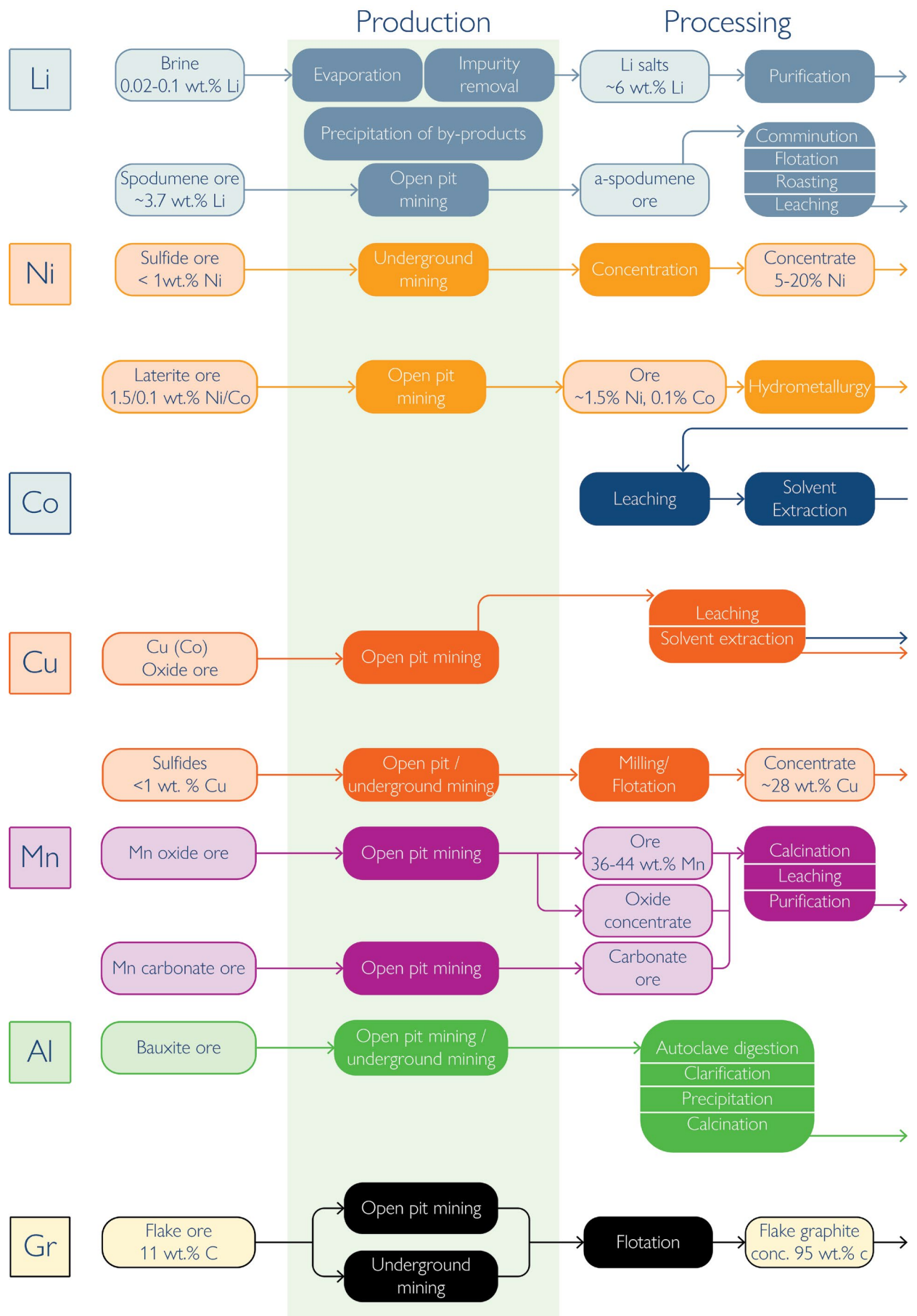
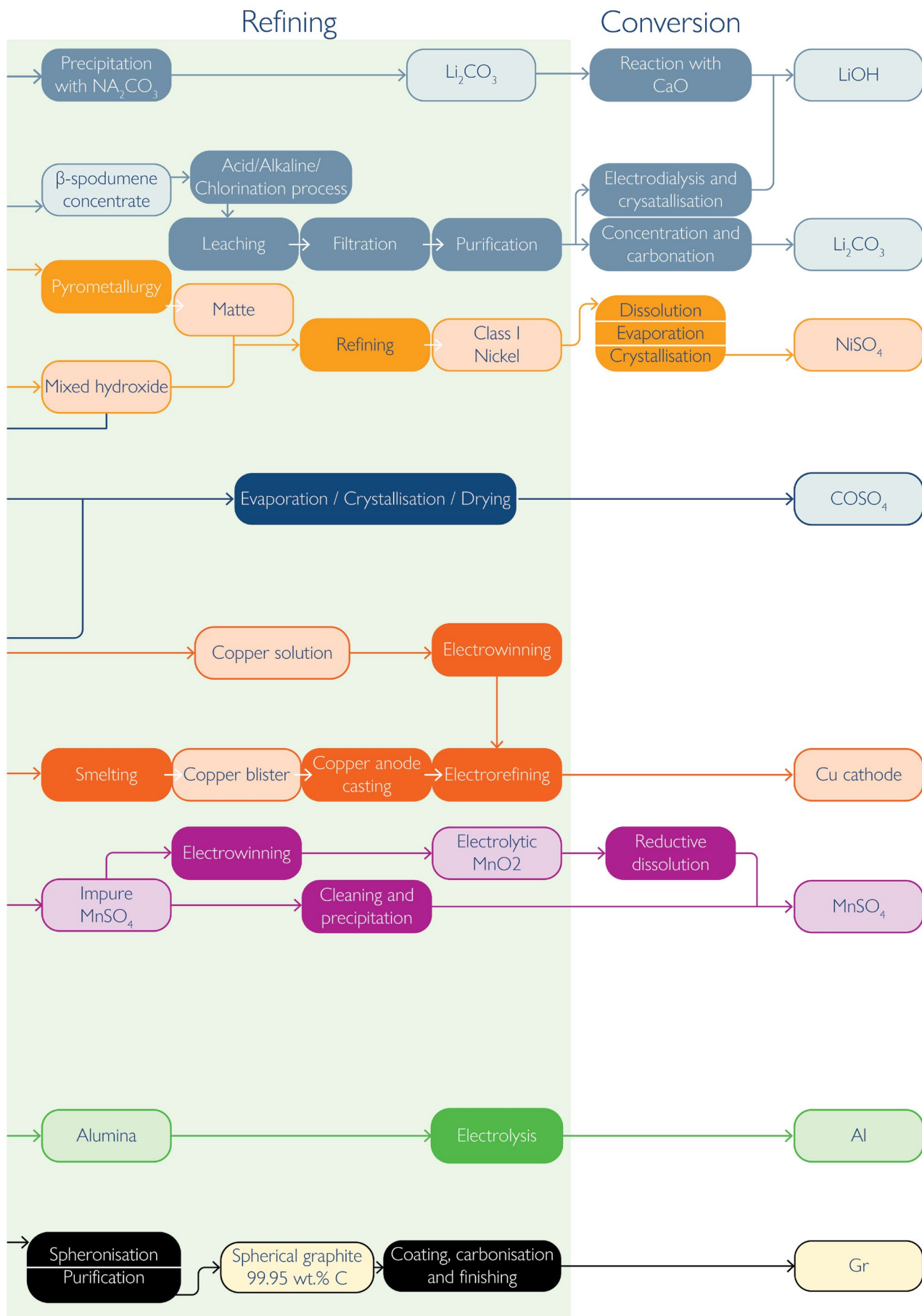


Figure 9. Raw materials extraction processes for materials commonly used in LIBs.



