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# Comprehensive Analysis of Lithium-Ion Battery Lifecycle and Sustainability in the Automotive Industry: A Perspective of the End of Life in Europe

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# Comprehensive Analysis of Lithium-Ion Battery Lifecycle and Sustainability in the Automotive Industry: A Perspective of the End of Life in Europe

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# Abstract

The global demand for lithium-ion batteries (LIBs) has increased significantly over the last decades and it is expected to continue growing. Electric vehicles (EVs) have dived into the automotive market to help reduce the environmental impact that traditional fuel vehicles produce. The electrification of the automotive industry is crucial for shifting humanity towards a greener future, and LIBs play a crucial role in this transition. However, this technology has raised concerns about the environmental impact and sustainability of the entire value chain, from raw material extraction to End of Life (EoL) management. This thesis provides a literature review that examines the lifecycle and sustainability of LIBs in the automotive industry from a circular economy perspective. It discusses critical raw materials like lithium, cobalt, and nickel, emphasizing the challenges associated with their extraction, processing, and vulnerabilities in the supply chain. The study also investigates emerging battery technologies, the significance of battery management systems (BMS), and the impact of aging during the use phase of the batteries. Finally, it examines the process of battery EoL and offers insights into this stage in Europe, evaluating the different alternatives from a circular economy perspective and challenges during the last phase of the LIB's life cycle.

Keywords: Electric vehicles, Lithium-ion battery, value chain, life cycle.

# Abstract in Spanish

La demanda global de baterías de ion de litio (LIBs) ha aumentado significativamente en las últimas décadas y se espera que continúe creciendo. Los vehículos eléctricos (EVs) se han adentrado en el mercado automovilístico para ayudar a reducir el impacto ambiental que producen los vehículos de combustible tradicional. La electrificación de la industria automovilística es fundamental para conducir a la humanidad hacia un futuro más verde, y las LIBs desarrollan un papel crucial en esta transición. Sin embargo, esta tecnología ha suscitado preocupaciones por su impacto ambiental y su sostenibilidad durante la cadena de valor, desde la extracción de materias primas hasta la gestión del fin de vida útil (EoL). Esta tesis proporciona un análisis de la literatura sobre el ciclo de vida y la sostenibilidad de las LIBs en la industria automovilística, aplicando una perspectiva de economía circular. Discute materias primas críticas como el litio, el cobalto y el níquel, enfatizando los desafíos asociados con su extracción, procesamiento y vulnerabilidades en la cadena de suministro. El estudio también investiga tecnologías emergentes de baterías, la importancia de los sistemas de gestión de baterías y el impacto del envejecimiento durante su fase de uso. Finalmente, examina el proceso de EoL de las baterías y ofrece perspectivas sobre esta etapa en Europa, evaluando las diferentes alternativas desde una perspectiva de economía circular y los desafíos durante la última fase del ciclo de vida de las LIBs.

Palabras clave: Vehículos eléctricos, batería de ion de litio, cadena de valor, ciclo de vida.

# Title in Spanish:

**Análisis Exhaustivo del Ciclo de Vida y Sostenibilidad de las Baterías de Ion-Litio en la Industria Automovilística: Una Perspectiva del Fin de Vida en Europa.**

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# List of Abbreviations

| | |
|---|---|
| LIB | Lithium-Ion Battery |
| EV | Electric vehicle |
| DRC | Democratic Republic of the Congo |
| BMS | Battery Management System |
| SoH | State of Health |
| SoC | State of Charge |
| EoL | End of Life |
| RUL | Remaining Useful Life |
| PCM | Phase Change Materials |
| NCM | Nickel, Cobalt, and Manganese |
| SEI | Solid Electrolyte Interphase |

# 1. Introduction

Lithium-ion batteries (LIB) have emerged as the battery of choice for electric vehicles (EVs) because of their high energy and power density, low weight, and long life (Mayyas et al., 2019). The mobility sector must reduce emissions by 90% by 2050 to achieve the European net-zero goal. Therefore, the evolution of EVs is crucial (Reinhart et al., 2023). Approximately 20 million EVs are on the road worldwide, and this will substantially increase (Wesselkämper et al., 2024a). To meet the European green deal, EV sales must increase to 55% by 2030; the forecasted growth of the EV market is causing concern about securing the raw materials supply chain and the whole EV value chain (Bruno & Fiore, 2024). LIB packs have a useful life of around 8–10 years, depending on their capacity, as they should be replaced when they reach 20% capacity loss. Assuming the average weight of a pack is 250 kg, the weight of spent EV batteries worldwide can be 1,700,000 tons by 2035 (Hua et al., 2020). The value chains of EV batteries are mainly focused on the extraction and refining process of raw materials, cell production, usage of the vehicle, and finally, the EoL (Bonsu, 2020). The concept of circular economy has increasingly gained attention in the 21st century, presenting an opportunity to reconcile economic growth with environmental preservation. This concept aligns with key principles such as the closure of material loops, the fostering of industrial symbiosis, the extension of product life cycles, the adoption of cradle-to-cradle design, and the promotion of product and component reuse (Cong et al., 2021). Figure 1 shows a model of circular economy applied to LIBs.

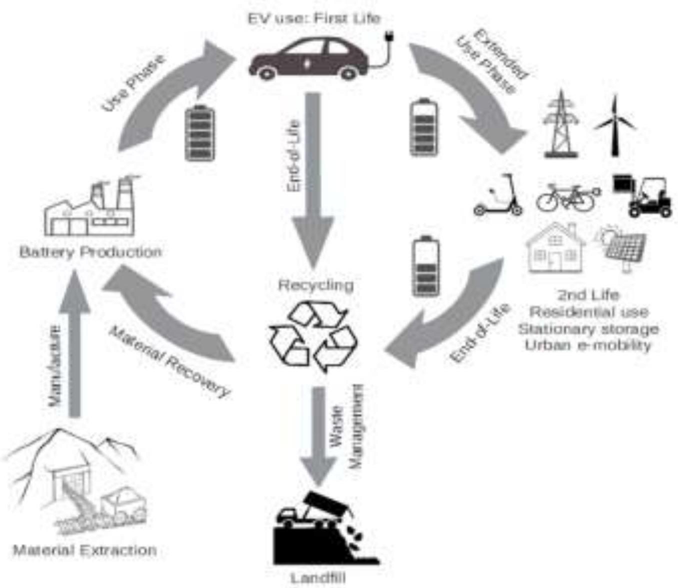


*Figure 1. Battery life from a circular economy perspective (Kotak et al., 2021)*

## 1.1. Extraction and Refining of Raw Materials

The LIB supply chain can be traced back to the extraction and processing of raw minerals (Z. Yang et al., 2022); this conforms to a considerable part of its value chain and is one of its critical aspects. It is also helpful to acknowledge that the EV and low-carbon revolution will substantially increase the mining of several key critical raw minerals and metals (Crenna et al., 2021). The primary metals in LIBs production are cobalt, nickel, lithium, Manganese, Aluminum, Copper, and Graphite (Mayyas et al., 2019). Critical materials can be defined by their relative specific economic value as a function of any spent LIB and their supply availability risks (Tan et al., 2020). Given this definition, the primary critical materials in the production of LIBs are lithium, cobalt, and nickel (Crenna et al., 2021). In the case of lithium and cobalt, EVs are the largest supply of these materials, as more than 40% of them are used in the manufacturing of LIBs. For other materials, such as nickel or manganese, which have more diversified applications, the current share is considerably smaller, often below 5% (Jones et al., 2023).

The distribution of the essential minerals is scattered globally. Given the dispersed distribution of raw materials, the LIB supply chain requires worldwide collaborations. Moreover, the leading countries that are dedicated to mine certain materials may change as new minerals are discovered and mining technology improves (Z. Yang et al., 2022). However, the production of many of the raw materials needed for their manufacture is limited to a few geographical regions whose trade policies could limit availability and impact prices (Mayyas et al., 2019). Mineral processing capability also plays a crucial role in the LIB supply chain, in addition to mineral reserves. The reason is that LIB production usually needs high-purity precursors, which require further processing after mining and specific mineral sources. The worldwide distribution of mineral processing is relatively concentrated. China has the most significant processing volumes for multiple essential metals. The global share of China for lithium, nickel, and cobalt processing is 55.0–58.0%, 29.9–35.0%, and 63.6 respectively (Z. Yang et al., 2022). The extraction and refining of the raw materials account for approximately 40% of the total life cycle emissions of an EV (Blömeke et al., 2022).

## 1.2. The Assembly Process of LIBs

The battery cells have five subcomponents: anode, cathode, separator, electrolyte, and cell container. When combining different battery cells, we create a battery module. Moreover, other battery modules must be combined to form an actual battery pack. (Ellingsen et al., 2014). One battery cell alone does not have enough power; therefore, combining all these battery modules makes it possible to meet the voltage requirements of EVs (Turksoy et al., 2020). The whole battery pack consists of four primary components: the cell, the BMS, the packaging, and the cooling system. The cell contains the active materials, the BMS oversees the performance and safety of the batteries, the cooling system is in charge of regulating the temperature of the battery, and the packaging, which incorporates insulation, electrical connections, and a housing, serves as the structure that connects the cells (Sankar et al., 2024a). Global battery manufacturing is expected to surge this decade. In 2021, the Asia Pacific region, dominated by China, was responsible for 84% of the world's LIB production. China had a production capacity of 558 GWh, 79% of the world’s total. By 2030, Germany is expected to dominate Europe’s LIB market capacity of 266 GWh, 10.4% of the world’s total (Llamas-Orozco et al., 2023).

## 1.3. Use Phase of LIBs

This is the main stage of the LIB life cycle. All the different technologies developed around EVs come together to achieve the electrification target of the automotive industry (Abdelbaky et al., 2021). Charging and discharging, high temperatures and different aging parameters accelerate battery degradation (Faria et al., 2014). Over its operational life, the battery's State of Health (SoH) decreases, resulting in a reduction of the energy storage capacity, increased internal resistance, and reduced roundtrip energy efficiency (Abdelbaky et al., 2021). Therefore, the prediction and study of the battery's SoH is beneficial in predicting maintenance services and improving the overall efficiency of the battery (Karthick et al., 2024). One of the main harmful aspects of these batteries' duration is temperature. A good cooling system extends the life of the batteries and improves their performance (Karimi & Li, 2013).

## 1.4. End-of-life and Circular Economy

A battery, under normal conditions, will reach its EoL when its capacity is under 80% of its initial, as it can no longer meet the requirements of the EV (Han et al., 2019). LIB packs have a useful life of around 8–10 years considering that the progress of EV manufacturing and using phase follows the expected trend. Each LIB weighs around 250 kg; therefore, 1,700,000 tons of spent EV batteries worldwide will have to be processed by 2035 (Hua et al., 2020). From a circular economy perspective, it is crucial to identify reuse and recycling strategies to sustain the demand fully (Ferrara et al., 2021). The need for sustainable and efficient recovery of critical materials is a matter of significant importance. The spent battery packs must undergo specialized processes in recovery facilities for safe, sustainable, and economical disassembly, treatment, and material recovery (Tan et al., 2020). Mandatory laws and regulations are crucial in encouraging and promoting battery recycling practices. Europe has already started to compile legislation on used batteries (X. Zhang et al., 2018). The European Parliament and the Council of the European Union have set battery directives for manufacturers in European nations to achieve a 45% LIB collection rate and recycle over 50% of any spent LIBs (Tan et al., 2020). A well-established infrastructure is crucial for handling the increasing demand for LIB material in the recycling industry to build a sustainable and profitable sector (Bruno & Fiore, 2024).

