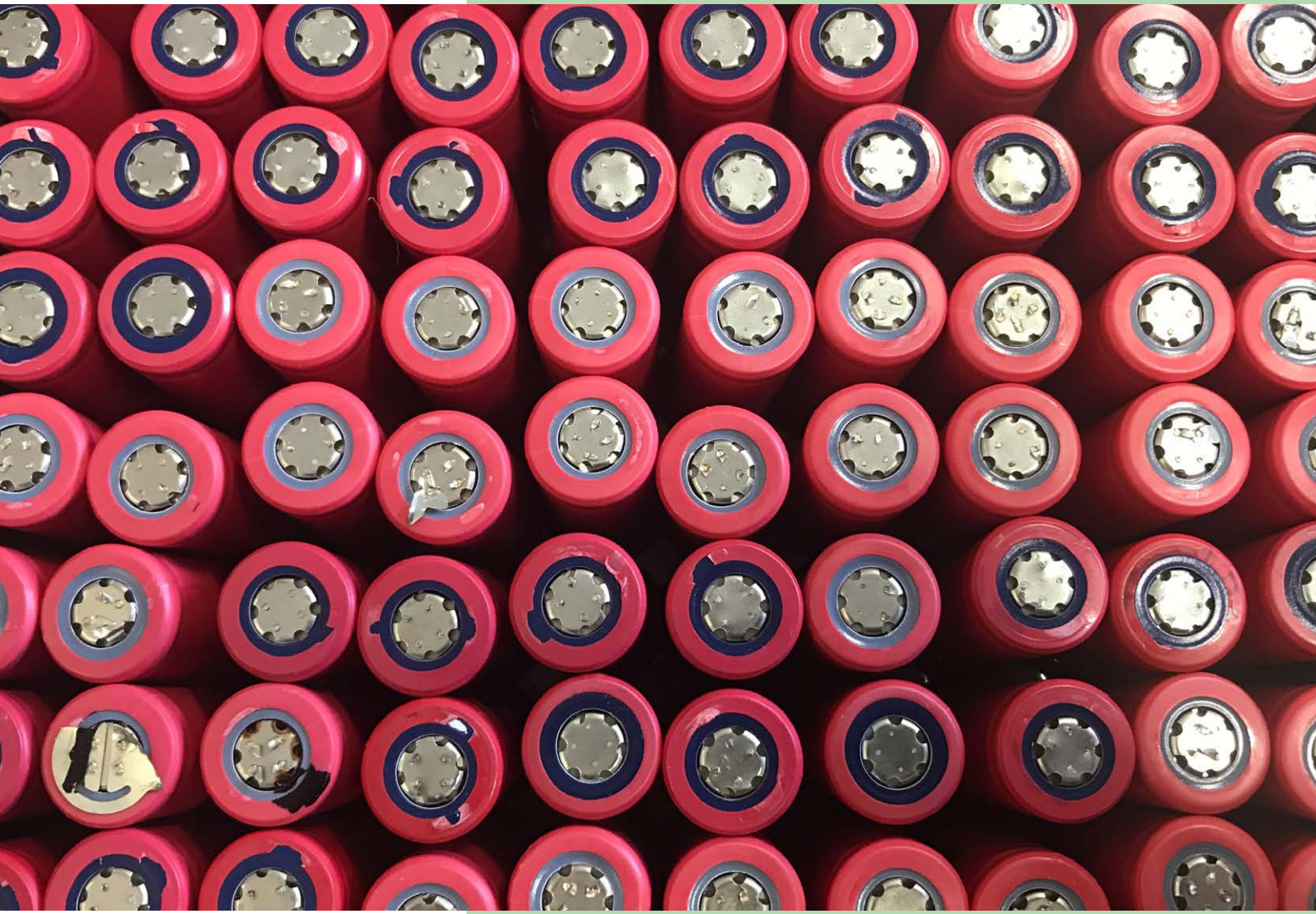
SRI SUSTAINABLE RECYCLING INDUSTRIES

# Management of End-of-life Lithium-Ion Batteries



## A PRACTICAL HANDBOOK

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## Acronyms

| | |
|---|---|
| **EEE** | Electrical and Electronic Equipment |
| **WEEE** | Waste electrical and electronic equipment |
| **PCBs** | Polychlorinated biphenyls |
| **LIB** | Lithium-ion battery |
| **EoL** | End of Life |
| **NiCd** | Nickel-cadmium |
| **NiMH** | Nickel-metal hydride |
| **NMC** | Lithium Nickel Manganese Cobalt Oxide |
| **LFP** | Lithium Iron Phosphate |
| **NCA** | Lithium Nickel Cobalt Aluminium Oxide |
| **LTO** | Lithium Titanate |
| **LCO** | Lithium Cobalt Oxide |
| **LMO** | Lithium Manganese Oxide |
| **CE** | Conformité Européenne |
| **UL** | Underwriters Laboratories |
| **RoHS** | Restriction of Hazardous Substances |
| **IEC** | International Electrotechnical Commission |
| **HF** | Hydrogen fluoride |
| **PF5** | Phosphorus pentafluoride |
| **EN** | European Norm |
| **IATA** | International Air Transport Association |
| **DGR** | Dangerous Good Regulation |
| **IMDG** | International Maritime Dangerous Goods |
| **ADR** | European Agreement Concerning the International Carriage of Dangerous Goods by Road |
| **CLP** | Classification, Labelling, and Packaging |
| **SP** | Special Provision |
| **OCV** | Open circuit voltage |
| **SoH** | State of Health |
| **SoR** | State of Resistance |

## Glossary of terms and technical definitions

**Terms related to business models and design and development according to the ISO/DIS 59004 [1]:**

| | |
|---|---|
| **Repair** | Action to restore a product to a condition needed for the product to function according to its original purpose. |
| **Reuse** | Use of a product after its initial use, for the same purpose for which it was originally designed. |
| **Refurbish** | Restore an item, during its expected service life, to a useful condition for the same purpose with at least similar quality and performance characteristics. |
| **Remanufacture** | Return an item to its original condition from both a quality and performance perspective using industrial process. |
| **Repurpose** | Adapt a product, or its component parts for use in a different function than it was or intended for without making major modifications to its physical or chemical structure. |
| **Recycling** | Activities to recover resources to use in a new process or product, excluding energy recovery. |

. . . . . .

**Technical terms associated with battery performance:**

| | |
|---|---|
| **Capacity** | **...** of a battery describes the amount of energy that can be obtained in a single discharge. It is expressed as Ampere hour (Ah) for large batteries and in milli-Ampere hour for small batteries (mAh). Usually, the label value of the battery is referred to as the rated capacity. |
| **Nominal voltage** | **...** of a battery is the average operating voltage of a device. It lies in between the maximum voltage that could be reached during charging and minimum voltage during the complete discharge of the battery. |
| **Cycle Life** | **...** of the battery refers to the number of charge and discharge cycles a battery can provide. |
| **Resistance** | **...** is the opposition that a material or component offers to the flow of electric current. It is measured in ohms (Ω). The higher the resistance, the harder it is for current to pass though. |
| **State of Charge (SoC)** | **...** refers to the amount of energy remaining in a battery relative to its maximum level of capacity. It is typically expressed as a percentage, where 0% indicates the battery is completely discharged, and 100% indicates it is fully charged. |
| **State of Health (SoH)** | **...** describes the condition of a battery compared to its original, brand-new state. It is commonly defined as the ratio between the actual maximum discharge capacity (at given time) and the rated (nominal) capacity of the battery. A lower SoH indicates a reduction in usable capacity, meaning the battery will deliver less energy before needing to be recharged when comparing under the same operating conditions. |
| **State of Resistance (RoR)** | **...** refers to the condition or level of electrical resistance at a given time. |

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# 1 Introduction

## 1.1 Background

When people discard their used Electrical and Electronic Equipment (EEE), different materials become available for reuse, refurbish, repurpose or recycling. Companies responsible for treating waste electrical and electronic equipment (WEEE) process this material and provide the sorted outputs to refining, manufacturing industries or recovery facilities to produce secondary raw materials. Certain components in WEEE contains hazardous compounds, such as toxic poly-chlorinated biphenyls (PCBs) in capacitors, mercury-containing backlighting in LCD monitors, and several chemicals in batteries from cell phones, laptops, and other appliances (Figure 1). These components must be removed prior to further treatment to avoid environmental pollution or risks to human health.

Batteries in particular present a unique challenge: in addition to containing hazardous substances, some compounds pose a significant fire risk, such as the organic solvents used as electrolytes. On the other hand, many batteries, especially in the case of lithium-ion batteries (LIBs), contain valuable metals and materials, such as cobalt, nickel or graphite, which are of high economic value and are considered critical raw materials. This dual nature necessitates their careful and responsible management of these devices at the end of its service life (EoL).

The objective of this handbook is to provide comprehensive information on the fundamentals of batteries, their safe and responsible management and economic considerations associated with their EoL processing.

## 1.2 Handbook aim

Users of this handbook are encouraged to implement, adapt and further develop the methods and processes discussed throughout the document based on their own requirements. While utmost care has been taken to collect precise and up to date information, users should be aware that the conditions and the market of batteries is changing quickly and that the methods described should only be performed while using adequate safety equipment and processes. The authors, organizations and persons affiliated to this handbook and the sponsoring organization cannot be held liable for any losses and damages in connection with the use of the information contained in this document.