End-of-life

At the end of their first life (usually at 70-80 % of their initial capacity), LIBs can either be refurbished, repurposed for a second life or recycled, following the principles of a circular economy.²⁴ The feasibility of second life applications depends on the residual useful capacity in the battery;¹⁰⁴ applications include EV fast charging, enabling time-shifted consumption of residential renewable energy, frequency regulation and deferral of upgrades through enhanced flexibility.¹⁰⁵ Off-grid energy storage in developing countries is another second life application.¹⁰⁶ Repurposing LIBs for grid storage applications would displace commonly deployed lead-acid batteries, so avoiding the additional GHG emissions related to lead-acid battery production, which has a higher environmental impact than LIB production.^{107,108} In order for second life batteries effectively to decrease the battery environmental impact and to be economically viable, their lifespan needs to be long enough to compensate for the emissions and costs of their refurbishment.^{26,107} Moreover, the emissions during LIB collection and transportation to their second life destination need to be taken into account.³⁰

To avoid end-of-life LIBs entering landfills, where metal ions and organic compounds could leak and contaminate the soil and groundwater, or where fires caused by damaged batteries could occur, LIBs need to be recycled systematically. Moreover, battery recycling and extraction of their valuable materials helps to buffer fluctuating material costs and rebalances geographically uneven raw material distribution and battery production, while avoiding unnecessary transportation between sites.^{26,28,30} Reusing recycled materials for battery production displaces extraction and processing of raw materials and their associated costs and environmental impacts.²⁹ While ca. 99 % of lead-acid batteries are recycled, at present the value for LIBs is far smaller, due to low collection rates and inadequate recycling processes.¹⁰⁹

Recycling LIBs is challenging, due to the diversity of elements in the batteries and the difficulty associated with separating and recovering them.²⁸ Following collection, battery packs are identified and sorted, based on their battery chemistries,¹¹⁰ and then undergo a series of physical and mechanical separation processes, during which the battery packs are disassembled into smaller components. Pre-treatment steps for packs include crushing, shredding, milling and sieving, as well as magnetic (for steel) or eddy current (for aluminium) separation, froth flotation separation and other processes.^{110–115} Depending on battery configuration and recycling method, it is possible to recover steel cases, plastics and electronics contained in the modules before or after the disassembly/pre-treatment. Next, cells are recycled via three dominant methods: pyrometallurgical, hydrometallurgical and direct recycling. The recycling processes are depicted in Figure 10.

In a pyrometallurgical process, whole LIB cells are smelted and high value cathode materials, such as Co, Ni, Cu and Fe, are recovered, while others, like Li and Mn are lost to the slag.¹¹⁶ The mixed alloy is then further treated via hydrometallurgical recycling, to separate the metal components.

Hydrometallurgical recycling may consist of a leaching / ion exchange / solvent extraction / precipitation sequence.^{28,110,111,115,117–121} Other than lithium(I) ions, metal ions in their higher oxidation states in positive (cathode) electrode materials such as LiCoO_2 , LiMn_2O_4 , LiMnO_2 , LiNiO_2 are insoluble in aqueous solutions, so have to be reduced to lower oxidation states to dissolve Co^{2+} , Mn^{2+} and Ni^{2+} ions, for further processing and separation. As sulfuric acid (H_2SO_4) is the cheapest acid, this is commonly used, with hydrogen peroxide (H_2O_2) as relatively expensive reducing agent. Organic acids such as citric, oxalic and formic acids can function both as reducing agents and as metal ion ‘complexants’, increasing the solubilities of the dissolved metal ions, so enabling less acidic conditions to be used, with the additional benefit of decreasing corrosion rates of steel process equipment. After leaching, the various metals may be separated via solvent extraction, chemical precipitation and electrodeposition. Unfortunately, processes with fully ‘closed loop’ liquid phases have yet to be developed, so end-of-pipe effluent treatment processes are required to minimise discharges to the environment.

Direct recycling aims to recover battery components in a functional state, so that they can be reused directly. The cathode material is removed and revived via solid state synthesis, hydrothermal, electrochemical or chemical lithium re-insertion, without changing the overall structure of the material.^{26,28}

The overall life cycle GHG emissions, which include those during recycling, depend strongly on the energy consumption and efficiency of the recycling process. Pyrometallurgical recycling is energy intensive and evolves toxic gases, so may even increase the overall life cycle GHG emissions, compared with direct and hydrometallurgical processes.^{28,122} However, while hydrometallurgical recycling is regarded as more sustainable than pyrometallurgical processing, it requires chemicals that are harmful to the environment. Direct recycling is an appealing alternative to both hydro- and pyrometallurgical processes, as lengthy purification steps are avoided and all battery components potentially can be recovered. However, it is still in the early development stages and its efficiency needs to be improved in order to make it a viable recycling route, especially when dealing with a wide variety of cathode chemistries that firstly need to be identified, sorted and then treated according to their chemical requirements.²⁸

Value chain emissions reduction pathways

The urgent, global need for decarbonisation, requires lowering the LIB GHG footprint, alongside reducing other emissions and improving the overall environmental performance of LIBs. Achieving this objective requires the mobilisation of numerous stakeholders throughout the LIB value chain and implementation of coordinated emissions reduction methods. A few of the most promising are discussed here and their performance is illustrated in Boxes 2 and 3.

Manufacturing with renewable energy Powering the energy-intensive cell manufacturing process with 100 % renewable energy can reduce the carbon footprint (CF) of LIBs significantly. Tesla has committed to this target and, more recently, Northvolt announced plans¹²³ to integrate the cathode powder production in the cell manufacturing facility and utilise hydropower. Powering cathode powder production with hydroelectricity has the potential to reduce its footprint by 40 %, while performing cell assembly with hydroelectric power can reduce the total CF of the battery by 30 %.⁹¹

Upscaling Reductions in the energy intensity of cell manufacturing are already achieved in battery gigafactories, exhibiting a 70 % lower energy demand for cell assembly compared to corresponding activities in pilot scale plants.^{20,124} As battery production scales ramp up, it is expected that the GHG intensity of battery production will decrease significantly.

Sustainable procurement Given the global scale of the battery value chain and the wide variety of materials used in the battery cells, the CF of the materials fed into the battery production process can vary significantly, depending on their source. For example, primary Al production in China, accounting for approximately half of the global supply, has a much larger CF than Al production in Europe and North America, much of which is powered by hydroelectric power. As a component of a battery, Al sourced from Europe may have a lower overall CF by ca. 30 %.⁹¹ Besides embedded carbon considerations, materials efficiency and the environmental impact of battery materials production substantially affect its overall sustainability.¹⁹ Implementation of sustainable procurement principles and regulations that reward sustainable production can improve battery sustainability significantly.

Increased battery energy density An indirect way of lowering the environmental footprint of a battery is by increasing its energy density, through modifications in the underlying chemistry. In battery production alone, blending the graphitic anode with silicon has been shown to offer a 32 % reduction in the CF. Augmenting this with an increased Ni-content cathode (NMC811), despite the additional CF of Ni production, leads to overall GHG emission reductions of 47 %.¹⁹ These benefits, associated with the increased energy density, extend also to other environmental impact categories, as a reduced amount of energy and materials is required to produce a kW h of battery pack capacity.

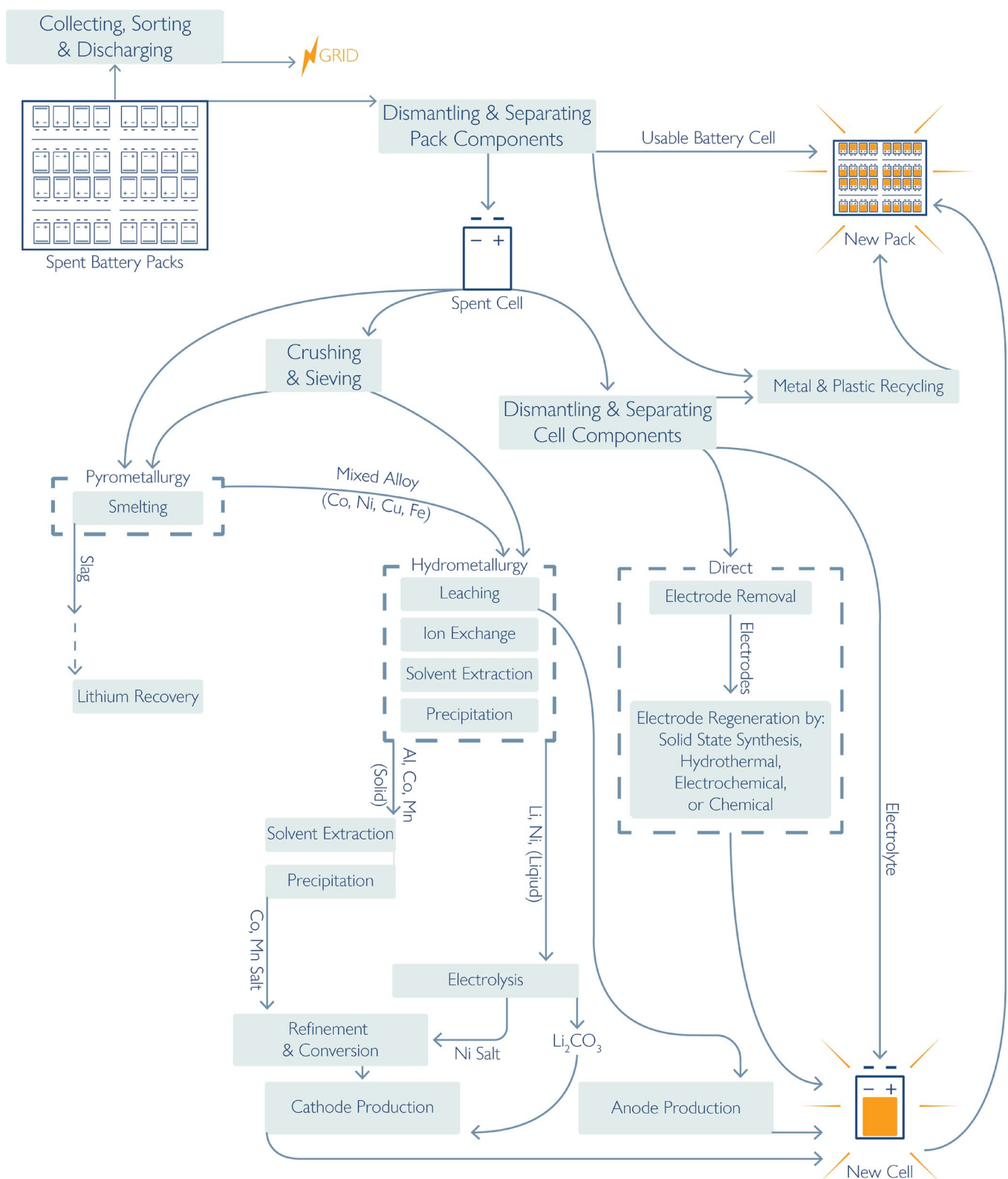


Figure 10. Recycling process flow chart showing possible pathways to new cells and packs, including pyrometallurgical, hydrometallurgical and direct recycling .