This text aims to provide a comprehensive overview and analysis of LIBs within the automotive industry, focusing on their entire value chain, from raw material extraction to EoL management, exploring and mapping the key processes, technologies, and environmental impacts associated with LIBs. Additionally, the research will focus on the importance of a circular economy perspective and the management of the LIBs after their useful life in Europe. A narrative literature review is conducted for this research to evaluate, examine, and analyze the existing literature of the LIBs value chain.

# 2. Literature Search

Reviews in the context of scientific research play a crucial role in consolidating literature pertaining to a particular subject of interest and providing an in-depth description of its current knowledge. A narrative literature review presents a comprehensive and insightful summary evaluating existing literature on a specific topic. It aims to provide a deep understanding and critical analysis of the work related to the chosen subject.

## 2.1. Collection of Past Literature

Scopus search tool was used to search articles online. It contains a wide range of articles and has a better citation forum than other sources. It is frequently used in literature reviews, has the most comprehensive database of peer-reviewed journals, and has an extensive database of English-speaking journals.

The parameters for conducting this search were identified. The primary parameters include the keywords most relevant to our scope of work and the option to restrict the search to a specific time frame, language, subject area, and type of studies.

The primary keywords used were “Electric vehicle*” or “EV”, "lithium-ion* batteries" or "Li-ion" or "lithium" or “lithium ion” or “lithium ion batteries”, and finally “life cycle” and “value chain”. The word “or” is used to avoid missing any important similar words that could potentially be used, for example, when exploring the keyword Electric vehicles, not missing the acronym EV. Using the truncation symbol “*” in the keywords considers all the grammatical variations; for example, when using lithium-ion*, we are searching simultaneously for the singular and plural words. Using quotation marks targets articles that include this word in their title, abstract, or the different keywords that each author includes. Then these primary keywords are further filtered by secondary keywords like “mining”, “anode and cathode”, “State of Charge”, "recycli*", "reus*", "remanufactur*", "end of life", "Europ*" or "EU" among others in different combinations to get a more accurate search on the topic.

Some irrelevant subjects, such as medicine, dentistry, and psychology, were removed from the search. The search was focused on English publication articles. It involves studies from 2012 until 2024. Also, some document types were excluded, keeping the articles, conference papers, reviews, and book chapters. All the details of the Scopus search are as follows:

( TITLE-ABS-KEY ( "Electric vehicle*" OR "EV" ) AND TITLE-ABS-KEY ( "lithium-ion* batteries" OR "Li-ion" OR "lithium" OR "lithium ion" OR "lithium ion batteries" ) AND TITLE-ABS-KEY ( "value chain" OR "life cycle" ) ) AND PUBYEAR > 2011 AND PUBYEAR < 2025 AND ( LIMIT-TO ( LANGUAGE , "English" ) ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) OR LIMIT-TO ( DOCTYPE , "cp" ) OR LIMIT-TO ( DOCTYPE , "ch" ) ) AND ( EXCLUDE ( SUBJAREA , "DENT" ) OR EXCLUDE ( SUBJAREA , "PSYC" ) OR EXCLUDE ( SUBJAREA , "PHAR" ) OR EXCLUDE ( SUBJAREA , "IMMU" ) OR EXCLUDE ( SUBJAREA , "ARTS" ) OR EXCLUDE ( SUBJAREA , "BIOC" ) OR EXCLUDE ( SUBJAREA , "AGRI" ) OR EXCLUDE ( SUBJAREA , "MED" ))

This search is inclusive enough to capture the most relevant articles within the conceptual boundaries while being selective sufficient to exclude less relevant ones. With this search, 797 different studies were analyzed.

## 2.2. Evaluation of Collected Literature for Appropriateness

After completing the initial search, we finally analyzed all the studies to see the work done in the specific research area. All documents were saved and added to different folders in Mendeley, where the selection process took place.

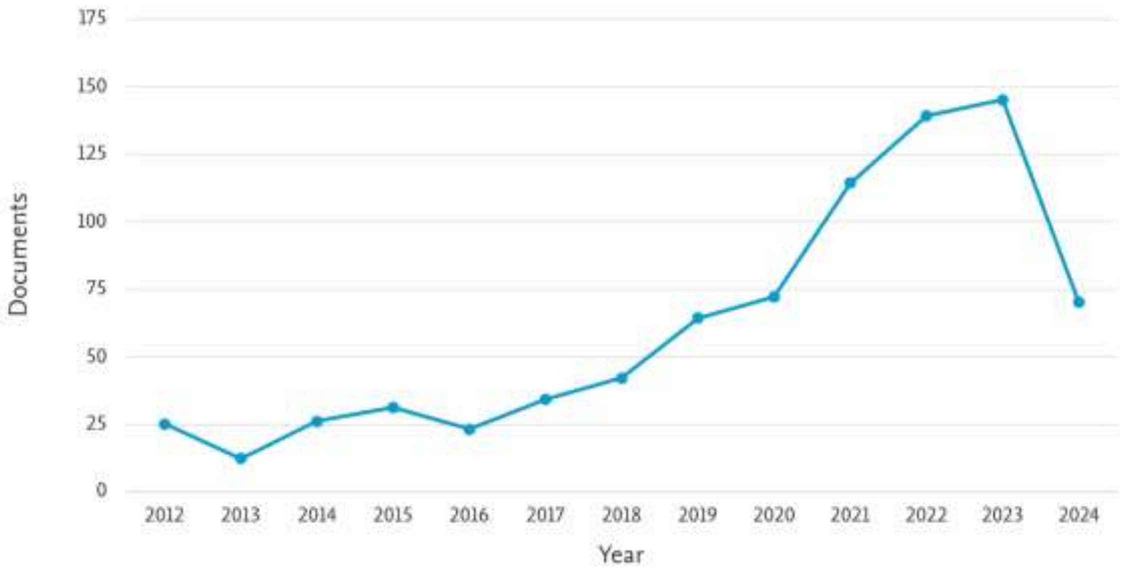


*Figure 2. Studies evolution over the years*

This graphic analyzes the trends in the studies on the topic. LIBs have been very popular in recent years and relevant for the shift towards low-carbon scenarios. This trend is expected to continue as more technology must be developed and new materials and alternatives studied. Research is crucial to create new and better technologies. Therefore, this growth is very significant for future generations of LIBs.

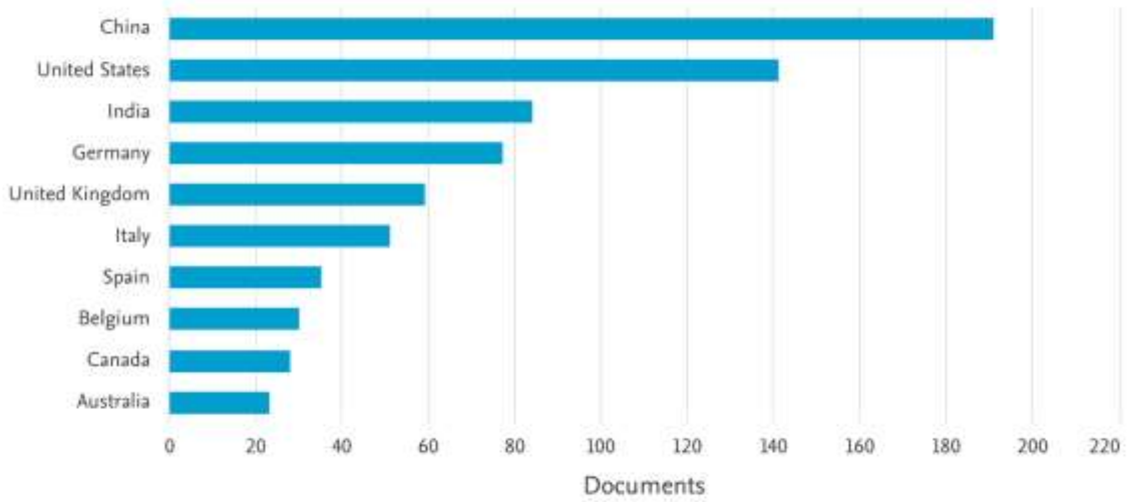


*Figure 3. Countries' input into research*

This graph shows the different countries that contributed to the research. The country with the most significant input is China. This is very coherent, as China is the most significant manufacturer of LIBs globally. The industry in this country is very developed and has an excellent infrastructure. We can appreciate that the European country with the biggest input is Germany, where they are starting to develop that infrastructure and become more relevant internationally. Other European countries, such as the United Kingdom and Italy, are beginning to play a significant role in the industry. The United States is on this list as the great technological power that this country represents in different aspects.

After gathering all the relevant documents, 797 documents had to be analyzed. Different filtrations were conducted to organize the information. First, all the titles and abstracts were read to eliminate the irrelevant articles. Also, some studies were unavailable, so they could not be analyzed. Secondly, the full text was reviewed by skimming and fast reading to eliminate some of these articles. During the duration of this research, at some point, the excluded articles were analyzed again to ensure that all relevant information was obtained.


*Figure 4. Research word cloud*

Voyant Tools was used to analyze the word cloud, Figure 4, which is a visual representation of the keywords that appear in the different studies of the research. The words that appear bigger are mentioned more often in the overall studies. This gave a first approach to the topic. After this, another tool was used to understand the keywords and the relationship between them, as shown in Figure 5.

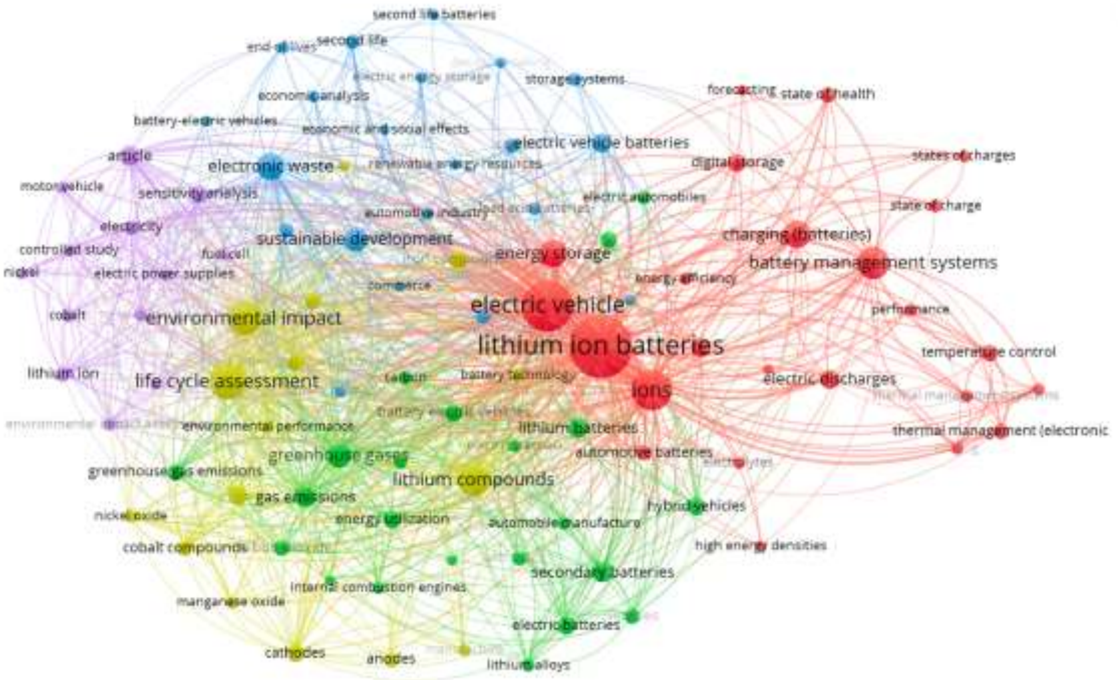


*Figure 5. Keyword Mapping Vosviewer*

Vosviewer was used to evaluate the different keywords in all the documents; it shows how they are all related, the various subjects they talk about, and the main relevance of each keyword. Different attempts and iterations of the interfaces were made to achieve the result. We can appreciate that the principal keywords that appear at the center of the diagram are electric vehicle and lithium ion batteries; these were the principle keywords used and are the most relevant for our search. Different clusters are identified as each color represents one or another. The main cluster is related to the BMS, color red, which has a significant role in the battery's life cycle. Other clusters are related to the anode and cathode, color yellow, and the EoL of the battery, color blue.