***Figure 1:*** *Waste Electrical and Electronic Equipment containing batteries*

# 2 Lithium-Ion Batteries (LIBs)

## 2.1 Fundamentals of the battery

Batteries are electrochemical energy storage devices that provide power to electronic equipment such as cell phones, laptops, and hearing aids. Some WEEE batteries are classified as portable batteries under EU and UK regulations[2]. These are small, sealed batteries used in consumer electronics e.g., smartphones, laptops, power tools, e-scooters. Batteries are typically classified into two main types: primary and secondary batteries (Figure 2). Primary batteries are non-rechargeable, designed for single use, and then disposed of, such as alkaline batteries. Secondary batteries, on the other hand, are rechargeable and have a longer lifespan. Examples of secondary battery types include lead-acid, nickel-cadmium (NiCd), nickel-metal hydride (NiMH), and LIBs. The type of battery used in electronic devices depends on the specific application. For instance, hearing aids commonly use primary cells, while laptops are equipped with rechargeable batteries.

Since their invention in the 1800s, the adoption of batteries has expanded widely in parallel with a growing electrification. However, despite their long history, EoL treatment of batteries remains a relatively novel concept. WEEE and battery recyclers continue to face challenges in this area. For instance, WEEE recyclers struggle to extract batteries from electronic devices, while battery recyclers must face the challenge of the rapid technical evolution of battery types and chemistries. This ongoing innovation complicates efficient management and value recovery. A deeper understanding of battery fundamentals and proper management practices can help WEEE and battery recyclers address these challenges more effectively. This knowledge enables them to seize emerging opportunities and potentially expand their market presence.

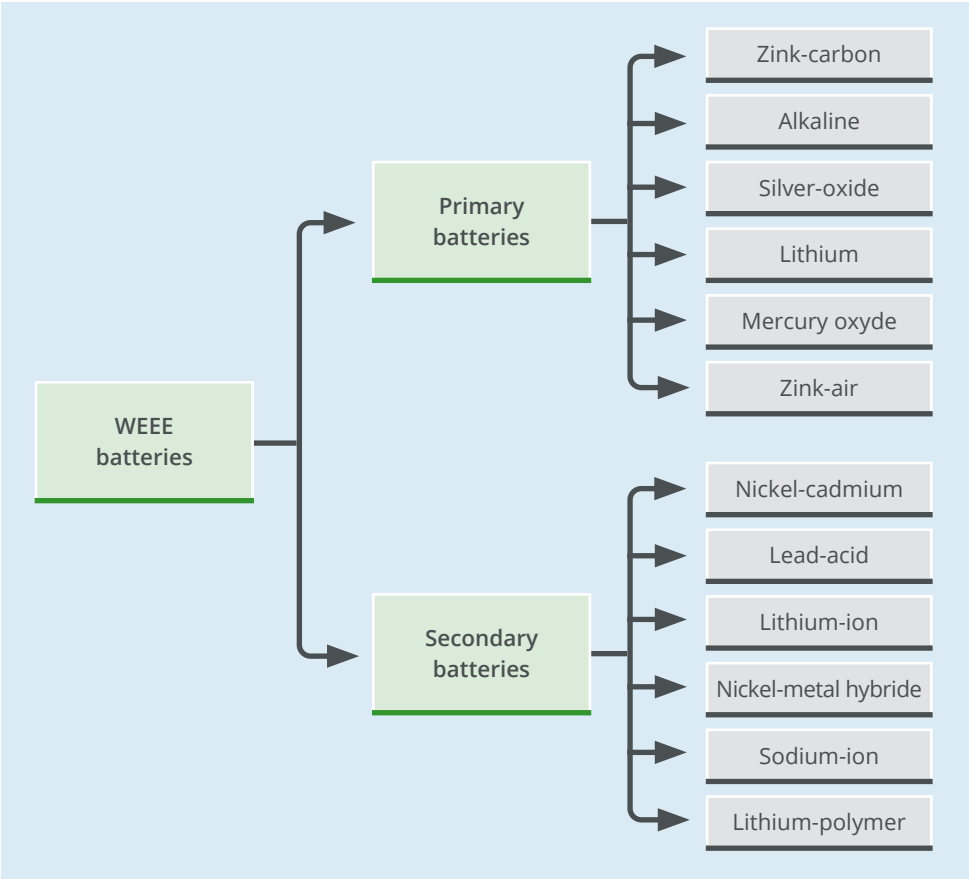
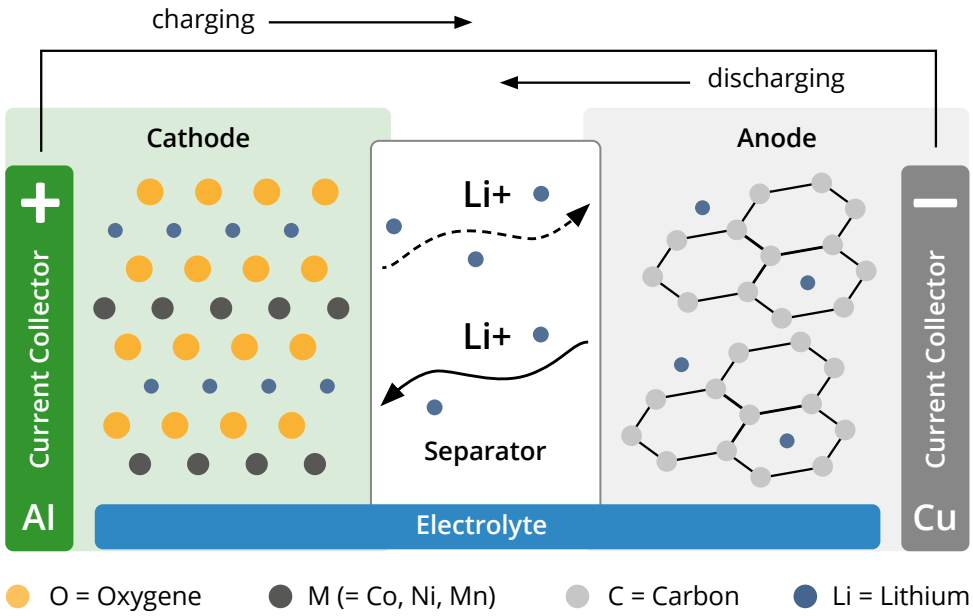



*Figure 2: Classification of WEEE batteries*

## 2.2 Lithium-ion batteries composition and classification

LIBs are the most widely used type of battery in modern EEE products. LIBs are rechargeable energy storage devices that use lithium ions as the primary carrier of electric charge. In LIBs, the process of charging involves the movement of lithium ions from the positive electrode to the negative electrode through the electrolyte, while electrical current flows move in the opposite direction. This results in the conversion of electrical energy to chemical energy, forming an electrolytic cell. Conversely, during discharging, the reverse reaction occurs, with lithium ions moving from the negative to the positive electrode, thereby generating electrical energy. Figure 3 indicates the working principle of LIB while discharging and charging respectively.

*Figure 3: Working principle of lithium-ion batteries*




They have a wide range of applications across various fields:

- **Consumer electronics:** smartphones and tables, wearables, computer and notebooks.
- **Mobility applications:** passenger cars, commercial vehicles, railway, aviation, maritime applications, industrial vehicles, construction vehicles, light electric vehicles (EV), e-bikes, defense.
- **Stationary energy storage:** off-grid systems, home storage, industrial storage, charging buffer, grid booster, grid balancing.
- **Industrial and services:** power tools, medical devices and microelectronics.

*Figure 4: Example of EV battery configuration, from cell to module and then pack to finally system. A battery manage-ment system is built up around the pack to moni-tor and regulate the conditions.*

In battery systems, the basic structural component is the battery cell. Individual cells are then grouped into modules to increase capacity and voltage. These modules are then assembled into packs to support larger scale applications. This hierarchical configuration enables both scalability and adaptability to the specific demands of the mentioned application types (Figure 4).

LIB cells are present in various formats which are usually divided in three groups: cylindrical cells, pouch cells, and prismatic cells (Figure 5). The cylindrical are the most common for many applications due to their versatility of including both high and low-capacity cells. Numerous cylindrical cell types are available in the market, including often found model types 14500, 14650, 18500, 18650, 21700, 26650, 32650. These designations follow the naming convention defined by the International Electrotechnical Commission (IEC) 61960-3 standard. These numbers correspond to battery cell dimensions, such as the 18650 model, which measures 18 mm (0.71 inches) in diameter and 65 mm (2.36 inches) in length. Among the different types, the 18650 variant is the most used cylindric LIB.

Pouch cells are known for their adaptability in conforming to the specific shape of the device, making them dominant in the majority of the markets from smartphones and tablets to electric vehicles [4], [5]. Furthermore, prismatic cells can have large capacities and therefore they are typically used in EV and for stationary systems.