Extended battery lifetimes Use of materials providing longer lifetimes is an attractive strategy to lower life cycle emissions, as the battery production footprint is compensated by an extended use phase.^{97,98,125} The LFP-LTO battery system has been shown to have a highly promising cycling lifetime and thus a reduced impact over its lifetime.⁹⁸ However, LTO has higher production costs and provides lower energy densities compared to graphite, so is deployed to a lesser extent. New battery chemistries, such as NMC811, have increased energy density and lower cost compared with other NMC materials, but show pronounced capacity fade, having potentially a negative impact on the life cycle environmental footprint of a battery.^{19,37,126} Cycling conditions, such as discharging to low potentials or frequent fast charging can destabilise the component materials, reduce usable capacity and shorten lifetime.¹²⁷⁻¹²⁹ Therefore, the development of well-defined charging protocols can extend a battery pack's lifespan. Moreover, engineering solutions to control cell operating temperatures, such as implementing a sophisticated battery thermal management system or modifying the cell design to lower operating temperatures, can reduce the total CF demonstrably by 25 %.¹³⁰

BOX 2.

The GHG intensity of battery production can be reduced significantly by production scale-up, integrating renewable energy sources, sourcing less carbon-intensive materials and increasing the energy density of battery cells, as 75 % to 80 % of the LIB CF comes from cathode production, cell manufacturing and the upstream production of Al. Figure 11 demonstrates the combined effect of such advancements in decreasing the cradle-to-gate CF of a battery based on a recently developed LCA model.¹⁴ Under baseline assumptions, NMC333-Gr battery produced in China has a CF of 262 kg CO₂eq (kW h)⁻¹, which is reduced to 246 kg CO₂eq (kW h)⁻¹ when the production chain is supplied with European Al. For gigascale manufacturing, the decrease in energy requirement reduces the battery production footprint to 133 kg CO₂eq (kW h)⁻¹, which decreases to 116 kg CO₂eq (kW h)⁻¹ when supplied by European Al and further decreases to 64 kg CO₂eq (kW h)⁻¹, when hydroelectric power is utilised in a battery gigafactory. The scenario is similar for the NCM811-SiGr chemistry, for which the pilot-scale footprint is estimated as 140 kg CO₂eq (kW h)⁻¹ and is reduced to 76 kg CO₂eq (kW h)⁻¹ for a gigascale plant, further reduced to 67 and 39 kg CO₂eq (kW h)⁻¹ for the EU Al and hydroelectric scenarios, respectively. The results demonstrate that accounting for the increased scale of battery manufacturing, technological developments aiming at increased specific energy and the transformation of the supply chain, reduces the CF of LIBs by 85 %, from 262 kg CO₂eq (kW h)⁻¹ in 2015 to 39 kg CO₂eq (kW h)⁻¹ in 2028.

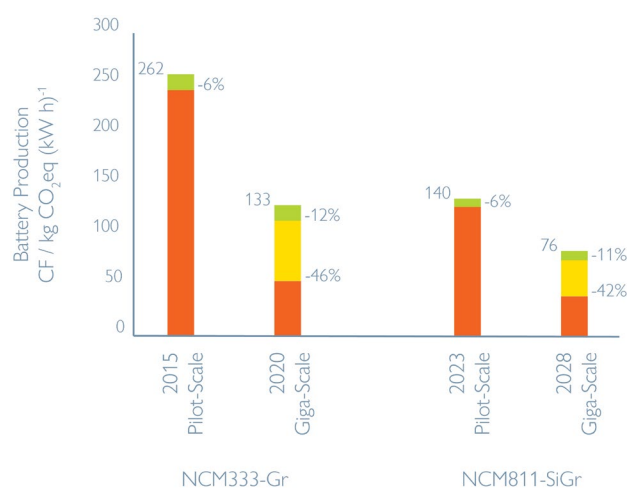


Figure 11. Battery production carbon footprint in kg CO₂eq (kW h)⁻¹ predicted for NMC333-Gr and NCM811-SiGr, and pilot-/gigascales. Green indicates CF reduction from European Al use; yellow indicates CF reduction from hydroelectric power use. Reference years are based on the battery commercialisation projections of the IEA.

Battery recycling While battery recycling introduces an additional burden on the battery value chain, significant environmental benefits can be achieved by the displacement of primary material with recycled material. Depending on the recycling process and battery chemistry, the relative CF reduction potentials may range from 18 to 29 %.¹³¹ These benefits occur as a result of recycling only the battery cells; when the recovery of battery pack materials is taken into account, such as Al, Cu and steel, the GWP benefit of battery recycling reaches 35 % (Box 3). Notably, energy-intensive pyrometallurgical recycling processes have been shown to result in net increases of the GWP footprint of a battery.¹²²

BOX 3.

Establishing a circular battery value chain can provide an important source of battery materials and substantial environmental benefits. Figure 12 presents the reductions in CF achieved by including recycling in the value chain for an NMC333-Gr battery pack. The battery cells are recycled by hydrometallurgical processing, while other battery pack materials such as Al, Cu and steel are recovered through well-established recycling processes. Introducing recycling increases the battery production CF by 12 % to 149 kg CO₂eq (kW h)⁻¹, due to additional materials and energy requirements. Circular use of battery materials in the value chain displaces primary materials (crediting), reducing the production CF of the battery by 31 % to 92 kg CO₂eq (kW h)⁻¹.

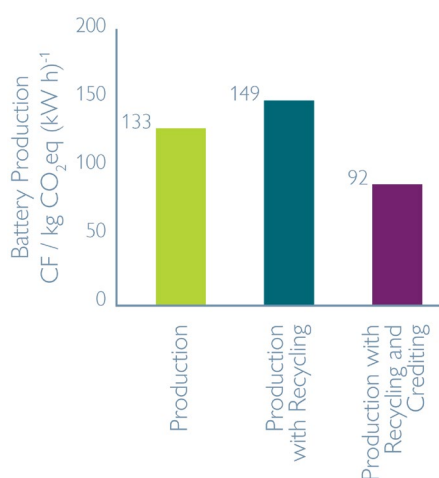


Figure 12. Effects of recycling and crediting on carbon footprint (kg CO₂eq (kW h)⁻¹) of NMC333-Gr battery production from primary materials.

Key findings

- Even though LIB production has negligible direct emissions, the demand for energy and materials leads to a significant environmental footprint from indirect emissions.
- The CF of a LIB can be traced to the energy source supplying its production, use and recycling.
- Upscaled battery production facilities reduce the energy required to produce LIBs owing to economies of scale.
- The increased uptake of renewable energy is crucial not only to minimising the environmental footprint of EVs, but also in reducing the carbon footprint of LIB production.
- Mining and processing of battery materials comes with detrimental acidification and ecotoxicity impacts.
- Sustainable procurement of battery materials is essential to producing greener batteries.
- Battery cycling efficiency and prolonged lifetime are key performance factors during the use phase determining the battery environmental impact.
- Battery second life applications increase battery lifetimes, so potentially can decrease the overall life cycle environmental footprint.
- Hydrometallurgical and direct recycling are more advantageous compared to pyrometallurgical recycling in terms of GHG emissions.
- Battery technology improvements, such as increased energy density using advanced materials and increased battery lifetimes, are promising strategies to reduce life cycle environmental impact.
- Economies of scale, developments in battery technology, supply chain shifts, and the uptake of battery recycling will reduce the environmental impacts of LIBs.