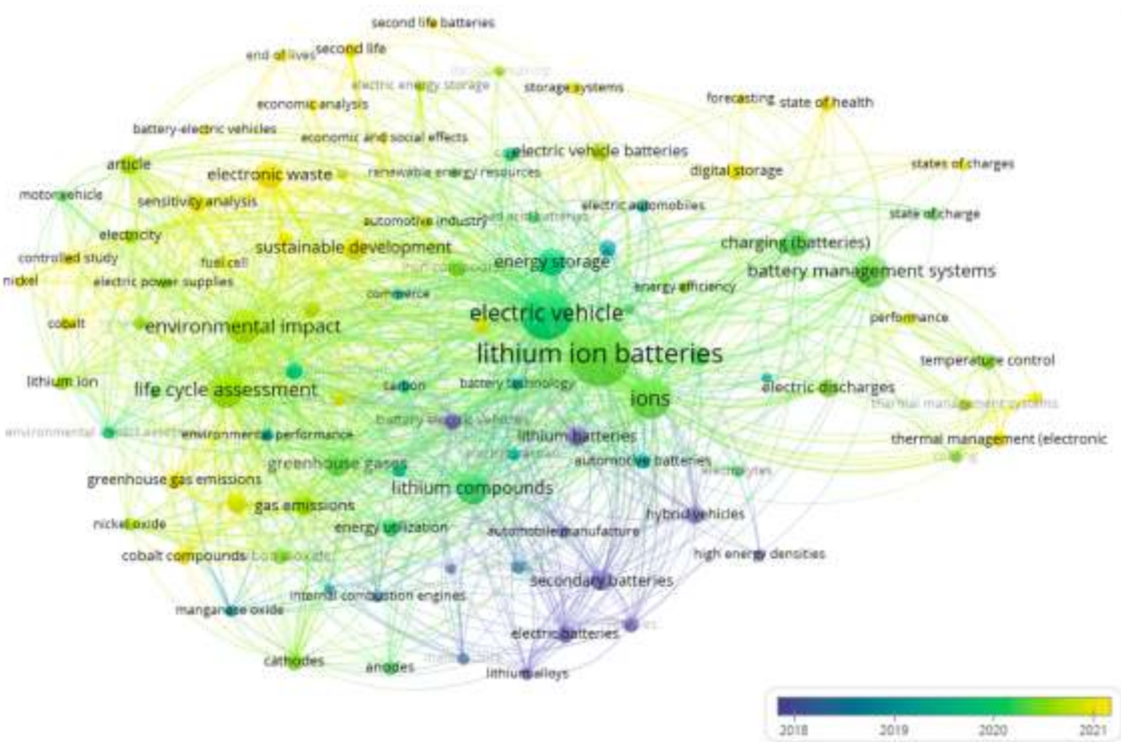


*Figure 6. Clusters related to year studies*

In Figure 6 we can appreciate when different clusters were more related. In 2018, many researchers started to develop the basis for the EV. Later, in 2020, the studies focused on understanding and developing the BMS and began to be concerned about the environmental impact of EVs. Recently, studies have focused on the second life and the EoL of batteries.

# 3. Findings

In this chapter, all the studies are discussed in detail, and all the different aspects related to the value chain of the LIB in the automotive industry are evaluated.

## 3.1. Raw Material Extraction and Refining

The primary metals used in LIBs production are cobalt, nickel, manganese, aluminum, lithium, copper, and graphite (Dunn et al., 2021). There are many different types of anodes and cathodes. Therefore, different combinations and amounts of each material are used depending on the performance of the EV (C. Yang & Mu, 2023). A vital definition is introduced when talking about the different materials used in producing LIBs, Critical Raw materials. Their relative specific economic value can define them as a function of any spent LIB, as well as their supply availability risks. (Tan et al., 2020). These materials have a considerable economic and social impact. The literature agrees that the critical materials are lithium, cobalt, and nickel (Wesselkämper et al., 2024a). While developing LIBs value chain, local communities are being destroyed, and child labor and human rights issues have become very frequent, all because of the EV revolution. Moreover, irresponsibly sourcing raw materials leads to resource shortages, high greenhouse gas emissions, and excessive use of water, waste, and energy, which causes irreversible impacts on the local and natural environment. (Crenna et al., 2021).

The global distribution of essential minerals is significant. In 2019 and 2020, Indonesia, the Philippines, and Russia emerged as the top three major nickel mining countries, representing 29.8-33.0%, 12.0-15.7%, and 10.1-11.3% of the global share, respectively. For cobalt mining, the Democratic Republic of the Congo (DRC) took the lead with 69.0-70.4%, while Australia and Russia contributed 4.0-4.2% and 4.0-4.7% to the global share, respectively. As for lithium mining, Australia 48.7-52.0%, Chile 21.9-22.0%, and China 13.0-17.0% emerged as the top three contributing countries (Z. Yang et al., 2022).

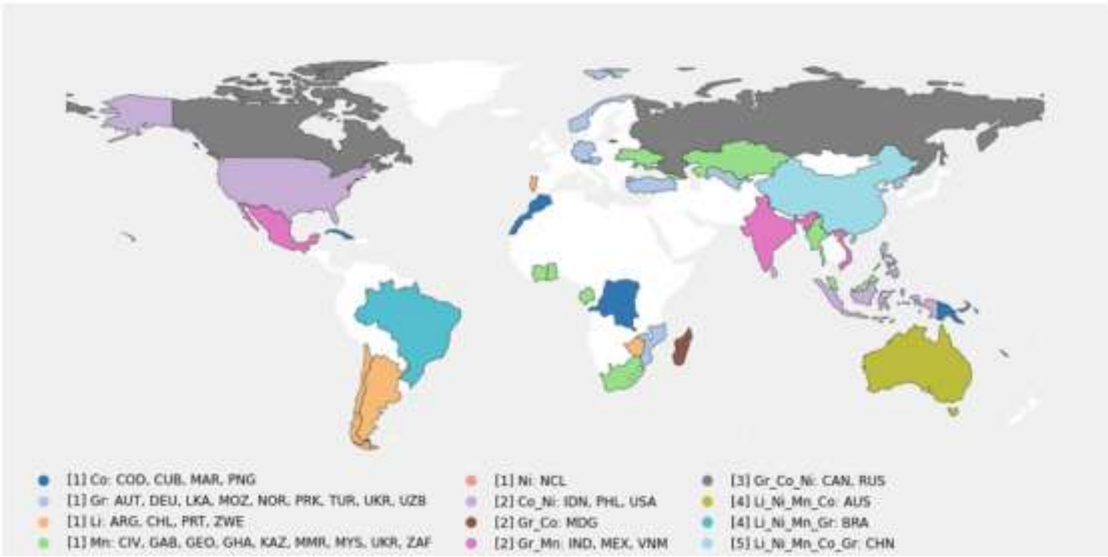


*Figure 7. Mapping of mineral production (Z. Yang et al., 2022)*

While talking about the refining process of the different ores and metals, a big concern is always paired with it, the environmental impact. The production of LIBs typically requires high-purity resources, which necessitate additional processing. Depending on the material refining process, different aspects of the environment are negatively affected; some are less harmful than others, but these are never considered clean (Ferrara et al., 2021).

### *3.1.1. Lithium*

Lithium is a crucial component in rechargeable lithium-ion batteries (LIB), and it is used in both the cathode and some electrolyte materials. It has the lowest reduction potential of any element, resulting in the highest possible cell potential. Additionally, lithium is the third lightest element and has one of the smallest ionic radii among singly charged ions. These properties ensure that lithium will remain essential in battery technology. Lithium carbonate, typically composed of 99.5% $Li2CO3$, constitutes most of the lithium used in EVs (Mayyas et al., 2019). Lithium demand will reach 2.2 million tonnes by 2030, but the supply of this material is only forecasted to reach 1.67 tonnes. Therefore, the market will not be satisfied. There are two main ways to obtain lithium: Lithium brines and traditional lithium ore mining (Kaunda, 2020).

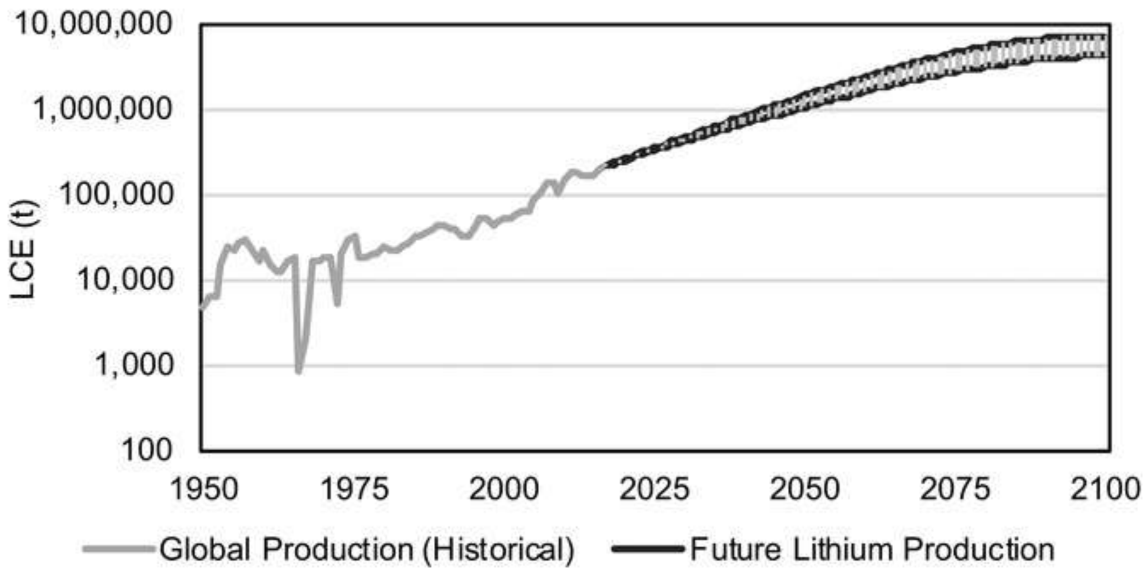


*Figure 8. Future lithium production (Ambrose & Kendall, 2020)*

Lithium brine deposits are accumulations of saline groundwater rich in dissolved lithium. Although abundant in nature, only select regions in the world contain productive sites where lithium salts can be extracted at a profit. Brine typically carries 200 to 1,400 milligrams per liter (mg/l) of lithium (Kaunda, 2020). This solution is pumped to the surface, and thanks to evaporation, the brine gets more and more concentrated in a series of artificial ponds, each one in the chain having a greater lithium concentration and a more yellowish color. The evaporation process must be conducted within specific climate conditions that do not occur all around the globe. Such conditions involve having large surface ponds in arid areas where the sun can consistently impact them. Given this, the process takes place in countries such as Argentina, Bolivia, and Chile, where the "lithium triangle" is located (Kaunda, 2020). Precipitated salts are harvested regularly to maintain the brine volume in the ponds. Once the lithium concentration reaches around 6%, the brine is brought to a lithium chemical plant to remove the impurities such as magnesium and boron. After this process, the conditioned brine is reacted with a soda ash solution to precipitate lithium carbonate (Ziemann et al., 2012). Over 95% of the water extracted from the brine is lost during the different evaporation steps and never recovered. As brine water is in a hydrodynamic relationship with its surroundings, the water-intensive mining process in extremely arid regions such as Chile causes aquifers to deplete and affects the water balance. The concentration process requires as much as 500,000 gals per ton. The water intensity of lithium production has raised concerns among the indigenous people in the arid regions of Argentina, Bolivia, and Chile, where brine processes take place (Mayyas et al., 2019).