***Figure 5:*** *Classification of lithium-ion battery formats*

Cylindrical lithium cells | Pouch lithium cells | Prismatic lithium cells

A typical battery consists of a positive electrode (normally cathode), a negative electrode (normally the anode), a separator, and an electrolyte, all encased within a protective casing. The composition of these components varies based on the battery type. In LIBs, lithium oxides materials are coated onto aluminum sheets to form the positive electrode, while the negative electrode consists of a copper sheet coated with graphite or silica. These electrodes are separated by a polymer e.g., poly(ethylene), poly(propylene) or poly(acrylonitrile). An organic solvent containing lithium salt (usually lithium hexafluorophosphate, LiPF6) serves as the electrolyte, filling the space between the electrodes[4]. Based on the composition of the lithium metal oxide material coated on the positive electrode, LIBs can be classified into different types, as shown in Table 1 (page 11). The specific metal oxide used on the positive electrode determines key characteristics of the battery, including nominal voltage, lifespan, and specific energy, which in turn influence its suitability for various applications. These performance characteristics are closely linked to the specific chemistry of the battery.

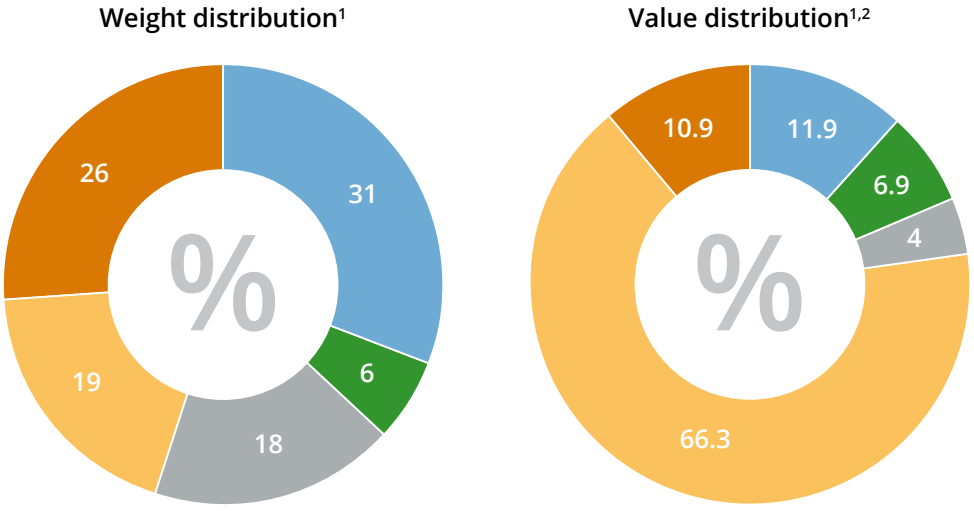
Figure 6 presents the material distribution within a LIB using NMC 622 chemistry. Aluminum accounts for the largest share, as it often serves dual function, acting as both the current collector and the cell casing. Although the cathode constitutes only 19% of the total battery weight, it represents 67% of the economic material value in the case of NMC 622-type batteries. This is due to the presence of more valuable metals like cobalt and nickel. As a result, battery recyclers typically focus on recovering cathode materials [6].

***Table 1:*** *Lithium-ion battery classification according to the metal-oxide material used in the cathode*

| Chemistry | Formula | Name acronym | Nominal | Lifespan (charge-discharge cycles) | Specific energy (Wh/kg) | Typical applications |
|---|---|---|---|---|---|---|
| **Lithium Nickel Manganese Cobalt Oxide** | $LiNi_xMn_yCo_{1-x-yO2}$ | NMC | Voltage (V) | 1000+ | 150–220 | E-bikes, medical devices, EV, Industrial |
| **Lithium Iron Phosphate** | LiFePO4 | LFP | 3.6 (3.0-4.2) | 2000+ | 90–120 | Stationary applications with high capacity, EV |
| **Lithium Nickel Cobalt Aluminium Oxide** | $LiNi_xCo_{yAlzO2}$ | NCA | 3.2 (2.5-3.65) | 500-1000 | 200–260 | Medical, industrial, electric powertrain |
| **Lithium Titanate** | $Li_2TiO_3$ | LTO | 3.6 (3.0-4.2) | 3000-7000 | 50–80 | electric vehicles and energy storage systems |
| **Lithium-Cobalt Oxide** | $LiCoO_2$ | LCO | 2.4 (1.8-2.85) | 500-1000 | 150–200 | Laptops, mobile phones, tables, cameras |
| **Lithium Manganese Oxide** | $LiMn_2O_4$ | LMO | 3.6 (3.0-4.2) | 300-700 | 100–150 | Medical devices, electric powertrains, power tools |

***Figure 6:*** *Weight and value distribution overview of a battery cell based on NMC 622.*

*[1] Based on NMC622 cathgode chemistry*
*[2] Based on material prices in 2023*




**GENERAL FACTS**

Recyclers can expect to find specific types of batteries based on their applications. This linkage between application and battery type is a fundamental criteria to orientate the battery sorting process. For instance, LCO batteries are commonly found in laptops, mobiles, tablets, cameras, etc., whereas NMC batteries are predominantly present in electric vehicles. However, LCO batteries are currently being replaced by NMC cells due to the supply risks associated with cobalt.

Figure 7 illustrates the global demand for various LIB chemistries. The share of nickel-rich batteries (NMC and NCA) is currently predominant and expected to stay dominant for the near to medium future. Lithium iron phosphate batteries (LFP) have also gained substantial popularity in recent years due to their avoidance of critical and expensive metals such as nickel and cobalt, as well as their improvement in safety and cost-effectiveness compared to many other battery chemistries. The growing importance of this chemistry is visible in the increase in production mainly in China but also in other parts of the world.