Battery safety

Battery safety has gained increasing attention, in accordance with the rapidly growing number of EVs on roads. Common safety concerns arise from the high battery potential difference, thermal runaway reactions and related fires and explosions. Given the lack of experience of the public with EV battery fires, incidents might deter customers from transitioning from an ICEV to an EV. It has been shown that the heat released during a battery fire is no greater than that released during a gasoline fire in an ICEV.^{132,133} Reducing the likelihood of the high risk event occurring has been the focus of ongoing research; major improvements have been achieved through advanced engineering and safety mechanisms. Reducing the magnitude of the risk is as important, so development of more fault tolerant, fail-safe or fail-soft, systems is at the forefront of battery safety research.^{134,135} As a result, safety events during the usage of LIBs have become incredibly rare, e.g. from the 8.2 billion of small cells that were produced in 2018, less than 1 % fail benignly and only 0.00002 % resulted in a safety incident.^{136,137} Safety considerations are important along the value chain of LIBs. The following section discusses material extraction and production, use phase and recycling aspects (Figure 13).

Materials safety

Battery safety refers not only to explosion risks of the battery itself, but also to safety during the raw material extraction and production processes. The toxicity of integrated materials can present serious safety risks, especially for workers along the chain (mining, refining, material preparation, etc.).

The mining industry has a reputation for being a risky business, with health risks that are varied and often quite serious. With the introduction of strict safety legislation and protocols,^{136–140} as well as advances in safety equipment, the industry has seen its fatality

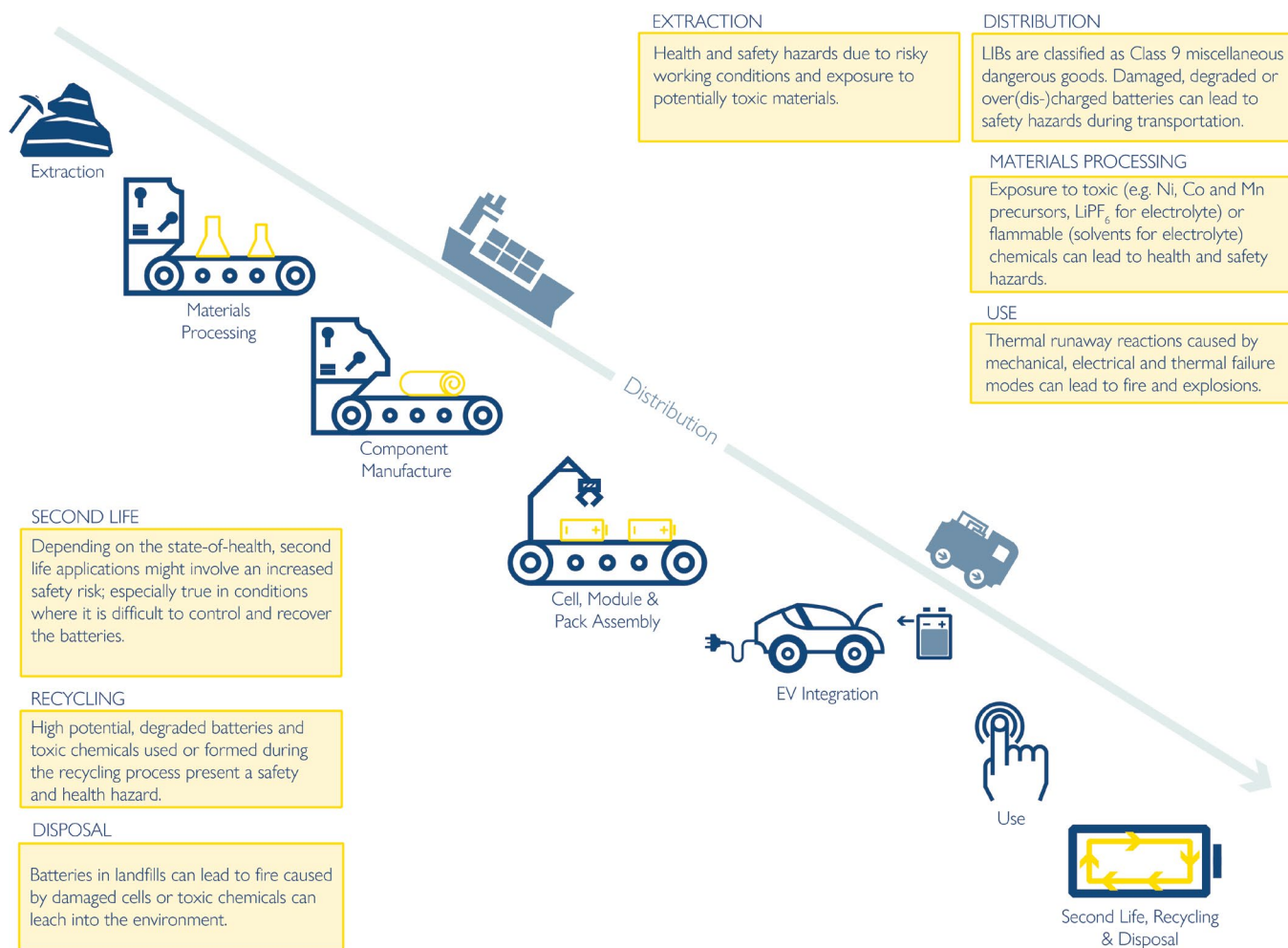


Figure 13. Safety hazards along the value chain of EV LIBs from raw materials extraction to end-of-life disposal.

rate decrease over time. However, the goal of zero harm has not yet been achieved and remains the standard that mining companies continue to strive towards.¹⁴¹ The main issues are: dust inhalation, noise and whole-body vibration, UV exposure, musculoskeletal damage, thermal stress and chemical hazards. Controlling these risks is very challenging where widespread illegal or artisanal mining activities take place, often ignoring occupational protection and safety control.¹⁴² In relation to cobalt extraction in the Democratic Republic of the Congo (DRC), hazardous cobalt(II) levels, which potentially can cause neurological, cardiovascular and endocrine health issues, have been detected in miners.^{141–143} Recent medical research has also linked mining-related pollution within the DRC to birth defects.¹⁴⁴ Therefore, a shift towards Ni-rich cathode materials might seem advantageous. However, nickel and manganese processing can also lead to hazard exposure that has severe health impacts. The dust produced throughout the refining process of nickel sulfides, impacts the respiratory system and might induce increased occurrences of lung and nasal cancer.¹⁴⁵ Similarly, repeated exposure to elevated manganese(II) levels during manganese mining and refining might induce brain damage and lead to neurological issues.¹⁴⁶

Safety hazards may also arise from synthesis of the electrolyte. Presently, LiPF_6 is used as a Li^+ salt in the electrolyte. For its preparation, hydrofluoric acid (HF) is used as a fluorinating agent.¹⁴⁷ HF is extremely toxic to the respiratory system and bone structure, causing severe

burns on contact with the skin. Moreover, the organic solvents used for the electrolyte, such as ethylene carbonate or propylene carbonate, are flammable and need to be handled with care.¹⁴⁸

It must be noted that these risks are controlled stringently where industry practices and local regulatory regimes are in effect for this purpose. In the case of Co mining, schemes including the *Responsible Cobalt Initiative*¹⁴⁹ and the *Cobalt Industry Responsible Assessment Framework*¹⁵⁰ have been developed to improve transparency, with the aim of removing illegal, artisanal Co from supply chains and thus limiting occupational health and safety risks.

Risks during distribution and storage

With a significant increase in EV utilisation, large quantities of batteries will need to be transported between the stages of their value chain, sometimes over long distances. Since April 2016, safety regulations¹⁵¹ forbid cells to be transported by passenger aircraft and, for other transport modes, require cells to be at no more than 30 % of their rated design capacity during distribution. However, the wide variety of battery chemistries, each having their own unique safety features, makes it difficult to define clear guidelines, so more research is needed in this area.¹⁵² The conditions under which cells are stored, such as temperature and State of Charge (SoC), can affect their durability and lead to hazards. Cells kept at either very high or very low SoC can degrade faster over time, so careful management of battery stores is required.

This is especially crucial for sensitive battery chemistries such as NMC811, which have a lower thermal stability and are more prone to chemical side reactions.^{37,153,154} In addition, at high charging levels, NMC811 shows significant volume changes, which can then lead to particle cracking, decreasing electrochemical performance.^{155,156} Storage and transportation conditions are especially important for the distribution and storage stages towards the end of the battery life cycle, when the battery is likely to be in a state of advanced degradation.

Fire risks during usage

In battery packs, which consist of many cells, safety issues related to LIB failure modes become increasingly complex and severe. Exceeding the window of parameters (temperature, potential difference and charging or discharging currents) within which LIBs can operate safely could have dramatic consequences, caused by thermal runaway.