Lithium ore mining processes use traditional drill and blast methods. The main lithium minerals are spodumene, lepidolite, and petalite (Ziemann et al., 2012). The lithium ore, which contains 1.0–4.2% Li2O, is processed in different plants where different operations such as gravity, heavy media, flotation, and magnetic take place to become lithium concentrate. Two types of lithium concentrate are distinguished: the technical-grade lithium concentrate, with below 6% of Li2O, and the chemical-grade lithium concentrate, with 6.0% of Li2O, which are made simultaneously and separated. The last one is further processed in lithium chemical plants to produce lithium chemicals. This process takes place in Australia, where 49% of lithium is extracted (Hao et al., 2017).

Hard rock mining of lithium is more energy-intensive and costlier than brine evaporation but has gained market share as the demand for lithium has increased. Lithium production is less responsive to changes in demand because of the two-year processing time required for brine plants and the ten-year time needed to start a new lithium mine (Mayyas et al., 2019).

### *3.1.2. Cobalt*

Cobalt is a material that enhances the durability, structural stability, and efficiency of the LIB; it is used in the cathode active materials of the most common cathode chemistries. Cobalt will likely continue to be used in vehicle LIB, but the cobalt content will decrease as modern technology aims to use less cobalt (Mayyas et al., 2019). DRC dominates the extraction of cobalt, accounting for over 70% of worldwide production. Still, other countries like Australia are getting involved and investing in new infrastructure to extract the material. Unethical activities are related to the production in DRC, such as child labor. This happens at artisanal mines, where roughly 40,000 children work washing and sorting the ore before it is sold (Sankar et al., 2024b). Significant cobalt buyers, including Apple and Tesla, are restructuring their suppliers and purchasing rules to ensure that all metal procedures satisfy high ethical and environmental standards. Tesla, for example, has changed its mind and is moving its suppliers from DRC to Australia to mitigate this problem (Jones et al., 2023). The supply dynamics of cobalt are complicated because it is not typically the primary product of mining operations, but it is produced as a co-product or byproduct. Almost all cobalt is produced as a co-product of nickel (50%) or copper (35%) mining (Mayyas et al., 2019). Cobalt extraction is conducted in two different ways depending on whether the material comes from nickel or copper ores. The two primary production routes for cobalt are nickel-cobalt sulfide ores and copper-cobalt sulfide and oxide ores. The extraction process typically starts with mining, followed by several refining steps that differ based on the ore type and desired final product (Schmidt et al., 2016).

For nickel-cobalt sulfide ores, the process involves mining and concentration through crushing, grinding, and froth flotation to produce a sulfide concentrate. Then, this concentrate is smelted, and a product called matte is created. Furthermore, hydrometallurgical processes are used to refine the matte and produce high-purity cobalt metal. In the case of copper-cobalt ores, two types of ores are processed: sulfide and oxide. Copper-cobalt sulfide ores follow a similar initial processing route as nickel-cobalt sulfide ores, involving smelting and refining to produce cobalt. However, copper-cobalt oxide ores are typically processed hydrometallurgically. This involves leaching, often with sulfuric acid, to produce a cobalt hydroxide intermediate, which is then refined into cobalt chemicals used in battery production, such as cobalt sulfate or oxide. The refining of these ores into cobalt chemicals predominantly occurs in countries like China and Finland, highlighting the global interconnections in the cobalt supply chain (Schmidt et al., 2016).

### *3.1.3. Nickel*

Nickel is used in the active material of LIB's cathode. Nickel increases power and energy capacity, lifespan, and performance. The nickel content of EV batteries is likely to increase in the future; this is because new technologies are contemplating different uses of materials and different combinations where less cobalt is used, and nickel is likely to replace it (Mayyas et al., 2019). The primary producers of nickel are Indonesia, producing around 30%; the Philippines, producing around 13,3%; and Russia, which produces 11% of the worldwide production. Recently, Indonesia announced plans to stop nickel exports to boost its own refining industry (Jones et al., 2023). One subject to consider is the power and impact that resource-rich countries such as the Philippines and Russia have in the price and administration of such materials (Bonsu, 2020). The Russia-Ukraine crisis has raised concerns about maintaining a stable and independent nickel supply. Consequently, nickel prices experienced significant fluctuations in 2022 (Wesselkämper et al., 2024b). Because of this conflict and the high demand for nickel material to produce batteries, the nickel price reached a decade-high of \$48,000 per ton in March 2022, a 400% increase compared to prices in March 2021 (Tarabay et al., 2023).

There are two primary types of nickel ores: laterite and sulfide. For nickel sulfide ores, the extraction process follows the same process as cobalt extraction, where it begins with mining and is followed by crushing, grinding, and froth flotation to produce a sulfide concentrate. This concentrate undergoes a smelting process, resulting in a product called matte. The matte is further refined through various techniques, such as hydrometallurgical, to obtain high-purity nickel metal containing more than 99% nickel, this percentage is suitable to produce LIBs. For laterite ores, two primary types are processed: limonite and saprolite. Limonite ores are generally processed hydrometallurgically through high-pressure acid leaching. This process involves leaching the ore with sulfuric acid at high temperatures and pressures to produce an intermediate nickel-cobalt sulfide or hydroxide. This intermediate is then refined to produce the high-purity nickel. An alternative technique for processing limonite ores is the Caron process. This method entails reduction roasting followed by ammonia leaching. (Schmidt et al., 2016).

The extraction and processing of nickel involve significant environmental considerations, especially regarding energy consumption and emissions. The choice of processing method and the geographical location of production sites further influence the overall environmental impact. Recent nickel-refining projects, including those in Indonesia, have proposed waste disposal in deep sea repositories. Such an approach is controversial and there have been widespread calls for its discontinuation, given the threat to local coral reefs and fish stocks from failures in tailings management. Such an environmental disaster occurred in 2019 at a nickel and cobalt processing facility in Papua New Guinea (Jones et al., 2023).

### *3.1.4. Graphite*

Graphite is the most common material used in the anode of the LIB because of its extensive surface area relative to their size, excellent carrier mobility, and outstanding electrical conductivity (Hossain et al., 2023). Graphite is concentrated in China, with over 78% of worldwide extraction (Jones et al., 2023). Graphite is a pure carbon compound that occurs naturally in many places and can be produced synthetically in the form of charcoal (from wood) and coke (from coal). Although LIBs use only a tiny fraction of global graphite production, the supply of high-purity flake graphite required for these batteries will likely be even more limited.

The mining process starts with the obtention of the carbon ore. The carbon content of the ore is approximately 11%, which means that almost 90% of the obtained ore must be disposed of. The extraction is followed by the crushing and milling processes. Afterward, it enters a multi-step flotation process with the aim of getting a concentration of carbon between 85% and 98%. After flotation, the wet carbon concentrate is filtered and then thermally dried. The following process step is spheronization.  The target of this process is to obtain spherical graphite particles. The graphite product requires these properties to be used in LIBs. The valuable spherical graphite particles are transferred to the purification process. This step is essential as different impurities are removed, resulting in a product that has more than 99,95% of carbon content. The mainstream process for purification is chemical leaching with hydrofluoric acid, nitric acid, and hydrochloric acid, which can be challenging to manage. Finally, a coating step aims to modify the graphite particles to increase their conductivity, sealing their surface to limit the loss of lithium ions in the atomic structure during the first charging cycle and giving particles higher physical strength (Engels et al., 2022).

## 3.2. Battery Pack Assembly

The battery cells are made of five subcomponents: anode, cathode, separator, electrolyte, and cell container (Ellingsen et al., 2014). When a LIB is fully charged, most of the lithium ions are present in the battery's anode (Gaines et al., 2018). The battery must be discharged to generate electricity by letting the lithium ions move from higher potential energy at the anode to lower potential energy at the cathode (Natesan & Prabhu, 2022). As its word suggests, the separator separates both electrodes and controls the rate at which lithium ions move from one electrode to another (Arambarri et al., 2019). While the ions are moving through the electrolyte, electrons are conducted from the anode to the cathode through the external circuit. The electron movement and voltage between the two electrodes are used to power an EV (Natesan & Prabhu, 2022). As shown in Figure 9, this process also takes place in the opposite direction when charging. The battery must be connected to an external power source; after that, lithium ions and electrons can be forced to move from the cathode back to the anode (Winslow et al., 2018). Each individual cell can produce a voltage of 4 V. EVs applications need higher voltages than this; therefore, several cells are connected in series, parallel, or a combination of both to reach the voltage requirements of EVs (Turksoy et al., 2020).