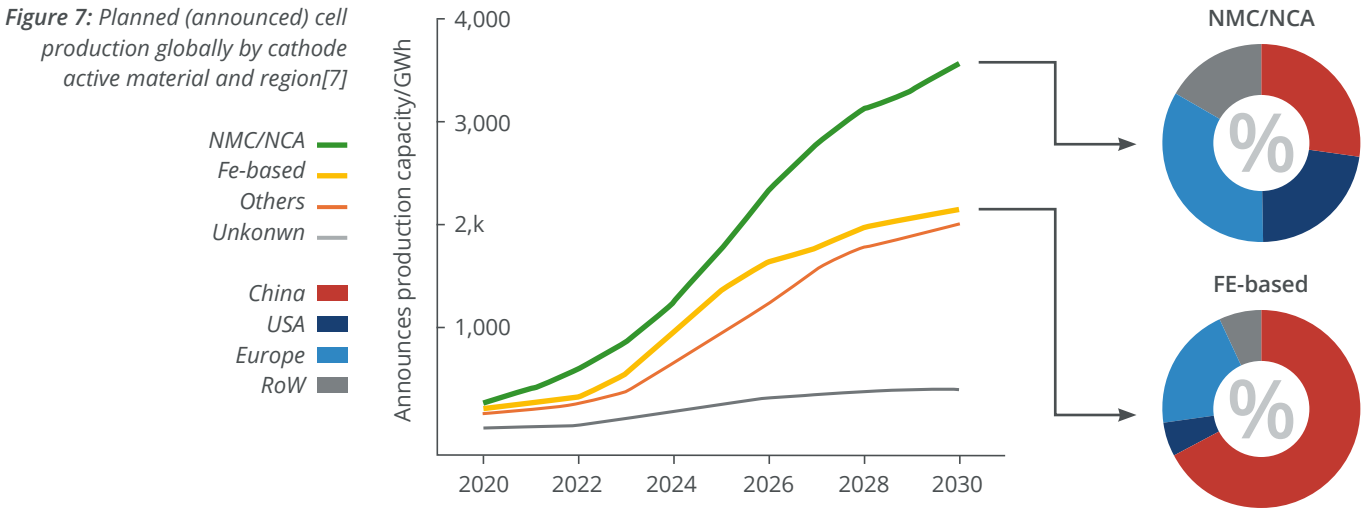



***Figure 7:*** *Planned (announced) cell production globally by cathode active material and region[7]*

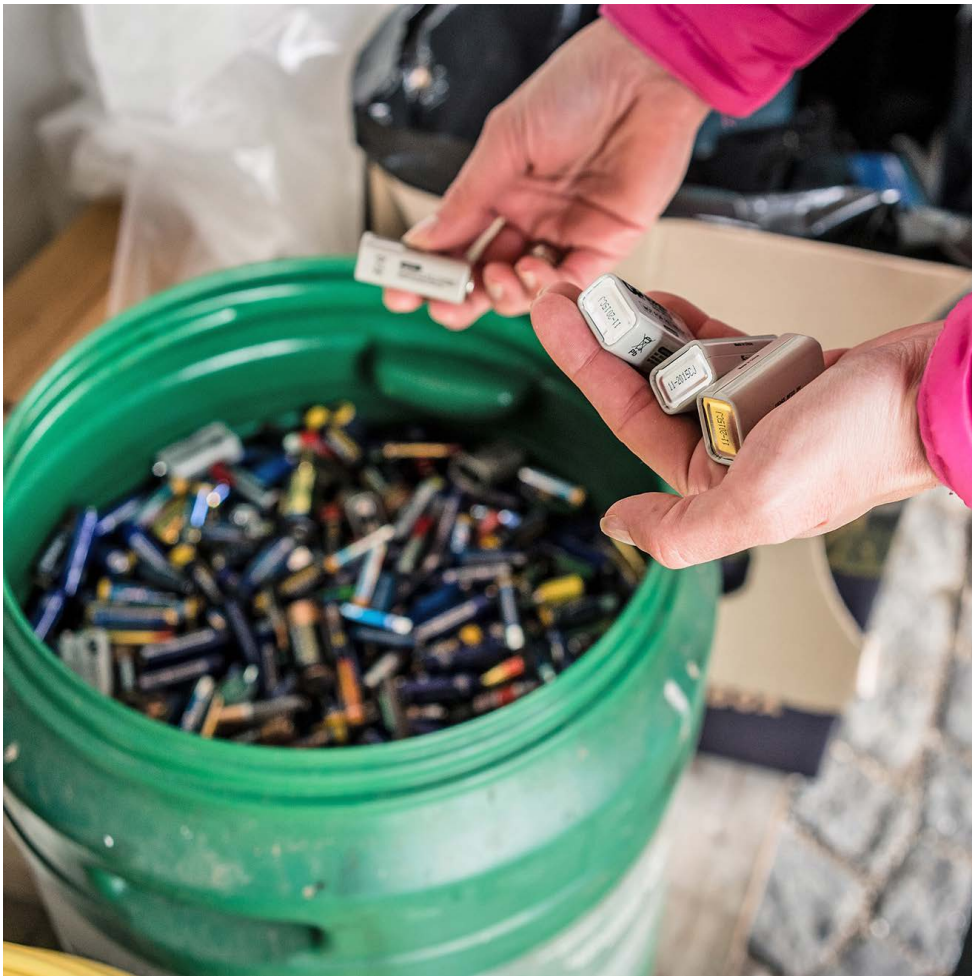


***Figure 8:*** *Many batteries, especially in the case of lithium-ion batteries (LIBs), contain valuable metals and materials, such as cobalt, nickel or graphite.*

# 3 Battery marking, labelling and nomenclature

Proper marking and labeling of batteries is essential, as it enables consumers to select the appropriate product and assists recyclers in correctly sorting batteries, as mixing different battery types and chemistries together can have significant risks of malfunction and fire hazards. Marking refers to permanent or semi-permanent inscriptions or symbols directly on the battery or its casing (e.g., manufacturer name/logo, model/part number, date code or batch number, polarity indicators, compliance symbols). For the case of labelling, here it refers to include text, symbols and warnings such as safety warnings, voltage and capacity, hazard symbols or transportation labels. Finally, nomenclature is the systematic naming convention used to classify batteries based on size, shape, chemistry, and application. Batteries from WEEE, like the one in Figure 8, are typically well-labeled and include the following information in their casing:

**Battery marking:**

**Battery marking:** Brand and manufacturer details, batch or serial number for traceability, battery chemistry.

**Identification information:** model or serial number, battery type, nominal voltage, and rated capacity.

**Country of origin:** production country of the battery.

**Regulatory compliance symbols:** such as CE (Conformité Européenne), UL (Underwriters Laboratories), or RoHS (Restriction of Hazardous Substances).

**Battery labelling:**

**Voltage and capacity:** the standard operating voltage, the energy storage capacity.

**Safety information:** regarding proper handling, storage and disposing instruction.

**Recycling or disposal information:** user guidance for End-of-life stage.

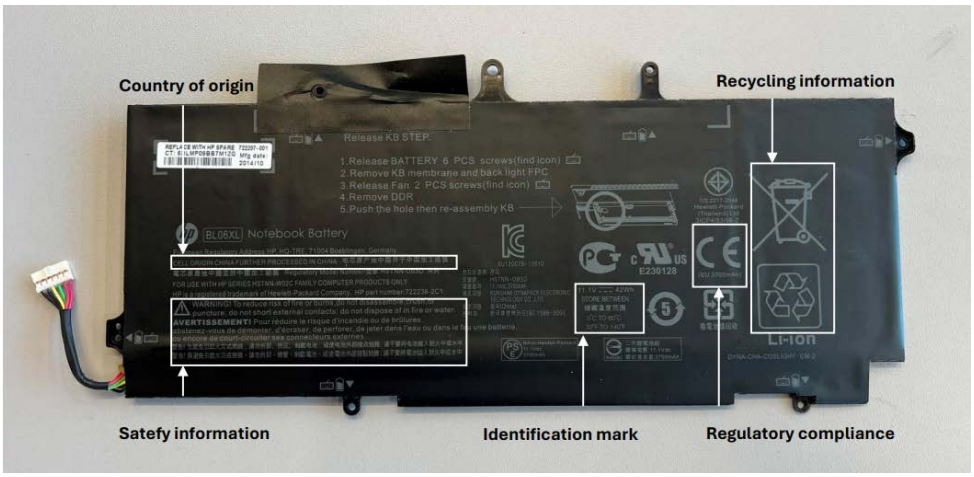



*Figure 9: Marking and labelling of an example of Lithium-ion battery.*

The way of labelling batteries can vary according to manufacturer and country of origin. Therefore, battery standardization is increasingly important. Battery standardisation enables the easy identification of different batteries, benefiting not only consumers but also manufacturers, producers and recyclers. Technical standards for battery types are developed by standard organizations such as IEC and American National Standards Institutes (ANSI).

Three different technical committees at IEC make standards on batteries: TC21 (lead-acid), SC21 (other secondary) and TC35 (primary). Each group has published standards relating to the nomenclature of batteries: IEC 60095 for lead-acid starter batteries, IEC 61951-1 and 61951-2 for Ni-Cd and Ni-MH batteries, IEC 61960 for LIB, and IEC 60086 for primary batteries. Battery types are designated with a letter/number sequence indicating number of cells, cell chemistry, cell shape, dimensions, and special characteristics.

**NOMENCLATURE OF BATTERIES BASED ON IEC STANDARDS:**

**IEC 60086:** Primary batteries
**IEC 60095:** Lead-acid batteries
**IEC 61951-1:** Nickel-cadmium batteries
**IEC 1951-2:** Nickel-metal hydride batteries
**IEC 61960:** Lithium-ion batteries

As an example of nomenclature, details are provided below for primary batteries and for LIBs as representative of secondary batteries. For other types of secondary batteries nomenclature, please refer to the official IEC documents cited above.

## Nomenclature codification for primary batteries

Primary batteries are classified based on chemistry, size and standard codes as it is represented in Figure 9 and details are presented in Table 2.

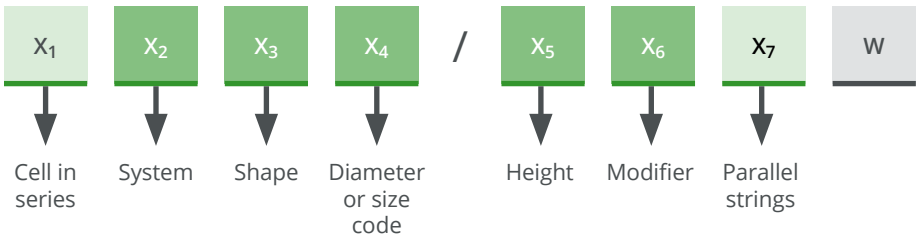



***Figure 10:*** *International Electrotechnical Commission designation system for primary batteries.*

*Mandatory components*
*Optional components*

*Height and diamenter can be suffixed by decimal adjustment codes*

***Figure 11:*** *Example of a primary battery label LR6 AA*

*Table 2: Description of the different symbols used in primary battery nomenclature*

| Symbol | Guide to symbols and corresponding meaning | | | |
|---|---|---|---|---|
| X2 | Common chemical system letters | | | |
| | L | Alkaline (Zn/MnO2) | | |
| | R | Zinc-carbon | | |
| | S | Silver oxide | | |
| | P | Zinc-air | | |
| | CR | Lithium (Li/MnO2) | | |
| | BR | Lithium (Li/CFx) | | |
| | FR | Lithium (Li/FeS2) | | |
| X3 | Format codes | | | |
| | R | Round (cyclindrical or buttom) | | |
| | F | Flat (rare in primary) | | |
| X4 | IEC size codes | | | |
| | | Common name | Size (mm) | Chemistry |
| | R03 | AAA | 10.5 x 44.5 | Zink-carbon |
| | LR03 | AAA | 10.5 x 44.5 | Alkaline |
| | R6 | AA | 14.5 x 50.5 | Zink-carbon |
| | LR6 | AA | 14.5 x 50.5 | Alkaline |
| | FR6 | AA | 14.5 x 50.5 | Lithium |
| | R14 | C | 26.2 x 50 | Zink-carbon |
| | LR14 | C | 26.2 x 50 | Alkaline |
| | R20 | D | 34.2 x 61.5 | Zink-carbon |
| | LR20 | D | 34.2 x 61.5 | Alkaline |
| | 6LR61 | 9V | 26.5 x 48.5 x 17.5 | Alkaline |
| | 6F22 | 9V | 26.5 x 48.5 x 17.5 | Zink-carbon |
| | CR2032 | Coin cell | 20 x 3.2 | Lithium (MnO2) |
| | BR2032 | Coin cell | 20 x 3.2 | Lithium (CFx) |

## Nomenclature codification for secondary batteries

LIBs have a different rule for naming, which applies both to batteries of multiple cells and single cell as is summarized in Figure 11 and with all details in Table 3. The initial number indicates the number of cells connected in series. These are followed by letters representing the phases of the anode and cathode, with the most abundant element in the case of the cathode. The third letter designates the battery's shape. This is followed by the dimensions – thickness (or diameter), width (for prismatic cells) and height – in millimetres.