Besides manufacturing defects, failure of cell internal components through electrochemical ageing, internal mechanical stress and undesirable side reactions, the most common failure modes of LIBs can be classified into mechanical, thermal and electrical. These can be external or internal; for example, external electrical failures include overcharge and over-discharge, and internal failures include short circuits within cells.^{135,155–157}

BOX 4.

Thermal runaway occurs when the heat generated by cell failure, abuse or misuse cannot be dissipated quickly enough.¹⁵⁸ This results in a significant release of heat, potentially initiating a range of associated hazardous effects (e.g. pressure build-up and gas release, emission of toxic materials, electrolyte leakage, fire or explosion).^{159,160} The cascade of thermal runaway events among cells in a module or pack is known as thermal propagation. The triggers for thermal runaway are: 1. manufacturing defects, 2. cell component failure, 3. mechanical abuse (crushing, piercing, tearing of the separator), 4. electrical abuse (overcharge/over-discharge) and 5. thermal abuse (high temperatures leading to exothermic reactions).^{152,157}

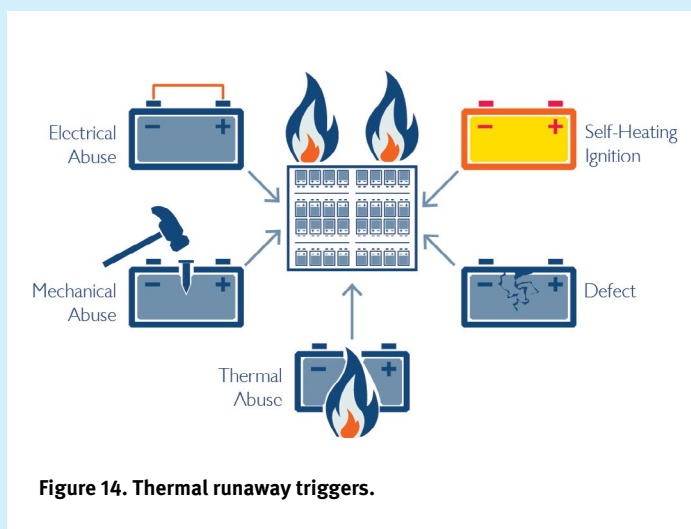


Figure 14. Thermal runaway triggers.

At present, no single approach has been identified to mitigate thermal runaway and thermal propagation risks. As a consequence, a wide range of different safety strategies are combined to achieve an adequate level of safety across all the protection layers (prevention, detection, compartmentation and suppression).^{152,160}

Prevention of critical thermal runaway events can be tackled at the material level, through the development of battery chemistries less susceptible to thermal effects; at the component level, through thermally stable structures; or at the cell and pack level, using designs that promote rapid heat dissipation.^{159–161} One approach is to use more stable cathode chemistries such as LFP, which has a higher thermal stability than LCO, LMO or NMC.^{137,157} The use of non-flammable electrolytes and solid electrolytes (solid state batteries) are encouraged, as they do not include a flammable liquid. Other strategies include the use of modified separators (with ceramic coating or particles), that raise the threshold temperature for thermal runaway, or incorporating shutdown separators that stop the flow of lithium ions once a threshold temperature has been reached. For cell, module and battery pack scales, thermal runaway and thermal propagation prevention is achieved by incorporating thermal fuses, temperature cut-off devices, positive temperature coefficient devices, current limiting fuses, current interrupt devices, vent disks or plugs. A BMS with a sufficient number of sensors installed can monitor potential difference and temperature of cells in the pack in real time and trigger an alarm if an abnormal signal is detected.^{137,157,162}

The next critical safety level is detection, with early detection of thermal runaway being crucial to avoiding thermal propagation. Detection methods can be classified into five categories: 1. Terminal voltage detection; 2. Identification of gases released from the battery during the thermal runaway process; 3. Internal battery temperature monitoring; 4. Current variation measurements to detect short circuits; and 5. Measurement of mechanical deformation using strain gauge sensors.^{163,164} A BMS is the most widely used device for failure detection in battery applications, combining methods 1 and 3. The BMS relies on built-in voltage and temperature sensors, to monitor the state of a battery.

Compartmentation is the next safety layer, aiming to avoid fire propagation by containing or delaying fire within a battery pack. Containment strategies focus on, firstly, hindering heat transfer paths to nearby cells (e.g. increasing space between cells,¹⁶⁵ allocation of thermal barriers,¹⁶⁵ flame retardant plates, incorporation of phase change materials to soak up excess heat)¹⁶⁶ and, secondly, improving cell heat rejection (e.g. venting,¹⁶⁷ implementing and optimising a thermal management system^{162,163} and designing cells with improved thermal conduction pathways).¹⁶⁸

Finally, if all previous protection layers fail, fire suppression must be achieved by smothering, cooling (e.g. by spraying ample water), chemical suppression (additives), or isolating the fire (via compartmentalisation strategies, such as thermal barriers).¹⁶⁷ As there is no universal approach to tackling LIB fires, the job of emergency responders is not straight forward. However, there is minimal literature on fire extinguishing approaches. Due to this lack of research, the arbitrary use of water remains a concern; it can be effective, but there could be better options. Therefore, further research is needed into all four areas of fire safety: prevention, detection, compartmentation and suppression.¹⁵²

Safety during second life

Cells in an advanced state of degradation pose an increased risk of thermal runaway incidents, so LIBs in second life applications can be hazardous during their refurbishment, distribution and usage. This can become problematic, especially for grid applications, where batteries might be exposed to extreme climates or used in uncontrolled conditions. Therefore, it is crucial to determine the battery State of Health (SoH) before second life applications, as well as on a regular basis during their use, to identify risks promptly. It is also critical to ensure that an extended producer responsibility is put in place, which requires battery manufacturers to trace and collect batteries and to ensure their appropriate disposal or recycling.

Safety during recycling processes

Battery recycling is an essential step towards decreasing LIB environmental impact over its entire lifetime. However, the high potential difference, complex materials and highly reactive components of LIBs pose various safety risks during the recycling process.¹⁶⁹ Considering that LIBs are classified as Class 9 miscellaneous dangerous goods, extra care needs to be taken during their handling. The safety hazards during LIB recycling can be categorised into electrical dangers (e.g. short circuits), chemical dangers (e.g. electrolyte evaporation) and fire and explosion risks.¹⁵²

The first critical phase is during battery extraction from the EV, where insufficiently trained service operators risk electrocution by high voltage batteries connected in series.^{28,170} Next, during LIB transportation, storage and disassembly, short circuits might occur, especially in damaged cells. Also, just simply crushing or shredding batteries during recycling can be dangerous, as the energetic cathode and anode are likely to touch and cause a short circuit or direct chemical reaction. These often then lead to temperature rise, gas formation, fire or explosion.¹⁵²

An essential measure to minimise safety hazards from the very beginning of the recycling process is the assessment of the battery SoH at its EoL. This will enable batteries to be classified according to their safety threat and define the precautions needed. In addition, pre-treatment procedures and mitigation strategies, such as battery deactivation, are deployed to further reduce the risk of harm.¹⁷⁰ These are especially important for the handling of damaged cells that have a significant deposit of metallic lithium on the anode, as they can react violently when exposed to oxygen and moisture, leading to hazardous gas formation and other threats.^{30,171}

Discharging cells before opening minimises their reactivity. Here, low currents should be applied to avoid cell over-heating and thermal runaway reactions. Discharge can also be conducted in salt solutions, which corrodes and thus deactivates the cell. Cells can also be frozen in liquid nitrogen, reducing their reactivity close to zero.^{115,170}

Opening cells within an inert atmosphere, such as nitrogen, argon and carbon dioxide, prevents the reaction of metallic lithium with oxygen.^{28,171} Generally, opening of cells should always be conducted in well ventilated areas, to avoid exposing service operators to the risk of inhalation of toxic fluorinated gases from the electrolyte, or carcinogenic particles from the electrode materials.¹⁷¹

While recycling of LIBs decreases their overall environmental footprint, the chemicals applied during the recycling process itself can still present hazards for worker health and the environment. For instance, chemicals such as nitric acid (HNO_3), sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2) and Cyanex 272 (Cytec / Solvay), used in the leaching and Ni^{II} -Coll solvent extraction separation steps of hydrometallurgical recycling processes, can cause skin burns, eye irritation or damage and fire or explosion, according to their material safety data sheets. They can be further harmful to the environment, especially to aquatic life in the case of H_2O_2 and Cyanex 272, or to plants and animals upon exposure to H_2SO_4 . On the other hand, citric acid, an alternative leaching agent, is less dangerous for human health, has a low aquatic toxicity and is readily biodegradable, so is a preferred though more expensive alternative.

Rigorous safety measurements, such as special training protocols for workers, electrical insulating tools and fire protection, can improve work safety significantly.¹⁷² Ultimately, the safest option remains the automation of the recycling process, but is still hampered by the different cell form factors (pouch, cylindrical, prismatic) and chemistries, all having different disassembly requirements and recycling procedures.²⁸ Therefore, detailed product labelling and a more standardised battery design would make the recycling process safer and more efficient.