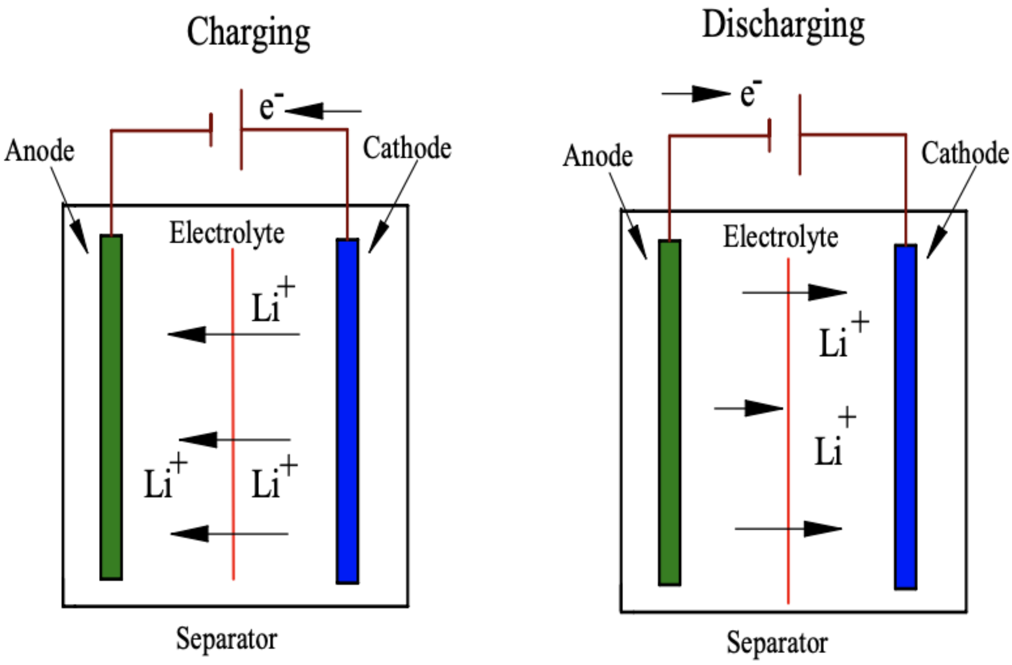


*Figure 9. Battery charging and discharging (Natesan & Prabhu, 2022)*

The whole battery pack consists of four primary components: the cell, BMS, the cooling system, and the packaging. The cell contains the active materials, the BMS oversees the performance and safety of the batteries, the packaging serves as the structure that connects the cells, and the cooling system oversees the thermal performance of the battery (Sankar et al., 2024a).

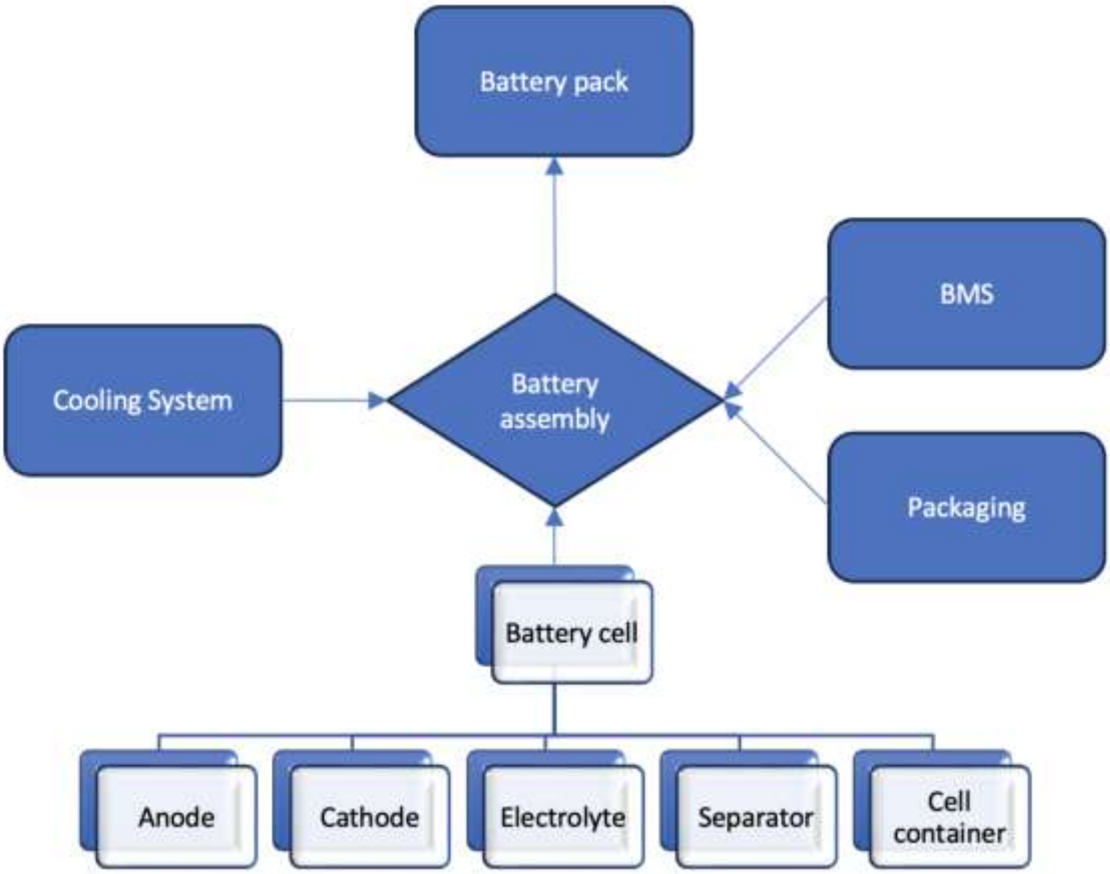


*Figure 10. Battery pack component (adapted from (Ellingsen et al., 2014))*

### 3.2.1. Battery Cell

The battery cell is where all the different critical raw materials are. The two main components of the battery cell are the anode and cathode, where electrons' movement occurs. LIBs use various types of chemistries when building different batteries. Depending on the composition of each LIB, it has different qualities and properties.

#### *Cathode*

The cathode is the positive active part of the battery and has been found to be a bottleneck in terms of the specific capacities of the battery. This part of the cell has the most significant amount of valuable materials and is where the main studies focus their attention. This battery component must have high discharge potentials compared to Li/Li+ and maintain good capacity retention. Due to their high technological maturity, nickel, cobalt, and manganese (NCM) are the chemicals that are primarily used in LIBs (Schmuch et al., 2018). This technology ensures that batteries can store large amounts of energy while maintaining safety. The cathode composition has been developed using different approaches regarding using nickel and cobalt in the battery. A higher nickel content increases the battery's capacity, which is crucial for the autonomy of EVs. It is also important to reduce the cobalt content due to the unethical practices involved in its extraction. Therefore, higher nickel-content batteries are gathering attention. Different materials, such as NCM622 and NCM811, have 60% and 80% nickel contents, respectively, and have shown great performance (Tan et al., 2020).

#### *Anode*

While the primary focus has been on investigating cathode materials, it is important to note that the anode also significantly contributes to the efficient operation of LIBs (Hossain et al., 2023). Graphite is the most used material for the anode composition, as over 89% of all commercial LIBs use it. There has been a new trend in the literature, and more studies focus on developing new anodes combining silicon-graphite materials. This is expected to improve the battery's performance (Engels et al., 2022).

### *3.2.2. Battery Design*

We can identify different characteristics such as the shape, the size, or the structure. These parameters directly influence the temperature, cost, efficiency, and safety. There are three main types of cell shapes used in EVs found in the literature: cylindrical, prismatic, and pouch (Han et al., 2019)(Reinhart et al., 2023)(Natesan & Prabhu, 2022).

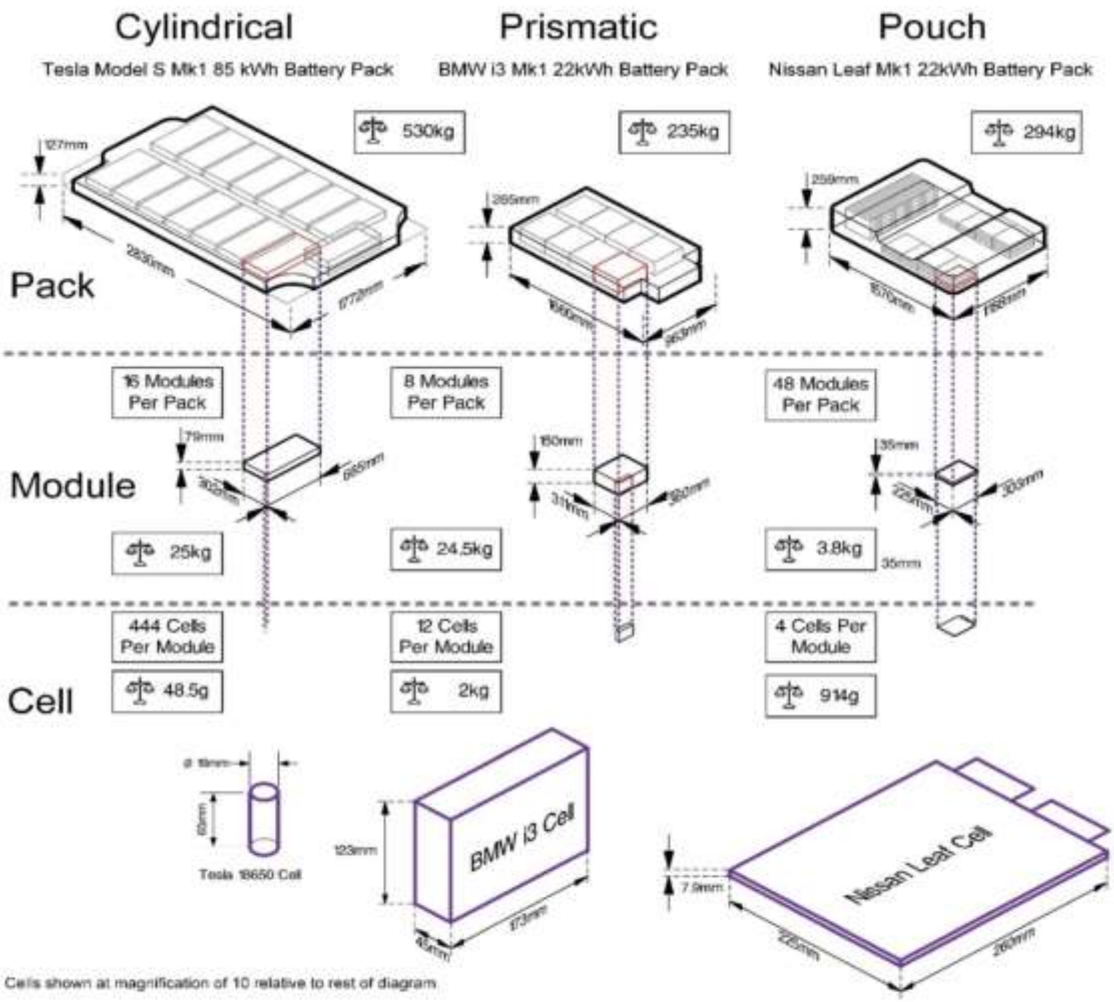


*Figure 11. Different types of battery cells and how they are organized to form modules and packs (Thompson et al., 2020).*

## *Cylindrical Cell*

The cylindrical cell is used widely in the automotive industry due to its low cost, ease of manufacture, and good mechanical stability. For instance, the Tesla Model S uses this kind of battery; it benefits from a low-cost and high-capacity density (Hamed et al., 2022). During charging and discharging, the battery's relatively small heat dissipation area, caused by its low specific surface area, results in higher internal temperatures (Han et al., 2019). This elevated temperature has a negative impact on the battery life. Also, the cylindrical cell is usually packed tightly, resulting in very high internal stress.

### *Prismatic Cell*

The prismatic cell design has great packaging efficiency and high efficiency; for example, this cell shape is used in the BMW i3 (Schmuch et al., 2018). Some of the advantages of this cell are related with its weight-volume efficiency, adaptable design, and low assembly cost (Han et al., 2019). Furthermore, it has a significant heat dissipation area and demonstrates minimal deformation. This is the cell type that provides higher energy content (Hamed et al., 2022). Although it presents challenges for cell manufacturers, it proves to be more manageable for module manufacturers.