*Figure 12: International Electrochemical Commission 61960 battery type designation system.*

*Cell and battery codes*
*Battery only codes*

*All dimensions in millimeter rounded up $N_3$ omitted if shape code is R dimensions*

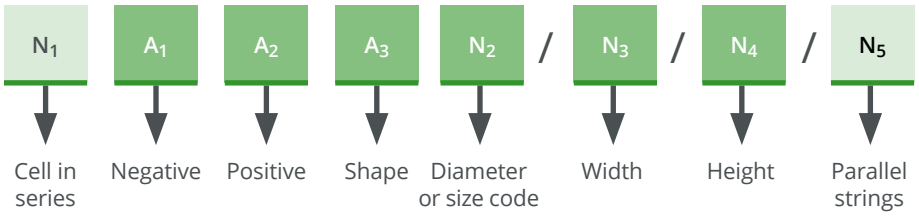


*Table 3: Description of each symbol used for lithium-ion battery nomenclature*

| Symbol | Guide to symbols and corresponding meaning | |
|---|---|---|
| N1 | is the number of series connected cells in the battery | |
| $A_1$ | designates the negative electrode basis | |
| | I | is carbon |
| | L | is lithium metal or lithium alloy |
| | T | is titanium |
| | X | is others |
| $A_2$ | designates the positive electrode basis | |
| | C | is cobalt |
| | F | is iron |
| | Fp | is iron phosphate |
| | N | is nickel |
| | M | is manganese |
| | Mp | is manganese phosphate |
| | T | is titanium |
| | V | is vanadium |
| | X | is others |
| $A_3$ | designates the format of the cell | |
| | R | is cylindrical |
| | P | is prismatic |
| $N_2$ | is the maximum diameter (if R) or the maximum thickness (if P) in millimeters rounded up to the next whole number | |
| $N_3$ | is the maximum width (if P) in millimeters rounded up to the next whole number (N3 not shown if R) | |
| $N_4$ | is the maximum overall height in millimeters rounded up to the next whole number | |
| | NOTE: If any dimensions is less than 1 mm, the units used are tenths of millimeters and the single number is written N | |
| $N_5$ | is the number of parallel connected cells if two or more (not shown if value is 1) | |

*Figure 13: Example of a LIB label: ICR18650.*

As an example, the  Figure 10 illustrates a LR03 AAA primary battery, where “L” denotes an alkaline chemistry, “R” indicates a round shape, and “RO03” refers to the AAA size classification. In the case of the LIB shown in Figure 12, the label “ICR18650” indicates that the cell uses carbon as the negative electrode material (“I”), cobalt as the positive electrode material (“C”), has a cylindrical shape (“R”) and dimensions of 18 mm in diameter and 65 mm in length.

This label can also be used to search for the specific LIB datasheet, which provides detailed technical specifications and performance characteristics to help users understand the battery’s capabilities, limitations, and proper usage like in the example of cell LIR18650 in Figure 13. The data sheet provides important information for recyclers, including the nominal voltage, which offers insight into the type of battery, as well as operating and storage temperature ranges. When testing EoL cells for potential second-life applications, the data sheet serves as a critical reference, enabling recyclers to assess the current condition of the battery in comparison to its original specifications (e.g., nominal capacity and internal impedance).

*Figure 14: Example of nomenclature [8] and nominal specific data sheet for lithium-ion battery LIR 18650 2600mAh.*

| Specific Data Sheet for LIR 18650 cell | |
|---|---|
| Capacity (25±5°C) | Nominal Capacity: 2600mAh (0.52A Discharge, 2.75V) |
| | Typical Capacity: 2550mAh (0.52A Discharge, 2.75V) |
| | Minimum Capacity: 2500mAh (0.52A Discharge, 2.75V) |
| Nominal Voltage | 3.7 V |
| Internal Impedance | ≤70mΩ |
| Discharge Cut-off Voltage | 3.0V |
| Max Charge Voltage | 4.20±0.05 V |
| Standard Charge Current | 0.52 A |
| Rapid Charge Current | 1.3 A |
| Standard Discharge Current | 0.52 A |
| Rapid Discharge Current | 1.3 A |
| Max Pulse Discharge Current | 2.6 A |
| Weight | 46.5±1g |
| Max. Dimension | Diameter (Ø): 18.4 mm |
| | Height (H): 65.2 mm |
| Operating Temperature | Charge: 0~45°C |
| | Discharge: -20~60°C |
| Storage Temperature | During 1 month: -5 ~35°C |
| | During 6 months: 0~35°C |

# 4 Safety aspects related to storage and handling

Due to its chemical composition LIBs pose potential safety risks and thus require careful handling during transportation, storage, and processing. Under unfavourable conditions, such as rise in temperature inside of the cell, mechanical or electrical abuse, a short circuit in the battery may occur, leading to the battery igniting as shown in Figure 14. The operating temperature for LIBs is rather narrow. For example, in the LIR18650 cell example depicted in Figure 12 , temperature of a discharged battery should be between -20 to 60 °C and charged between 0 to 45 °C. Above 60 °C the batteries can undergo degradation and catch fire, while below 0 °C , they suffer rapid capacity loss and have increased chances of causing short circuit.

***Figure 15:*** *Thermal runaway causing battery in a laptop to ignite*

Additionally, inadequate handling and storage can result in battery leakage, potentially releasing toxic gases such as hydrogen fluoride (HF) or phosphorus pentafluoride (PF5), which can adversely impact the environment and human health. Exposure to HF can cause mild acute symptoms, especially with low concentrations, but can lead to severe long-term harm such as skin burns, eye and lung damage. Furthermore, it can disrupt calcium levels in the body, leading to heart failure. The formation of these gases results from the electrolyte salts and organic solvents decomposition. HF is formed either at high temperature of 117 °C or in the presence of water traces, therefore thermal and mechanical abuse of the batteries should be avoided.

Additionally, LIBs commonly contain carcinogenic and toxic substances such as cobalt and nickel, highlighting the importance of proper EoL management to protect both the environment and human health. The uncontrolled disposal of LIBs in landfills not only poses environmental hazards but also results in significant economic losses due to the presence of critical metals like nickel, cobalt, and lithium.

LIBs are engineered for high energy output with minimal weight, which makes their thin partitions and coatings fragile and susceptible to puncture. Any action that connects the battery's positive and negative terminals – either internally or externally – can cause a short circuit. Depending on the battery's SoC, this may result in harmless effects or escalate into thermal events such as sparks, fire, or explosions. Furthermore, excessive heat can trigger thermal runaway, a dangerous condition where internal pressure builds up, potentially leading to an explosion.

Safety issues can arise from several causes. A summary of the main ones is provided below [9]:

**Chemical reactions:** Under normal voltage and temperature conditions, only Li+ shuttles through the electrolyte during insertion/extraction cycles at the cathode and anode. However, at high temperature and voltages, complex reactions occur, including decomposition of the solid electrolyte interface film, oxygen release from the cathode, and parasitic side reactions. These processes accelerate heat generation, leading to thermal runaway, which can result in battery rupture or explosion due to the ignition of flammable gases in the presence of ambient oxygen.

**Thermal runaway:** It is a major safety issue for LIB, triggered by side reactions in the electrolyte, cathode, anode, and electrodes, caused by mechanical, thermal, and electrical abuse. The most common causes of battery safety incidents are short circuits from separator damage, electrical abuse, and mechanical abuse.

Chemical reactions and thermal runaway can be triggered by mechanical, electrical, or thermal abuses.

**Mechanical abuse:** Mechanical abuse refers to physical damage inflicted on a battery through actions such as crushing, puncturing, or dropping. This can cause internal short circuits, puncture the separator, and lead to direct contact between electrodes, resulting in excessive heat and potential thermal runaway[10].