Key findings

- Toxic chemicals used during raw material extraction, processing and recycling can lead to safety hazards for the environment.
- SoH assessments of EoL batteries are crucial to identify damaged cells and to decrease the likelihood of safety incidents during transportation, use phase, second life and recycling.
- Smart battery engineering solutions including efficient BMS can reduce the risk of safety hazards such as thermal runaway.
- Worker safety needs to be guaranteed through rigorous safety protocols and controls.
- Battery tracking and extended producer responsibility for battery disposal can prevent battery being sent to landfills and potential associated risks such as landfill fires and leakage of toxic chemicals.
- Detailed product labelling and a more standardised battery chemistry and design would simplify both emergency response and handling during recycling.

Future opportunities

Sustainable procurement, production and recycling

Meeting the increased demand for automotive LIBs will require the establishment of localised value chains in order to reduce reliance on imports and mitigate supply risks. Ensuring that LIBs are produced, used and recycled in a sustainable manner poses a significant challenge for governments worldwide. On the production side, the utilisation of renewable energy and the implementation of sustainable procurement principles remain a priority. Extending battery lifetimes through engineering solutions can also reduce their environmental footprint and cost, and increase the feasibility of second life applications. However, reuse presents a trade-off with the benefits of recovering valuable battery materials that can re-enter the supply for automotive batteries sooner.¹⁵ Battery recycling comes with a series of economic and environmental benefits and can ensure the domestic availability of valuable and strategic materials.

In Europe, establishing a regional battery supply chain is imperative for a clean energy transition and globally competitive industry. Battery production capacity is expected to grow 20-fold, reaching 95 GW h per annum by 2025, with a number of domestic battery gigafactories having been announced.¹⁷³ Feeding those gigafactories with regionally produced materials will require ramping up Li^I, Ni^{II} and Co^{II} compound refining capacity in Europe. The mined raw materials mostly will still need to be imported, as significant deposits exist mostly outside Europe. Presently cathode precursor materials are produced in Asia, but this could be developed in Europe or be integrated vertically in gigafactories. An alternative source of battery materials may arise from upscaled battery recycling operations, but there is limited availability of retired batteries at present, with experts expecting battery recycling to start providing significant amounts of raw materials only after 2030. On the downstream, passenger car production in Europe is a strong industry, adjusting to the electric vehicle era by transforming ICEV production facilities. Overall, establishing a European battery supply chain would bring significant economic and environmental benefits. However, as the battery industry engages in a race to reduce costs, European-produced batteries may come with high safety standards, sustainability requirements and labour costs, presenting a challenge or opportunity when competing with Asian rivals, depending on one's perspective.

Low impact manufacturing processes

Depending on the battery material, LIB manufacturing can require large specific amounts of energy. For instance, NMC compounds are prepared at temperatures around 800 °C and higher, sustained for several hours. Therefore, manufacturing processes should be chosen that fall under the definition of green chemistry, i.e. processes that reduce or avoid health and environmental impacts.¹⁷⁴ Low-energy manufacturing processes which avoid toxic or environmentally damaging chemicals, would significantly reduce the impacts. Various strategies are being explored, including solvothermal and hydrothermal processes, which use organic and aqueous solvents and can decrease reaction temperatures significantly.^{16,175}

Alternative electrolytes

Solid electrolytes, such as $\text{Li}_{1.3}\text{Al}_{0.3}\text{Ti}_{1.7}(\text{PO}_4)_3$ (LATP), improve battery safety along the value chain and have attracted great attention as an alternative to the flammable organic electrolytes in conventional LIBs.¹⁷⁶ However, these new chemistry candidates are still in the research and development phase and are not yet fully commercialised. Challenges include lower ionic conductivities, which decreases power densities, chemical instabilities and more difficult cell processing and manufacturing.

Another strategy towards safer and more sustainable electrolytes is to replace the present organic electrolytes with aqueous alternatives, consisting of a lithium salt (e.g. nitrate or sulfate) dissolved in water. Aqueous electrolytes not only eliminate the risk of flammable organic solvents, but also significantly reduce manufacturing costs, so are rivals to solid electrolytes. However, the electrode potential window of water stability (1.23 V) ultimately limits the open circuit potential difference and hence achievable energy densities in aqueous LIBs, though kinetic stabilisation of negative and positive electrode materials such as $\text{Li}_4\text{Ti}_5\text{O}_{12}$ and LiMn_2O_4 , respectively, can extend that potential difference.^{176–178}

Alternative electrode materials

The rapidly growing production of LIBs necessitates the use of more sustainable, abundant and low-cost materials. This holds true for both cathode and anode materials, but also for the other cell components. Graphite anodes are prepared mostly from petroleum coke or coal-tar pitch at high temperatures, making this a less than environmentally benign process.¹⁷⁹ Therefore, increasing interest is being paid to the use of biomass as graphite precursors. Intensive efforts are invested in the research for appropriate materials and preparation methods to obtain natural graphite that can compete with artificial graphite, in terms of electrochemical performance.^{171,172,179–182} Alongside artificial graphite replacement options, research and industrial developments (Amprius, Enevate, Enovix, Nexeon, BASF Shanshan, Shenzhen, Sila, Zenlabs) of Si anodes, with charge capacities of e.g. $\text{Li}_{15}\text{Si}_4$ approaching an order of magnitude greater than its graphite counterpart (LiC_6), are reported to be on the verge of large-scale commercial implementation.¹⁸³

Cathode processing incurs detrimental impacts that potentially could be avoided. Currently, polyvinylidene difluoride (PVDF) is used as a cathode binder, usually requiring toxic NMP as a continuous liquid phase. Replacing PVDF with carboxymethyl cellulose- or guar gum-based binders would allow for cathode processing using water as the solvent.^{184–186} This would reduce processing costs, improve the environmental footprint by removing fluorine-containing and toxic solvents, and facilitate recycling processes, as such materials are more easily and safely dissolved for disassembly.^{187,188}

The addition of self-healing materials indirectly can decrease the life cycle environmental impact further, by extending the battery lifetime.^{189,190} Repetitive cycling can cause the formation of fractures in the electrode materials or loss of electrical contact between particles, leading to accelerated capacity fade. Si anodes suffer from significant volume changes and microfractures, but coating them with a stretchable polymer, for instance, can heal these microfractures and extend the cycling life.^{191,192} Also liquid metal anodes have been proposed, which, due to their fluid nature, are able to self-repair mechanical damage.¹⁹³ A solution for macroscopic fractures (e.g. breaking of the battery) occurring through external forces potentially can be self-repaired by coating the electrode materials on self-healing polymer layers.¹⁹⁴

Replacing LIB chemistries with equivalent sodium-ion batteries (NIBs) can avoid the supply chain issues with lithium compound availability and open up pathways towards GHG emission reduction, as has been shown by LCA studies.¹⁹⁵ Na is more abundant than Li and can be extracted readily from sea water, for instance, making the raw material extraction a more sustainable and cost-effective step. Moreover, in contrast to LIBs, NIBs do not require a copper current collector at the anode, but can use cheaper Al, avoiding the need for copper mining and significantly decreasing cost.¹⁹⁵ The Na-salts used for the liquid electrolyte are less toxic than their Li-counterparts, improving the lifetime safety of NIBs, when compared with LIBs.¹⁶