### *Pouch Cell*

Pouch cells are characterized by their flexible, flat, and rectangular shape. It uses soft packaging, is very safe to use, and has great weight-volume efficiency because it has a big adaptability to different casing shapes (Han et al., 2019). This cell type is widely used; an example of a car model is the Nissan Leaf (Schmuch et al., 2018). This cell has an excellent heat dissipation performance (Hamed et al., 2022); however, it lacks mechanical strength (Han et al., 2019). Although it presents challenges for module manufacturers, it proves to be more manageable for cell manufacturers (Hua et al., 2020). In Figure 12, we can appreciate a comparison between different shapes.

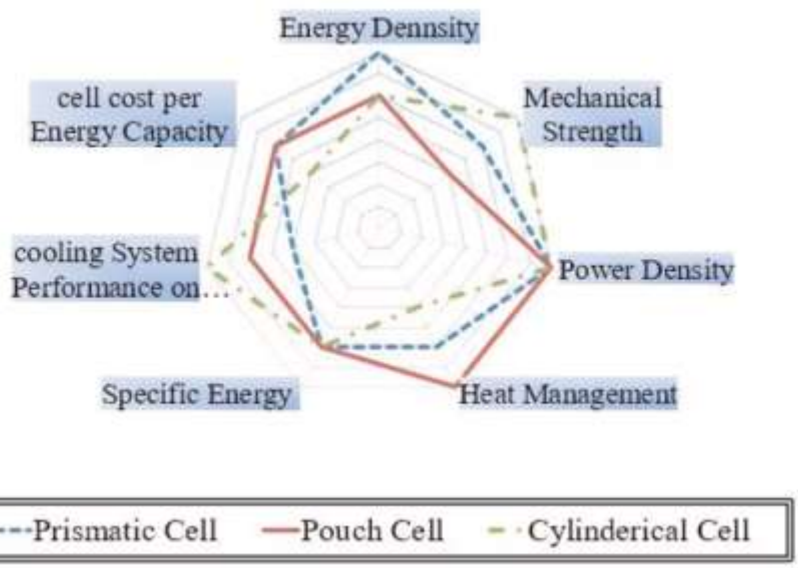


*Figure 12. Comparison between properties of common lithium-ion cell designs (Hamed et al., 2022).*

*Cell Size*

The cell size is also very important for the performance of the EV. The main purpose of cell size optimization is to make the current flow through the active materials more uniform, preventing side reactions and decreasing the rise in temperature (Han et al., 2019).

*Internal structure*

The internal structure of the anode and the cathode greatly impacts the life of the LIB. Two different types of structure can be defined: stacked and wound. The process of making wound-type jelly rolls is simple and efficient. In contrast, the production of stacked-type electrodes is relatively inefficient. During the production and due to its shape, the wound type has large deformation in the production, leading to possible safety and durability problems. During the charging and discharging process, there is a volume change, this change affects the mechanical stress much more to the wound type than the stacked. Regarding internal resistance, the wound type has more resistance than the stacked one. Based on the analysis, batteries with a stacked-type structure generally last slightly longer than those with a wound-type structure (Han et al., 2019).

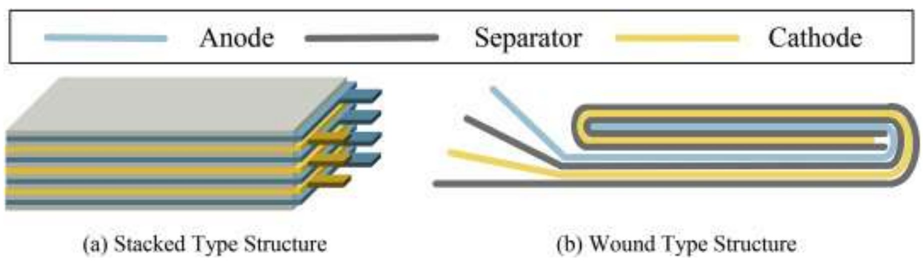


*Figure 13. Different types of cell internal structures (Han et al., 2019)*

### 3.2.3. Battery Management System

To control and manage each cell that is involved in the battery pack, a BMS is needed (Ellingsen et al., 2014). With this system, the battery performs under favorable conditions. Some crucial tasks that the BMS must consider are monitoring the battery, estimating battery states, protecting the battery, heat management, recording the key data, and communication (Massaoudi et al., 2024). It is considered an electronic system that serves as the brain of the battery system (Shrivastava et al., 2023). In Figure 14, there is an overview of the different assignments that the BMS takes into consideration.

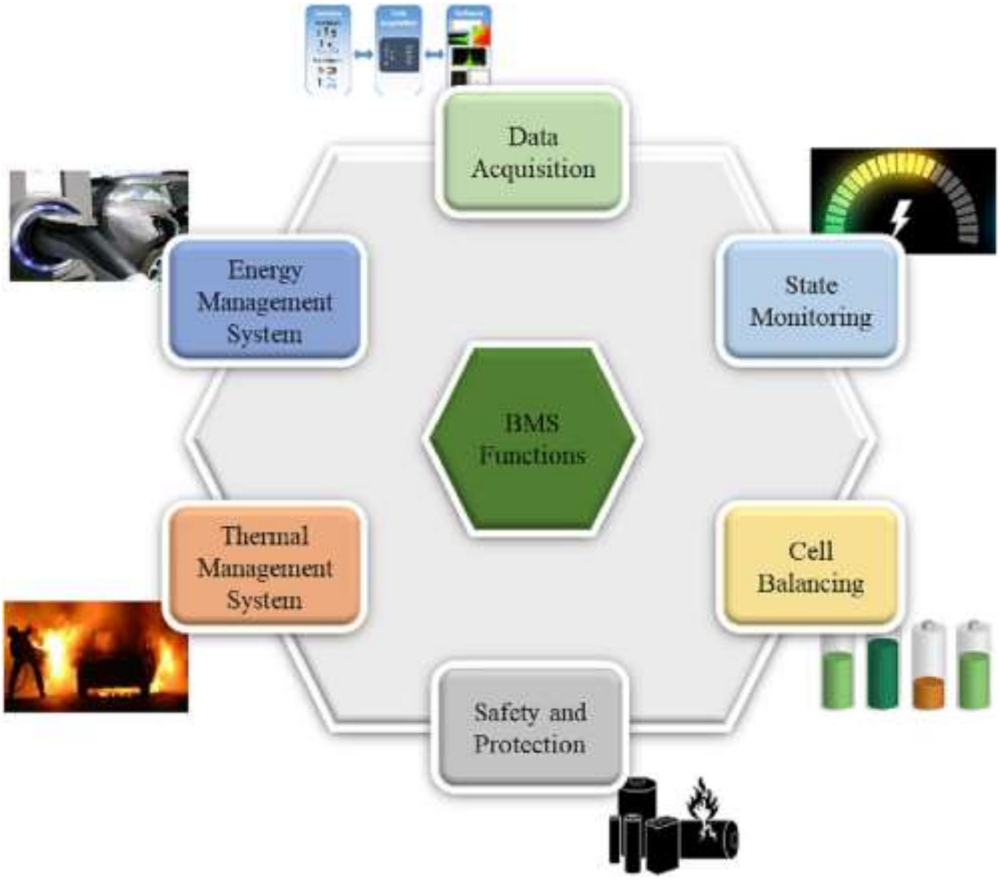


*Figure 14. Overview of the BMS (Shrivastava et al., 2023)*

The main battery cell monitoring parameters that the BMS must consider are the voltage, the current, and the temperature (Massaoudi et al., 2024) (Karthick et al., 2024). With this information, it controls the charging-discharging rates, estimates the SoH or the State of Charge (SoC), and manages heat dissipation (Karthick et al., 2024). It can also estimate the state of power and the state of energy (Shrivastava et al., 2023), but the literature mainly focuses on SoH and SoC.  With this information, the BMS assesses and diagnoses to protect the battery from overcharging, over-discharging, and high temperatures, ensuring safety control of the LIB (Turksoy et al., 2020).

### 3.2.4. Packaging

The packaging incorporates the electrical connections and housing; it serves as the structure that connects and protects the cells. The battery housing is the one in charge of protecting the internal components from any external impacts (Tan et al., 2020). The perfect characteristics for the battery case are lightweight and structural strength. A very heavy battery may cause trouble as more energy is consumed to move it. Therefore, aluminum alloys are commonly used. During the using phase, the casing must maintain its integrity when exposed to vibrations and mechanical impacts. Dimensions of the battery housing are crucial. It must fit the number of cells the battery needs to satisfy its voltage demand while being efficient enough to not weigh too much and have proper structural resistance (Shui et al., 2018). The battery tray oversees housing all battery components and is closed with a sealed lid that is usually made from steel. The housing accounts for a battery retention system, which keeps the battery modules in place within the battery tray using straps, restraints, and foams (Ellingsen et al., 2014).

### *3.2.5. Cooling Systems*

Thermal issues associated with the EV battery pack can significantly affect their performance and life cycle. A proper cooling system configuration is vital for the LIB to operate among its ideal temperature characteristics. As mentioned in Hamed et al. (2022), the ideal temperature performance of LIBs is between 15 ◦C and 35 ◦C. The temperature difference between each cell should be maintained below 5 °C to maximize its performance (Akinlabi & Solyali, 2020). If the battery works at low temperatures, its capacity and power output will be decreased, and the internal resistance will increase; it was even found that while working below -20ºC, the power, and energy are virtually missed (Hamed et al., 2022). Also, if working with high temperatures, the battery degradation will be significantly higher, and there will be a risk of thermal runaway, leading to safety hazards such as fire or explosions; that is why searchers don’t usually work over 60 ºC (Li et al., 2023). Reducing uneven temperature distribution is also an essential aspect that this system must handle (Karimi & Li, 2013).

Three different cooling systems have been identified in the literature. Depending on various battery characteristics, such as the cell shape, power demand, materials, or configuration, one method will be more suitable than others (Kalaf et al., 2021). Different types of cooling methods and fluids are used to control the LIBs' temperature as shown in Figure 15.

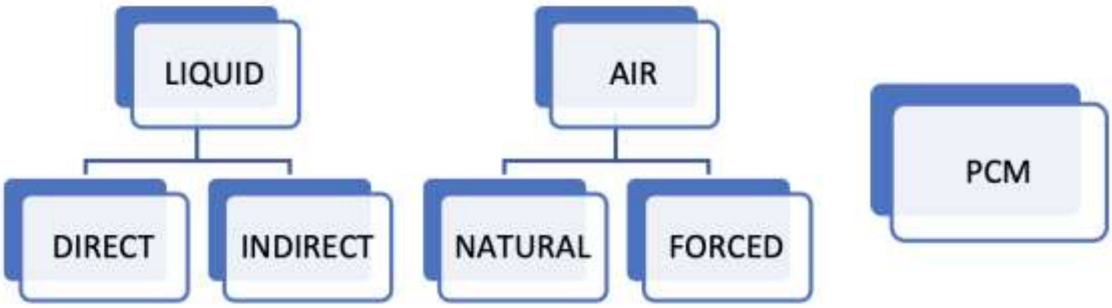


*Figure 15. Classification of the different cooling system methods (adapted from Akinlabi & Solyali, (2020))*

The most traditional method is air cooling, a simple and affordable approach. We can identify two different ways of managing temperature with this fluid, the active method, using forced convection, and the passive method, using natural convection (Akinlabi & Solyali, 2020).