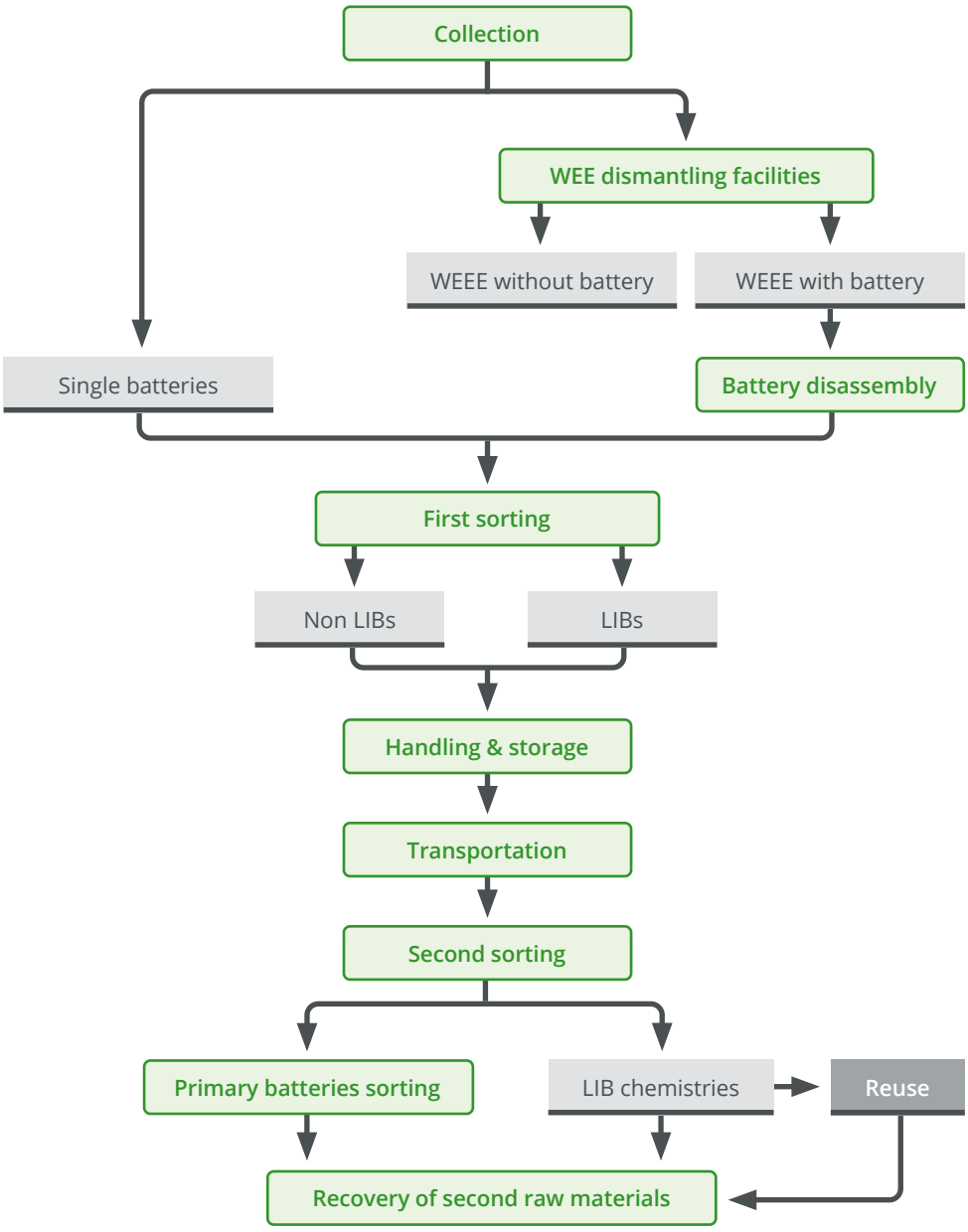
**Electrical abuse:** Electrical abuse occurs when a battery is subjected to improper electrical conditions, including overcharging, overdischarging, or external short circuits. These conditions can degrade battery materials, generate excessive heat, and increase the risk of thermal runaway.

**Thermal abuse:** Involves exposing a battery to temperatures beyond its specified operating range, either too high or too low. Such exposure can alter internal chemical reactions, cause gas generation, and increase internal pressure, potentially leading to swelling, leakage, or thermal runaway.

# 5 Processing EoL LIBs

This chapter provides a detailed explanation of the various steps involved in handling LIBs at the EoL. An example of these steps is provided below in Figure 15. While individual takeback systems may vary slightly – particularly during the initial sorting phase – this example serves as a general guideline.

*Figure 16: Summary example of a process sequence for EoL LIB treatment.*




## 5.1 Collection

In specific WEEE dismantling facilities that can handle batteries, the initial step involves categorizing waste into two groups: **those containing batteries and those without.** Ideally, this separation should occur early in the treatment process. WEEE containing LIBs, as well as standalone LIBs, must be stored in a designated area that is clearly labeled. The dismantling of WEEE to recover specific materials, including batteries, and to segregate waste streams can provide significant economic benefits. Batteries require special handling during both treatment and storage, as outlined in the following section.

## 5.2 First sorting

After collection and battery disassembly from WEEE, the next step involves sorting the batteries. In a recycling facility, trained workers are employed to sort the waste batteries through visual inspection. If the battery classification is still indecisive, batteries typically come with clear labeling, such as, abbreviation of battery type, and nominal voltage.

The initial process can differentiate between lithium-ion and non-lithium-ion batteries. As a second step, LIB can be further separated according to chemistries. LIB labels should contain information about the chemistry [11]. See for more details about labelling in previous section 3. In addition, chemistry can often be distinguished by their nominal voltage, typically indicated on the casing (see Table 1 in section 2.2). It is worth noting that some manufacturers may label non-Lithium Iron Phosphate (LFP) batteries with a 3.7 V voltage for marketing purposes. However, this should not be mistaken for LMO batteries.

*Table 4: Summary of the main points to identify between primary and secondary batteries. For more details on the labelling, see section 3.*

| 1. Labeling and Markings | | |
|---|---|---|
| Feature | Primary Battery | Secondary Battery |
| Label Terms | "Primary", "Non-rechargeable" | "Secondary", "Rechargeable" |
| Common Prefixes | Eg. LR03, CR2032 | E.g. ICR, LIR, NiMH |
| Recharge Symbol | None | "recycle" or "recharge" symbol |
| Voltage | Typically fixed e.g., 1.5V for alkaline | Can vary depending on chemistry, e.g., 3.7V for LCO cells, or 2.4V for LTO cells |

| 2. Nomenclature (for details here see the section 3) | |
|---|---|
| Primary | Alkaline, Lithium, Zinc-air |
| Secondary | Li-ion, NiMH, NiCd, Lead-acid |

| 3. Physical Design or Documentation | |
|---|---|
| Secondary | datasheet, nominal voltage, charge/discharge cycles, battery packs |

## 5.3 Handling and storage

Proper handling and storage of LIBs are crucial to ensure safety and environmental compliance. Due to the potential risks associated with LIBs, such as thermal events or fires, specific protocols must be followed [12].

- Protection gloves against chemicals (EN 374, European Norm which defines requirements for protective gloves against dangerous chemicals and microorganisms)
- Safety glasses (EN 166, European Norm for personal eye protection)
- Protective clothing, including corrosion-proof clothing (the best EN 14605 or as second option EN 13034, European standard for chemical protective clothing that provides liquid-tight or spray-tight protection against chemicals).
- Dust production: dust mask with filter type P3 (preferable), if not P2 or P1
- Only when handling LiPF6 and producing high dust production, self-contained breathing apparatus (EN 136 and EN 137 mask will be needed, European standards for respiratory protective equipment)

*Figure 17: Image of battery sorting*

**Handling procedures:**

- During the collection and dismantling of WEEE, it is essential to handle LIBs carefully to prevent damage. Damaged batteries can lead to thermal runaway, posing significant safety hazards.
- Personal involved in handling LIBs should receive adequate training to recognize potential hazards and implement appropriate safety measures.

**Storage guidelines for containers:**

- For storage, special containers that can mitigate the risk of explosion, damage and risk should be used.
- The containers should be clearly marked, waterproof sealed, filled with sand or mineral vermiculite and lidded. The container should also be filled fully to minimize internal movement during transit.
- The container should be located at least 6 meters away from any buildings, plant equipment, waste or combustible material. If the 6 meters distance cannot be achieved, the battery container shall be stored within a fire-resistant enclosure.
- Cover terminals or provide plastics covers for LIB to prevent short circuiting. Isolation tape should be used to cover the open contacts of batteries.

*Figure 18: Containers specialized for LIB battery storage (source: INOBAT)*

**Storage guidelines for room facility:**

- Storage should be at room temperature (i.e., between 20°C and 25°C), in a dry area (e.g., protected against weather influences).
- Storage should be well ventilated and clearly marked and have accessible emergency exits.
- Implementing fire prevention measures, such as maintaining appropriate spacing between stored batteries and installing fire detection and suppression systems, is critical. At the collection facility, sufficient fire detection alarms should be placed.
- A separate place in the facility should be dedicated to WEEE waste containing the LIBs and should be labelled clearly.

**KEEP LIBS AWAY FROM ...**

- » Heat sources
- » Ignition sources
- » Oxidizing or reducing sources
- » Strong acids and basis
- » Water or moisture
- » Halogens

## 5.4 Transportation

LIBs are classified as dangerous goods under several regulations, including United Nations Recommendations on the Transport of Dangerous Goods (see Table 5) [13], International Air Transport Association (IATA) Dangerous Good Regulation (DGR) [14], International Maritime Dangerous Goods (IMDG) Code [15], European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR)[16], and Regulation (EC) No 1272/2008 on Classification, Labelling, and Packaging (CLP Regulation) [17].