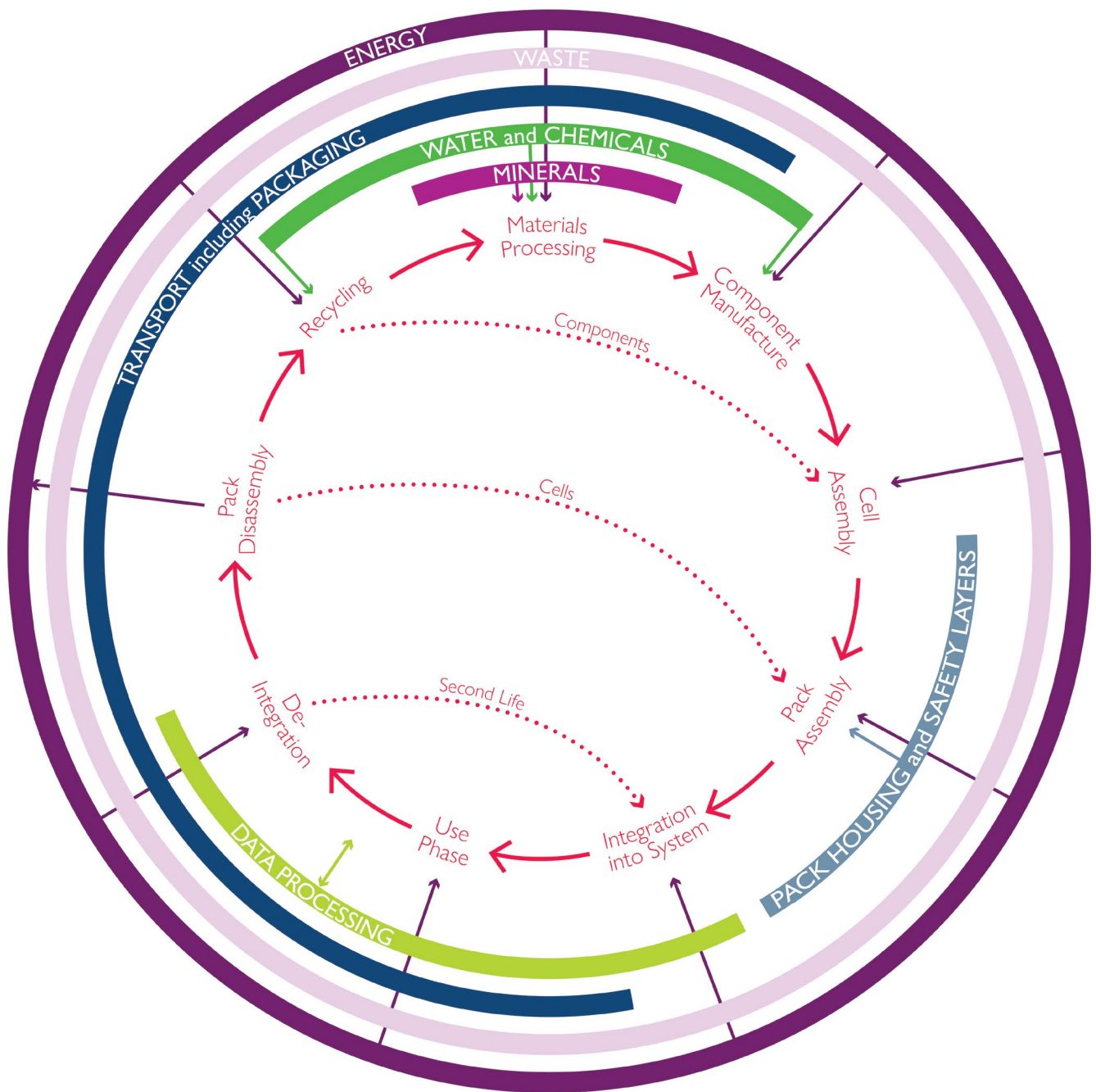


Figure 15. The battery life cycle, showing major input and outputs for each step.

Redesigning cells and packs

Battery engineering and design can have significant impacts on battery safety, performance and lifetime, thereby reducing the environmental impact. Increasing the battery lifetime by integrating sophisticated BMS and sensors to monitor potential difference, temperature, SoC and SoH. They can further balance the operation of the battery pack by controlling the charge load of each cell, so extending the use phase and lowering the overall CF. More advanced BMS programs deploy digital twinning, in which a virtual pack is modelled based on real-time physical data from the embedded sensors and its expected future behaviour and performance parameters extrapolated. This allows the BMS to determine if any cells are in danger of failing and mitigate this in advance. Moreover, non-invasive *in operando* sensors, able to detect the SoH and SoC of the battery with high accuracy, would enable the BMS to control the battery pack cycling more efficiently.¹⁹⁶ To this end, amongst others, ultrasound, acousto-ultrasonic waves and fibre optics have been proposed recently as diagnostic methods.^{196–199}

Cell and pack designs need to be revised to enable an efficient recycling process.³⁰ Using readily recyclable materials, reducing the variety of materials, labelling cells thoroughly and assembling the cells into packs in a way that can be easily disassembled, are some of the ways that potentially can increase the recovery and reuse of materials.²⁰⁰

Methods for tracking progress

Ensuring that batteries are produced sustainably requires analysis and measures for tracking their environmental footprint, from a whole life cycle perspective. At the point a battery leaves the factory, it should have a passport (such as the one proposed by the Global Battery Alliance),²⁰¹ including the CF associated with its manufacturing and technological information, such as the chemistry of its cells. The former is crucial in implementing incentives and regulations that favour low-carbon batteries on the market and the latter provides important information for recyclers and repurposers.¹⁵ During the utilisation phase, the emissions profile of the EV can be evaluated based on the carbon intensity of the electrical energy used to charge it. Additionally, monitoring the cycling conditions of the battery is crucial to estimating its remaining useful life, which provides valuable information on whether to recycle or reuse it after its first life. Such traceability mechanisms can ensure that automotive LIBs are produced and consumed sustainably.

Conclusions

Meeting climate goals in the transport sector requires ramping up lithium-ion battery production rates by an order of magnitude to achieve increased market penetration of electric vehicles as soon as possible. However, increasing LIB production rates will result in increasing demands for raw materials and energy. To replace one set of environmental problems with another is not acceptable, so in the transition from fossil fuels to electrification, it is extremely important to establish a safe and sustainable battery value chain. That chain is distributed globally and includes more than fifty individual raw materials and a wide range of battery chemistries. Therefore, upscaling production in a cost-effective, safe and sustainable way presents challenges. Transparent and reliable environmental impact assessments and safety analyses are required to ensure, for example, that lithium carbonate from Latin America, cobalt from the Democratic Republic of Congo, nickel from Russia and other components are combined in a battery gigafactory anywhere in the world to produce a battery meeting certain safety and sustainability standards. From a technological standpoint, the industry predominantly is decreasing cobalt by increasing the nickel content of the cathode and blending Si with graphite anodes. This trend is associated with cost and performance improvements and is expected to contribute towards the increased market adoption of electric vehicles. However, sometimes these modifications can result in shorter lifetimes.

The fastest way to have the most impact in improving how batteries are produced, used and recycled sustainably involves identifying the steps in the lithium-ion battery value chain that are most detrimental for the environment. Life cycle assessment is the most powerful tool for identifying these steps and justifying decision-making. The increased amount of materials and energy required for battery production is associated with detrimental environmental impacts. Energy-intensive aluminium production, cathode production and cell assembly are currently the dominant contributors towards the carbon footprint of battery packs. Additionally, mining and processing of battery materials are associated with a series of negative impacts on ecosystem quality. When a lithium-ion battery is used in an electric vehicle, the energy source used to charge it and its intrinsic performance indicators (lifetime, efficiency) also strongly influence its environmental impact. Recycling spent battery packs can divert them from landfills, but recycling introduces an additional environmental burden to the lithium-ion battery value chain, though this can be environmentally beneficial if it displaces the use of primary materials.

Decision makers and other stakeholders can take several steps towards reducing the environmental impact of the lithium-ion battery value chain. Supplying battery production, use and recycling with renewable energy reduces the carbon footprint. Moreover, the implementation of sustainable procurement principles can ensure the sourcing of battery materials with reduced environmental footprints. This requires the establishment of traceability and audit mechanisms, which also can provide essential information for end-of-life management that can contribute to the establishment of a viable circular battery economy. Technological improvements can lead to more energy-dense, longer-lasting and more efficient lithium ion batteries, which, together with economies of scale, can ensure significantly net positive environmental benefits of lithium ion batteries. Combined action towards the establishment of a sustainable battery value chain can contribute to minimising the life-cycle environmental footprint of lithium-ion batteries within the next decade.

Battery safety also needs to be considered, specifically safety for workers, users and the environment. Each step in the value chain bears safety risks either from the use of harmful chemicals during materials mining, processing and recycling, unsafe working conditions or through the inherent battery features such as high potential differences and volatile and flammable chemicals.

Good practices of the mining industry would target not only the environmental footprint but could also create a safe working environment. Continuous battery research and improved engineering are crucial to reduce the severity and likelihood of safety incidents. The use of non-toxic materials, safety engineering using thermally stable battery components, and the replacement of liquid organic electrolytes by solid-state electrolytes are promising routes towards enhanced battery safety. The latter also reduces the risk of environmental pollution as toxic emissions from the liquid electrolyte production and disposal are avoided. Accurate and regular assessment of the battery state-of-health using sophisticated battery management systems can also help reduce the number of safety incidents caused by degraded or damaged cells during battery usage, as well as transportation, second life and recycling.

Increased battery safety often goes hand in hand with reduced environmental impact, especially with regards to toxic products used during chemical processing or in the battery itself that are hazardous for human health and the environment alike. Combining both aspects and achieving a high level of battery safety, while at the same time reducing the life cycle environmental footprint along the value chain will create a battery system that responds to the societal, environmental and technological requirements for the present urgent energy transition.

Glossary

Anode: An electronic conductor (metal or semiconductor) at which oxidation of an electron donor occurs, i.e., a reduced state R (e.g. Li) injects electrons and / or ions across an anode|electrolyte interface and becomes an oxidised state O (e.g. Li⁺).