The liquid cooling system is designed to efficiently remove substantial amounts of heat because of the liquid coolant's superior heat capacity and mass flow rate when compared to air. We can distinguish between two different approaches to liquid cooling: direct and indirect cooling systems. In direct cooling, the coolant directly contacts the battery cells or modules (Jang et al., 2022). While the indirect method, the coolant circulates through channels or tubes that are in thermal contact with the battery cells but not directly (Saw et al., 2015).

Phase change materials (PCM) are substances used in thermal management systems to absorb, store, and release thermal energy. This material can release or absorb an amount of thermal energy at phase change (Hamed et al., 2022).

## 3.3. The Middle Life of the Battery

While using the LIB, different aspects of the battery's health related to its performance, such as available capacity, available energy, and available power, will be degraded when the battery ages (Han et al., 2019). The literature agrees that with proper use and without abuse or safety accidents, a battery's capacity will typically decrease over time until it reaches 80% of its initial capacity. At this point, it is considered to have reached EoL because it can no longer meet the requirements of the vehicles (Li et al., 2023) (Shah et al., 2022). The average life expectancy of a new LIB is around 8 years, but of course, it can vary depending on the use and other factors. Also, the average run of EVs varies from 100 to 400 km, which is not enough for long drives (Hasan et al., 2021). The main topic of study during the using phase of LIBs is focused on the SoH of the battery and SoC (Han et al., 2019).

### 3.3.1. Charging and Discharging

To be able to reuse the battery repeatedly, it must be charged. By charging the battery, a flow of electrons takes place, Li-ions flow from the battery cathode and intercalate in the anode (Natesan & Prabhu, 2022). The reverse process occurs in the discharging phase. This constant movement of electrons creates a charging cycle or loop. Cycling aging is the factor that most contributes to capacity loss and directly affects charging and discharging. As the battery ages, the discharge voltage and time shortens. Also, the charging time is influenced by this aging but less than the discharging time (A. Yang et al., 2019).

#### *State of Charge*

The SoC determines the weight of both the charging and discharging processes. A relationship to understand how much energy remains in the battery compared to when it was fully charged must be determined to understand the SoC (Song et al., 2020). The ratio of remaining charge to normal charge best suits measuring it. This can be complicated as unexpected acceleration, deceleration, and charging cycles make it difficult (Shah et al., 2022). The BMS plays a critical role in monitoring the LIBs using phase, maximizing the using life by determining the SoC (Shah et al., 2022). Petit et al. (2016) showed that the ideal range of charging and discharging rate is “Just in Time” charging, where the battery is charged up to 90% of its SoC and discharged to up to 10% of its SoC. Later, Shrivastava et al. (2023), studied the effects of temperature while charging/discharging and came up with the same rate of charging/discharging of 90-10%. If overcharged or over discharged, there is a significant concern regarding safety and the risk of explosion as the battery degrades (Hamed et al., 2022).

#### *State of Charge Estimation*

The usage phase of LIBs for EV purposes ends when the battery reaches 80% of its initial capacity. The successful operation of an EV depends on the operation of the BMS. SoC is one of the main parameters of the BMS. Therefore, an accurate estimation of the SoC will lead to a longer battery life and help prevent accidents. The main methods to conduct this estimation are model-based and data-driven (Song et al., 2020).

The model-based estimation methods are designed using the knowledge of the background processes. This method is widely used in the engineering domain to solve and provide a reasonable solution to different problems. This method is very powerful and accurate for the estimation of LIBs SoC due to its deep understanding of the system and the use of mathematical models (How et al., 2019).

The data-driven method is built upon empirical observations with not much knowledge of the subprocesses. It relies extensively on analyzing data from the process, as it does not require a deep understanding. This method is heavily dependent on the data quality and the accuracy and performance of the model (How et al., 2019).

The standard or specialized laboratory tests do not consider the LIB's different operating conditions. Moreover, all the data available to model a system could be unbalanced and mislead the system. Therefore, a combination of both methods, data-driven and model-based, must be taken into consideration to merge the strengths of both approaches. This method is the Hybrid method and is used to improve the accuracy and robustness of SOC estimation (How et al., 2019).

### *Battery Balance*

Due to the physical properties that differ from one and another battery cell, a consecutive charge-discharge cycle creates stress and charge disequilibrium. This is because not all cells are manufactured the same, there is some tolerance between each battery, and their properties may change due to temperature or aging problems (Hasan et al., 2021). Because of this, each cell can be discharged and charged at different rates, as shown in Figure 16. Kim et al. (2013), used a battery monitoring integrated circuit centralizing the equalization converter and integrating the control into the monitoring integrated circuit to balance the cells, while Ji et al. (2014) using multi winding transformers, effectively balanced the voltage of LIB cells by transferring energy both within and between modules, ensuring uniform cell voltage.

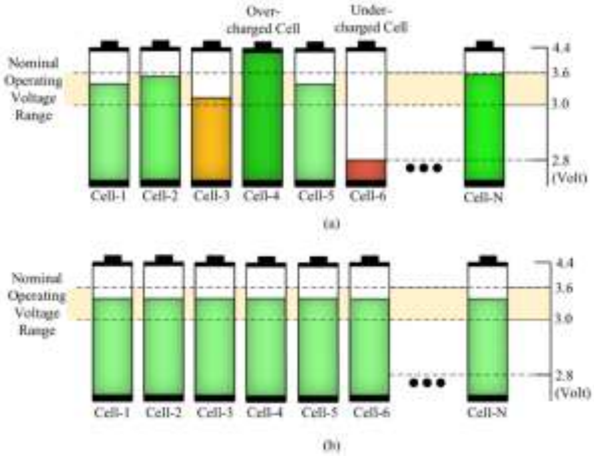


*Figure 16. a) Unbalanced cell, b) Balanced cells (Turksoy et al., 2020)*

### 3.3.2. Temperature Management

Thermal control during the use phase of the battery is essential to conduct a responsible and safe use of it. As mentioned during the cooling systems, the battery must operate at a coherent temperature of 15–35 °C to maximize its performance and cycle life and reduce its degradation due to high and low temperatures. The cycle life and capacity of the LIB are inversely proportional to the temperature of the cell (Hamed et al., 2022). Also, the battery design is influenced by the temperature gradient. Bigger batteries have bigger temperature gradients due to the larger thermal resistance of the layered active material. Meanwhile, smaller batteries have a more uniform profile and less thermal resistance. The temperature difference between one and other cell is crucial, around 3 to 5 ºC should be the biggest divergence to have an optimal performance (Saw et al., 2014).

Temperatures that are outside the scope of the optimal performance of the LIB causes loss of active material, increasing the internal resistance. High temperatures can lead to the decomposition of the electrolyte, resulting in the formation of by-products that contribute to material loss on both the anode and cathode. In addition, the metals in the cathode can dissolve into the electrolyte, which not only reduces the structural integrity of the cathode but also leads to the deposition of these metals on the anode, reducing the SoH of the battery (G. Zhang et al., 2024).

### *Thermal runaway*

Thermal runaway is a very important safety issue, this happens when the battery's temperature is very high and large material decomposition occurs. This is typically caused by severe abuse, including mechanical, electrical, and thermal abuse. When an internal short circuit occurs due to these abuses, it causes an immediate release of electrical energy and results in significant heating (Kumaravel et al., 2021). As a result, the battery heats to extreme temperatures due to this released heat, and thermal runaway occurs. A single cell's ignition can cause nearby cells to undergo thermal runaway, potentially leading to the entire battery pack failing and creating serious safety hazards. Temperatures around 165 °C in the central cell are required to trigger the thermal runaway in the module. (Jiang et al., 2022).

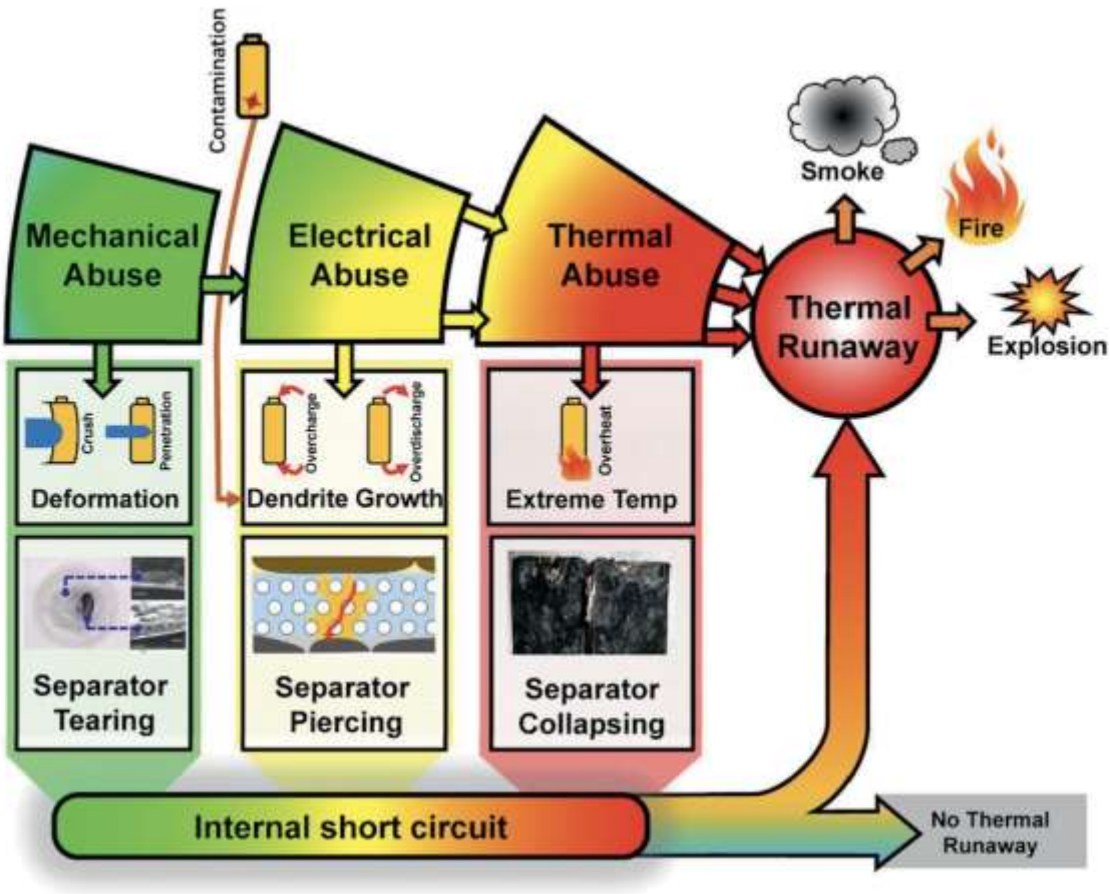


*Figure 17. Thermal runaway abuse conditions (Kumaravel et al., 2021)*

### 3.3.3. Components Aging

Repetitive cycling and continuous use of the LIB will inevitably lead to mechanical aging and degradation of its various components. All parts of the LIB will be affected to some degree, with changes to their composition occurring. Mechanical stress in repeatedly charging and discharging processes can cause the active material particles in the anode to break. Also, the anode material undergoes expansion and contraction during cycling, which can cause mechanical degradation over time. Mechanical stress makes the cathode active material susceptible to particle fracture like the anode. The cathode's structural degradation will eventually reduce its ability to effectively store and release lithium ions (Hendricks et al., 2015).