The ADR regulates the international transport of dangerous goods across countries that have ratified this treaty, applying to cross-border transport between at least two member countries. The ADR treaty has been incorporated into European law through Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods. For transporting such material, their packaging should contain all the information along with assigned UN codes. The following Table 5 indicates UN code that should be mentioned based on method of packing of lithium-based batteries[18]:

*Table 5: UN codes for the transportation of lithium-ion batteries.*

| UN Codes | Description |
|---|---|
| UN3480 | LIB packed alone and not installed in equipment |
| UN3490 | Lithium metal battery packed alone and not installed in equipment |
| UN3481 | LIB contained or packed in the equipment |
| UN3491 | Lithium metal contained or packed in the equipment |
| UN3536 | LIBs installed in cargo transport unit |

Each shipment must display a LIB sticker with the UN number (see example in Figure 19). Batteries integrated into equipment must be protected against damage and short circuits, with measures to prevent accidental activation. This protection should prevent contact with conductive materials in the packaging that could cause a short circuit. Additionally, any transport of dangerous goods must be accompanied by proper documentation, including a description of the goods: **UN number, shipping name, label model, packing group, the number and description of packages, the total quantity of each item, the sender's name and address, the receiver's name and address, and the date and signature.** For LIB, the equivalent lithium content per cell is calculated using the formula: Ah per cell x 0.3g. The following Table 6 summaries a detailed overview of the shipment and labeling requirements for certain materials in LIB.

Transporting LIBs requires strict adherence to UN, the IATA and ADR regulations to ensure safety compliance. The Table 4 provides a summary of the

*Figure 19: Transportation label for batteries, (a) Battery label with appropriate UN code, and (b) battery label with hazardous class.*

**LABEL INFORMATION:**

- UN number
- Shipping name
- Label model
- Packing group
- Number and description of the package
- Total quantity of each item
- Sender's name and address
- Receiver's name and address
- Date
- Signature

most commonly applicable UN codes, Special Provisions (SP) number, IATA and ADR classifications for LIB transport scenarios. All cells and batteries must be protected against short circuits and secured to prevent physical damage during transit. Each cell or battery should be individually packed and separated by inner packaging to prevent contact. It is essential to use non-conductive, non-combustible cushioning material to fill voids and ensure the contents remain stable and immobile within the package.

*Table 6: Transport detailed information. SP number refer to Special Provisions, IATA PI numbers indicates Packing In-structions for air transport and ADR PI numbers refer to Packing Instructions for road transport under ADR regulations.*

| SP Number | Description | |
|---|---|---|
| SP188 | Exemption for small batteries (<100Wh). | |
| SP230 | Defines LIBs and sets rules for classification and naming | |
| SP310 | Packaging test samples or prototypes | |
| SP348 | When batteries are transported for disposal or recycling | |
| SP376 | For damaged or defective batteries that pose hazard during transport | |
| SP377 | For waste of used batteries, not presenting hazards (PI 903, see below) | |
| SP636 | Applied to transport of used LIB under specific safety conditions | |
| **IATA PI** | **Description** | **Requires** |
| P965 | LIBs shipped alone (UN3480). | Class 9 label |
| P966 | LIBs packed with equipment (UN3481). Batteries and equipment are packed together but not installed in the device | Short-circuit protection, inner packaging |
| P967 | LIBs contained in equipment (UN3481). Batteries are installed inside the device (e.g., phones or laptop) | Protection against accidental activation or damage |
| **ADR PI** | **Description** | **Special Provision** |
| P903 | Used, waste, or defective LIBs that are not hazardous | SP 377 |
| P908 | Damaged or defective LIBs that pose a risk during transport | SP376 |

If LIBs are transported in designated containers, such as the one illustrated in Figure 17, appropriate labeling is required. For additional information on transportation guidelines and requirements, the Battery Transport Initiative has launched a dedicated website for reference and consultation. A publication from 2021 gives details about regulation, guidelines and transportation of different types of lithium batteries[19].

**BATTERY TRANSPORT INITIATIVE**

Batteries Transport is a joint industry initiative designed to support the implementation of legal requirements for transportation battery cells, batteries, and battery-containing equip-ment. Transport regulations apply to various battery technologies, including lithium-. Lead-, nickel-, and sodium-based batteries. Professionals transporting batteries must comply with UN packaging, reporting, and safety regulations to ensure legal and safe transportation. The initiative provides targeted guidance to help navigate specific transport requirement effi-ciently. All information can be found here: ***www.batteriestransport.org***

## 5.5 Reuse of End-of-life LIBs

Based on waste hierarchy, reuse and repurposing should be given priority over recycling to maximise environmental benefits. WEEE-LIBs must follow a series of preparation steps to determine if they are suitable for reuse in new or same equipment [20], [21]. LIBs that are not suitable for direct reuse must be disassembled to reach their individual cell level which can be a time consuming and expensive process, therefore recycling of such packs is usually preferred. The preparation steps involve:

**1. Initial inspection:** The batteries should be visually inspected for physical damage, swelling, or leakage. The damaged batteries should be processed further and should be stored in containers filled with sand or mineral vermiculate. All damaged cells including swollen pouch cells should be sent directly for recycling.

*Figure 20: Swollen and damaged pouch cell*

**2. Sorting and classification:** After passing the visual test, batteries are categorized based on their chemistry, voltage, capacity, and application potential. The batteries with sufficient remaining charge capacity are prioritized for reuse. For electrical inspection, instruments like multimeter, and hand tools (pilers set and insulated screwdrivers set) are required.

**FIRST ELECTRICAL INSPECTION PROCESS FLOW:**

- **Connector integrity:** Fix the connector if damage and continue the inspection for check open circuit voltage
- **Open circuit voltage (OCV) check:** using calibrated digital multimeter (DMM). Con-nect probes to the positive and negative terminals without applying any external load to record the OCV. Measure the OCV at different SOC e.g., 30%.
  - If the batteries are in discharge state (i.e., around 2V), it should be charged first with low current
  - If Voltage = 0, then pack should be disassembled and cell extraction should take place
  - If voltage = nominal operating voltage of battery pack, then diagnosed further
- **Interpret OCV results:** compare the measured OCV to the nominal voltage (it can be found in the datasheet). The results will depend at SOC the OCV has been measured. As an example for a 30% SOC:
  - Healthy cells: OCV close to the nominal voltage (e.g., ~3.6 – 3.7V for a typical LIB)
  - Degraded cells: significant drop (e.g., below 2.5V) indicates deep discharge, aging, or failure.
  - Overcharged cells: OCV above expected maximum (~4.2V for standard cells) – dangerous, risk or thermal events.
  - Since the results depend on the SOC, measurements of OCV taken at full charge will yield higher values. Conversely, if the OCV is measured at a low SOC (e.g., 10%), the values will be lower. However, this variation does not necessarily indicate cell degradation.
- **Decision making:**
  - Acceptable OCV range: cells can proceed to deeper testing e.g., capacity, im-pedance
  - Low or abnormal OCV: cells should be flagged for safe disposal and recycling

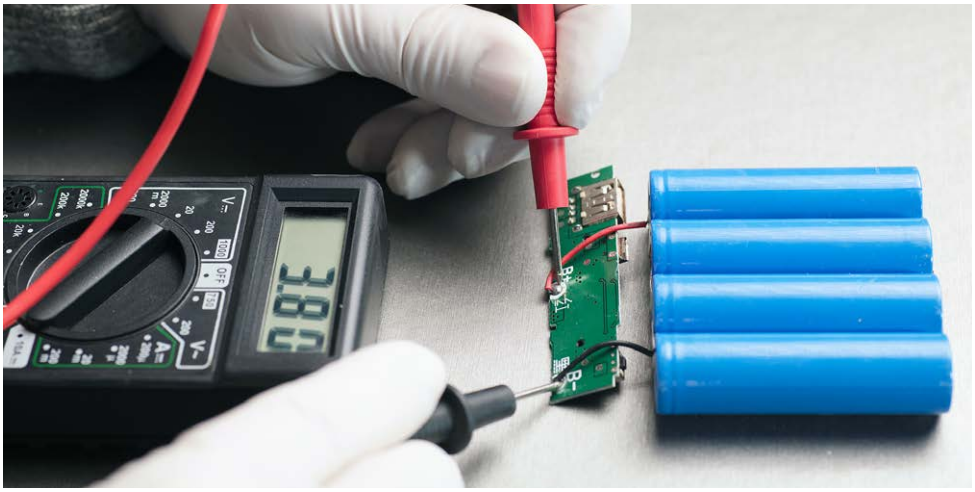


*Figure 21: Electric inspection of battery with multimeter.*

## 3. Testing and diagnostics:

Two key parameters used in this evaluation are **State of Health (SOH) and State of Resistance (SOR)**. These two parameters should be measured at the pack, module and cell level. SOH represents the remaining capacity of the battery compared to its original capacity, indicating how much energy it can still store and deliver efficiently. Over time, LIBs degrade due to chemical and

mechanical factors, leading to a reduced SOH. SOR, on the other hand, measures the internal resistance and impedance of the battery, which affects its efficiency and power delivery. Higher resistance can lead to increased heat generation, voltage drops, and reduced performance. By conducting regular SOH and impedance tests, manufacturers and users can monitor battery degradation, predict lifespan, and optimize performance (see details in the following section). For all the details, see the next section on "Diagnostic for battery pack" and additional literature[22]. Instruments to program an electronic load, power supply and cables are used to further diagnose the reusability of the battery pack. To diagnose the battery pack capacity, which represents its SoH, and SoR the following procedure can be followed:

**A** **Voltage and internal resistance measurement:** Use a multimeter or internal resistance tester to measure the open-circuit voltage (OCV) and internal resistance of the battery pack. This provides an initial indication of its condition.