Battery Management System (BMS): An electronic system that manages a rechargeable battery cell or pack by protecting the battery from operating outside its safe operating temperature, monitoring its state, calculating secondary data, reporting data, controlling its environment, authenticating it and / or balancing it²⁰².

Bauxite: Ore comprising aluminium oxide compounds (alumina), silica, iron oxides and titanium dioxide.

Brine and salar brine: naturally occurring highly concentrated aqueous salt solutions.

Calcination: Thermal treatment at high temperatures.

Calendering: A process of compaction using a series of hard pressure rollers to finish or smooth a sheet of material such as paper, textiles or plastics. Electrodes are calendered before they can be used.

Calendar life: Time until a battery reaches its end-of-life criterion, in storage without being used.

Calendrical ageing: Degradation processes occurring during the storage of a LIB without it being used.

Capacity: The maximum charge (A h, mA h or C) stored in a battery, depending on battery size (amount of active material) and its chemistry.

Carbonisation: Transformation of organic matter such as plants into carbon through heat.

Cathode: an electronic conductor (metal or semiconductor) at which reduction occurs of an electron acceptor, i.e., an oxidised state O (e.g. Li_{1-x}CoO₂) becomes a reduced state R (e.g. LiCoO₂) by electrons and / or ions (e.g. Li⁺) being injected across a cathode|electrolyte interface.

Charge: Integral of current with time (C).

Charge (verb): To inject electrons from an external power supply.

Circular economy principles: Reduce, Reuse, Recycle. The goal of the circular economy is to use materials for as long as possible and reduce waste.

Co-precipitation: Simultaneous precipitation of more than one species from a solution.

Crediting: Recycling of a material at the end of a product's useful service life is rewarded by assigning a credit of primary material that corresponds to the recovered mass of secondary material.

Current: Rate of flow of electrons or ionic species (A or C s⁻¹).

Cycle life: Number of charge/discharge cycles a battery can perform before reaching its average end of life criterion. This depends on both the battery chemistry and cycling conditions such as depth of discharge, cycling rate and temperature.

Discharge rate: at which a battery is (dis-) charged; 1 C means that a battery charge (Q) is (dis-)charged completely in 1 h.

Dendrites: Tree-like structures of metallic lithium that can form by electrodeposition on the negative electrode during charging and which can cause short circuits if they penetrate through the separator and reach the positive electrode.

Depth of discharge (DoD): The percentage of capacity (Q) that is discharged from the fully charged battery. It is the complementary value to the State of Charge.

Direct recycling: A process aiming at the reuse of battery components through removing and refurbishing materials without changing their chemical form.

Discharge (verb): To convert chemical to electrical energy by drawing current / energy from a battery.

Ecotoxicity: Toxic impacts on ecosystems.

Eddy current separation: a process, based on differences in electrical conductivities, to separate non-ferrous metals from waste using a powerful magnetic field.

Electrolysis: A process for converting electrical to chemical energy, by passing a current between anode(s) and cathode(s), in an otherwise anti-spontaneous reaction.

Electrolyte: Battery or fuel cell component; liquid, polymer or ceramic conductor of current by the transport of ions rather than electrons, which it should not conduct, as it would then short circuit a battery or fuel cell.

(Electrical) Energy of a battery or fuel cell (W h or J).

Energy density: The output energy of a battery or fuel cell divided by its volume (W h dm⁻³).

End-of-Life (EoL): The state at which the battery is deemed unusable for a certain application. For EVs, EoL is commonly set to 80 % of the initial capacity.

Eutrophication: Overly enriching a body of water with minerals and nutrients, inducing excessive algal growth and leading to depletion of oxygen in the water, depletion of fish species and a general deterioration of water quality.

Exothermic: A chemical reaction that releases energy into the surroundings.

Four-effect evaporator: An apparatus for efficiently using heat from steam to evaporate water.

Froth flotation separation: A process for selectively separating hydrophobic from hydrophilic particulate materials.

Global warming potential (GWP): The amount of heat absorbed by a greenhouse gas in relation to the heat absorbed by the same mass of CO₂. The GWP of CO₂ is 1.

Graphitisation: The structural transformation from disordered carbon to ordered graphite through high-temperature heat treatment.

Hall–Héroult process: Electrolytic process to produce aluminium from alumina (aluminium oxide) dissolved in a molten salt electrolyte; alumina is produced from bauxite by the Bayer process.

Hydrometallurgy: Recovery of metals from mineral concentrates / ores using aqueous solutions.

Hydrothermal: Reactions performed in aqueous solutions at high temperature / pressure. Specific case of solvothermal reactions.

Intercalation: The process whereby lithium ions insert into layered electrode materials such as graphite or LiCoO₂.

Lithium: An alkali metal that has a standard electrode potential of 3.045 V vs. standard hydrogen electrode (SHE) and oxidises to Li⁺.

Lithium-ion (Li-ion): Cation (positively charged ion) of elemental lithium, obtained by oxidation.

Life Cycle Assessment (LCA): A method to assess the environmental impact of a product or a process throughout its life cycle stages including raw material extraction, manufacturing, usage, recycling and disposal.

Magnetic separation: The process of separating components of mixtures by using magnets to attract magnetic materials.

Ore: A natural material that contains one or more valuable minerals that can be extracted from the earth through mining and treated or refined to extract valuable metals or minerals.

Overcharge: When a battery cell reaches too high a potential difference; e.g. excessive lithium ions are extracted from the positive electrode leading to its decomposition, e.g.: $\text{LiCoO}_2 \longrightarrow \text{CoO}_2 + \text{Li}^+ + \text{e}^-$.

Over-discharge: When a battery cell reaches too low a potential difference; e.g. an excessive lithium ions are inserted in cathodes (over-lithiation), leading to their degradation, e.g.: $\text{LiCoO}_2 + \text{Li}^+ + \text{e}^- \longrightarrow \text{Li}_2\text{O} + \text{CoO}$.

Oxidation: The loss of electrons during an electrochemical reaction of molecules, anions or cations, the oxidation states of which increases.

Phase change material: Materials that absorb or release energy during a phase transition and thus provide cooling or heating of the environment.

Potential Difference (V): Energy required to move an electric charge between two ends of a current path, divided by the magnitude of the charge, i.e., energy per unit charge (c.f. voltage, which refers to the unit).

Power: The differential of energy (J or W h) with respect to time (s); the product of current (A) and potential difference (V) (units: W).

(Volumetric) Power density: The output power of a battery or fuel cell divided by its volume (units: W dm^{-3}).

Pyrometallurgy: Processes using a combination of thermal, electrical and chemical energy to produce metals from mineral concentrates.

Recovery: Amount of successfully extracted metal as a percentage of the actual metal content in the ore.

Reduction: The gain of electrons during an electrochemical reaction of molecules, anions or cations, the oxidation state of which decreases.

Slurrify: To combine and mix a solid substance with a liquid substance into a slurry, wherein the solids, usually of a lesser amount, are suspended in the liquid of greater quantity.

Smelting: Extraction of a metal from mineral concentrates by heating and melting.

Solid electrolyte interphase (SEI): The passivation layer on the anode, which is formed through electrode-electrolyte interaction in the first few cycles and which prevents further decomposition of the electrolyte.

Solvent extraction: Separating compounds based on their relative solubility in organic and aqueous solvents.

(Mass) Specific energy: Output energy of battery or fuel cell, divided by its mass (W h kg^{-1}).

(Mass) Specific power: Output power of battery or fuel cell, divided by its mass (W kg^{-1}).

Slag: Molten oxide, which solidifies on cooling, comprising stony waste matter separated from metals during the smelting or refining of ore.

Solvothermal: Reactions performed on high-temperature solutions such as water or organic solvents.

State of Charge (SoC): Level of charge relative to its full capacity. 100 % SoC means fully charged, 0 % SoC refers to fully discharged.

State of Health (SoH): Describes the condition of a battery compared to its ideal condition (usually after manufacturing).

Tailings: The finely ground residue from ore extraction created as part of mining, smelting, refining, and water treatment processes.

Temperature coefficient: This quantifies the change of resistance as a function of temperature. A positive temperature coefficient means that the resistance increases as the temperature increases; a negative temperature coefficient indicates a decrease in resistance with increasing temperature.

Thermal management system: Controls the temperature of the battery through cooling or heating to maintain it inside safety limits and to increase the lifetime of the battery.

Thermal runaway: Current flow in batteries may lead to temperature rises, increasing ionic conductivities and self-reinforcing current flows, with potentially catastrophic effects.

Vertical integration: Taking two or more processes that are usually performed in different facilities and performing them in a single plant.

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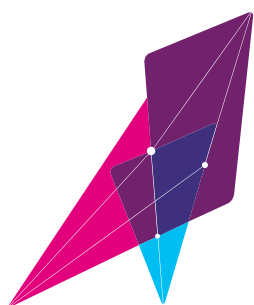
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