**B** **Discharging process:** The first step involves discharging the batteries in constant current mode at a 0.5C cycling rate until they reach the minimum voltage specified in the data sheet.

**C** **Voltage relaxation:** A 15 min waiting period is required to allow for voltage relaxation, ensuring accurate measurement and stability before further testing or analysis.

**D** **Charging process:** The charging process begins by using a programmable power supply set to 0.5C, where the battery is charged in constant current mode until it reaches the specified maximum voltage. Once this voltage limit is reached, the charger switches to constant voltage mode, and the current gradually decreases until it stabilizes at approximately 0.05C.

**E** **Discharging process:** The battery is then discharged again at 0.5C to calculate the capacity of the battery pack, ensuring it is discharged to a safe voltage as specified in the data sheet.

**F** **Cycle testing (optional):** Perform multiple charge-discharge cycles to assess the battery's degradation behavior over time.

**G** **SoH calculation:** Compare the measured capacity with the battery's original rated capacity. The SoH (%) is typically calculated as:

$$\text{SoH} = \frac{\text{Measured Capacity}}{\text{Original Capacity}} \times 100$$

**4. Disassembly and module-level evaluation:** If necessary, battery packs are disassembled into modules or individual cells. Each module is tested separately to determine usability.

**5. Refurbishment and repacking:** Suitable cells or modules are reassembled into new battery packs with proper balancing. Battery Management Systems (BMS) may be replaced or upgraded to enhance safety and performance.

**6. Safety testing and certification:** Refurbished batteries undergo rigorous safety tests, including thermal stability, short-circuit resistance, and overcharge protection. Compliance with industry standards (e.g., UN 38.3, IEC 62619) is ensured before deployment.

**7. Reuse applications:** Batteries meeting required specifications can be repurposed for second-life

applications such as energy storage systems (ESS) for renewable energy integration, power backup solutions for residential or industrial use, or low-power applications like e-bikes or portable electronics. Second-life applications are feasible for LIBs originally used in mobile applications (e.g., EVs, light electric vehicles, and e-bikes). However, repurposing batteries from consumer electronics presents greater challenges. This is primarily due to the prevalence of pouch cells, which are more difficult to reuse, as well as the fragility of the BMS, which are prone to damage and challenging to replace. See examples in Table 7.

***Table 7:*** *Sorting criteria for second-life application of battery cells originally used for mobile applications (e.g., e-bikes).*

| Second-life application | SoH requirement | SoR requirement |
|---|---|---|
| **Second-life battery pack for the same application** | >90%<br><5% variation for multicell batteries | < 120% with respect to original |
| **Energy storage system** | >70%,<br><5% variation within battery | < 150% with respect to original |
| **Power bank** | >60%,<br>< 5% variation within battery | – |
| **Second-life battery pack for less power-consuming equipment** | >50%,<br><5% variation for multicell batteries | – |

## 5.6 Recycling of LIB from WEEE

EoL LIBs that are damaged or unsuitable for reuse should be sent to recycling facilities to ensure the recovery of valuable materials. As previously mentioned, LIBs contain critical raw materials such as nickel, cobalt, and lithium, making their recovery a key focus of recycling processes.

LIB recycling is typically carried out through three main methods: pyrometallurgy, hydrometallurgy, and direct recycling [23]. Pyrometallurgical and hydrometallurgical processes have been widely adopted and are considered state-of-the-art in the industry. In recent years, direct recycling has also gained significant attention from both researchers and industry professionals as a promising alternative.

Different industries employ various approaches to LIB recycling. A typical recycling process begins with discharging the batteries, either by immersing them in saline water or through controlled discharge with energy recovery. Following discharge, several pre-treatment steps are carried out, including disassembly, comminution (shredding), sieving, magnetic separation, washing, or thermal pre-treatment. The specific pre-treatment method influences the recovery of materials such as copper and aluminum, which in turn determines the subsequent steps in the recycling process.

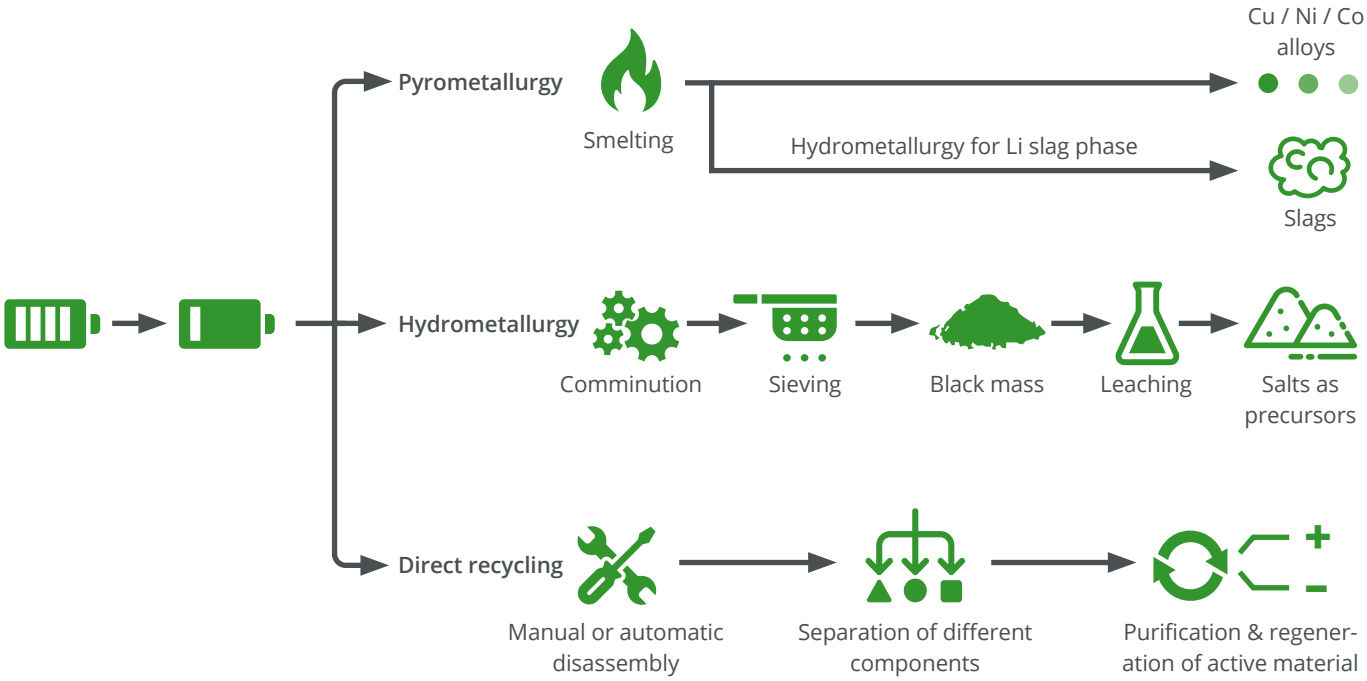
Pyrometallurgy is a process used to recover cathode materials in the form of alloys by subjecting LIBs to high temperatures. This process requires minimal pre-treatment, and its economic viability largely depends on the cobalt and nickel content of the battery. The primary materials recovered through this process include nickel, cobalt, and copper, while graphite, iron, aluminum, lithium and electrolytes are lost during the main treatment. The recovered alloy will be sent for further processing to extract valuable metals, while the slag is either discarded or repurposed as a construction material [24].

Hydrometallurgy involves multiple pre-treatment steps for LIB recycling, including discharging, dismantling, crushing, and sieving, to obtain the so-called black mass. Black mass is a mixture of mainly both cathode and anode active materials. The next steps involve leaching and precipitation processes to recover the valuable metals and convert them into precursor materials in the form of LIB salts. Then the remaining graphite is either discarded in landfills or sold to pyromet-allurgical plants for use as a reducing agent [24].

Direct recycling is a process aimed at recovering intact battery components – such as the cathode and anode active materials – without breaking them down into their elemental constituents. This method involves several key steps, including battery discharging, disassembly, mechanical shredding, electrolyte recovery, and the separation of cathode and anode materials.

*Figure 22: Three main lithium-ion batteries recycling processes.*

These processes aim to retain the structural integrity and functionality of the materials, making direct recycling a more energy-efficient and cost-effective approach.




**Export requirement and recommendations**

Cathode and anode waste, although chemically stable under normal conditions, should be kept away from sources of ignition including flames, sparks, and excessive heat, as well as dust, moist, and strong oxidizing or reducing agents. In the case of black mass, classification depends on the physical state of the material at the time of loading. If no free liquid is present, the material may be transported under **UN3077** (Environmental Hazardous Substance). However, if visible liquid is present, it must be classified as **UN3082**. In either case, transport containers must be leakproof.

The export of black mass has been subjected to significant regulatory changes within the EU to support its circular economy and strategic autonomy goals. As of March 2025, The EU has classified black mass as hazardous waste. This classification imposes stricter controls on its shipment, particularly restricting exports to non-Organisation for Economic Co-operation and Development countries. The purpose of these export limitations is to retain valuable materials like lithium, cobalt, and nickel within its economy, ensuring a stable supply for battery production and reducing reliance on external sources.

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