The Solid Electrolyte Interphase (SEI) layer forms when the electrolyte goes through reduction reactions at the anode surface. When new cells are used for the first time, they undergo an initial formation process where the original SEI layer is created to stabilize the battery performance. This layer develops on the surface of newly exposed particles and initial cracks (Shao et al., 2023). The SEI layer is made of lithium salts, organic carbonates, and other decomposition products. The primary function of the SEI layer is to protect the anode by creating a barrier that prevents further reactions between the electrolyte and the anode, thus stopping the electrolyte from breaking down. Nevertheless, a non-stable thickness can lead to great degeneration, safety issues, and decreased LIB performance (Li et al., 2023).

Lithium plating occurs when lithium ions deposit as metallic lithium on the anode surface instead of intercalating into the anode material. This is caused by high charging rates, low temperatures, overcharging, and high SoC (G. Zhang et al., 2024). Lithium plating reduces the amount of active lithium available for intercalation, increases internal resistance, and can cause safety hazards. It directly affects the battery’s performance and reduces its SoH. Lithium plating results in the formation of lithium dendrites on the anode surface, which can deform or penetrate the separator, causing a short circuit and thermal runaway of the battery (Li et al., 2023).

Electrolytes mainly degenerate due to high temperatures and overcharging. As a result of the decomposition of the Electrolyte, the SEI layer thickness gets bigger, and CO2 gas can be generated. The degeneration can cause internal short circuits, leading to thermal runaway and potential fires or explosions. The electrolyte aging has a big impact on the separator. If the separator's integrity is compromised, the electrodes can come into contact, causing an internal short circuit (Hendricks et al., 2015).

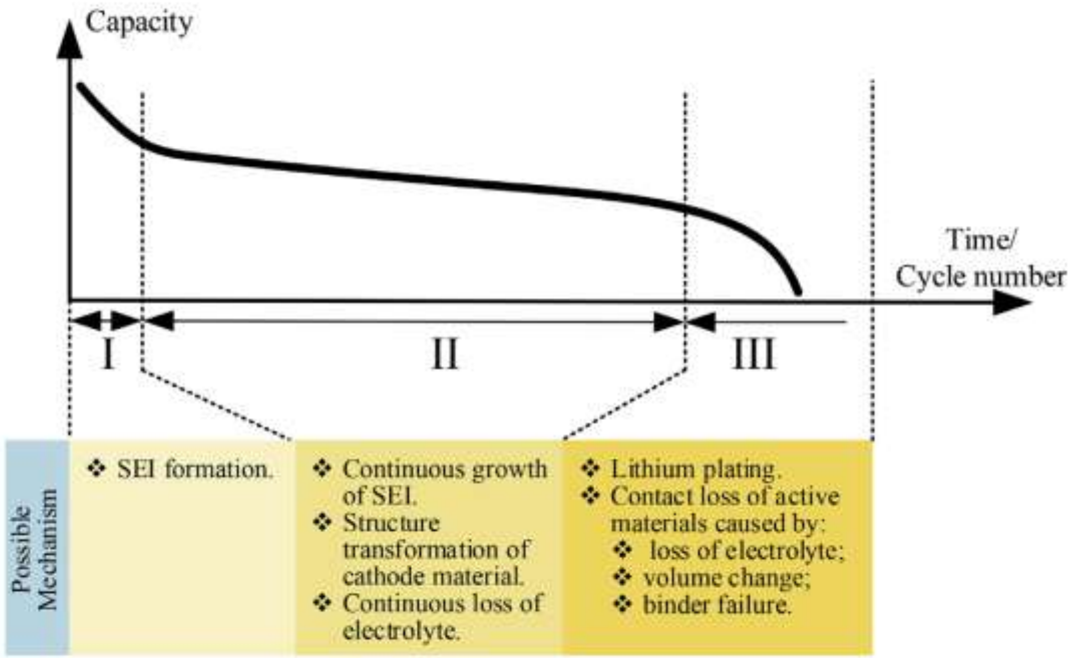


*Figure 18. Different stages of the mechanism degradation (Han et al., 2019)*

## 3.4. End of Life

The global market for retired LIBs is projected to increase by 2035 significantly. As a result, it is crucial to address the EoL of LIBs properly. The management of retired LIBs traditionally involves disposal, recycling, and reuse. Disposing of the batteries means they will be abandoned and discarded, releasing pollutants into the environment and affecting human health. Some of these LIBs are sent to waste-to-energy plants, where they get incinerated to generate energy, and most of the disposal LIBs are sent to landfills directly (Hua et al., 2020). In addition, disposal results in significant waste due to the loss of valuable materials such as Cobalt and Lithium. In Figure 19 the preferable waste hierarchy is defined and can be observed that disposal is the last approach to be considered. In response to the increasing demand for EVs, there has been a notable rise in the prices of cobalt and lithium in recent years; therefore, wasting this material is both economically and environmentally inefficient, as virgin materials will have to be extracted instead of recovering them from the batteries that are being disposed of. Alternatively, the process of recycling involves carefully breaking down retired batteries into their individual components. Through this process, valuable materials such as metals and cathode active materials can be carefully extracted using a combination of physical and chemical techniques. This sustainable approach allows for the recovery of precious resources and reduces the environmental impact of spent batteries (Hua et al., 2020). Effectively utilizing retired LIBs can lead to extended battery life, conservation of natural resources, and enhanced environmental protection. Even when LIBs reach the end of their useful life, they still retain 70–80% of their initial capacity (Hua et al., 2020). They no longer meet the high requirements of EVs but still have a reasonable capacity for other applications. That is why recycling is not the first option to consider in some cases. The reusing business model of LIBs is more sustainable and can extend the battery's life, giving it a second life (Kampker et al., 2023). Europe should take more responsibility for managing waste batteries, even though key European policies, such as the Batteries Directive (2006/66/EC), the EoL Directive (2000/53/EC) and Directive 2009/125/EC, provide a framework to manage the environmental impact of batteries throughout their lifecycle, including their collection, treatment, and recycling (Bonsu, 2020). Based on the literature review, there has been a noticeable trend towards the EoL stage in recent papers. Older studies tend to emphasize recycling and repurposing due to growing environmental concerns. Many earlier papers also suggest future research on the impact analysis of the recycling stage, indicating an existing awareness of material shortages.

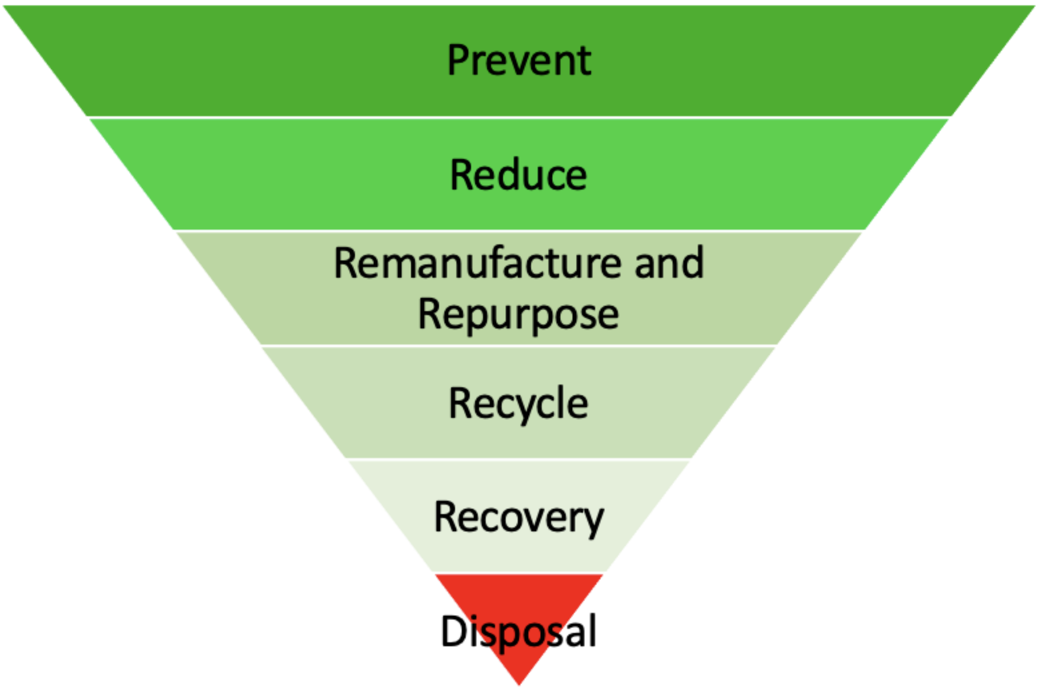


*Figure 19. Preferable waste hierarchy.*

### 3.4.1. Reusing

Following the natural path of the battery's life, reusing is the first approach to consider when the battery is no longer useful for EVs. With the advent of new technologies and renewable energies, a need for storage energy has appeared. The batteries that are no longer useful for EV porpoises are still very useful for other storage applications, giving them additional value and extending their total service lifetime (X. Zhang et al., 2018). Establishing a reuse strategy gives Europe the opportunity to become a significant battery manufacturer. Currently, Europe is dependent on external suppliers, primarily Asian. Once battery reusing settles, Europe will be able to position itself as a major global provider, given that many EVs (around 40%) are being sold in Europe. Managing this substantial battery volume and giving it a second life could generate significant revenue and enhance Europe's importance worldwide (Kotak et al., 2021). Two different approaches can be taken into consideration when reusing a battery. We can distinguish between remanufacturing and repurposing.

#### *Remanufacturing*

Remanufacturing consists of restoring retired LIBs to their original specifications so they can be used again in their initial application. This method is mostly used when a particular module cell is damaged or in case of an accident. Before restoring the battery, an assessment process must be conducted to consider whether the battery is suitable for remanufacturing or not. The SoC estimation and Remaining Useful Life (RUL) studies of each battery are essential for evaluating and examining them (Hua et al., 2020). Screening is very important as it identifies degraded cells within the battery module. This uses non-destructive detection of cells that may cause safety hazards (Romanenko & Jerschow, 2021). Once the battery is suitable for remanufacturing, it undergoes a minor disassembly and assembly to meet the specifications required. The last step of the battery to be used again is a series of tests ensuring it meets all required specifications, including capacity, power, and safety standards. This battery can be put in circulation again in automotive applications or sold as spare parts (Hua et al., 2020). Some automotive companies have begun to commercialize products using second-life batteries, which are much more affordable (Fan et al., 2020). Remanufacturing spent LIBs saves 40% of the cost of using new batteries (Chen et al., 2019).

### *Repurposing*

If a battery pack is unable to hold its desired capacity, such as when it is only at 80% capacity, remanufacturing may not be economically viable. In such cases, repurposing the batteries becomes a viable alternative (Chen et al., 2019). Repurposing involves a process like remanufacturing, where the batteries are tested for their remaining capacity and safety. Based on the condition of each battery, it can be repurposed for use in different applications, giving it a second life (Hua et al., 2020). Nevertheless, repurposing not only involves changing the damaged cells but also reconfiguring the modules or packs and establishing a new battery BMS to accommodate other applications (Chen et al., 2019). These reused batteries can be used in different fields, such as industrial, commercial, and household. The main purpose is mainly for stationary applications, but it can also be used for mobility as an e-scooter, forklift, or e-bicycle (Hua et al., 2020). Energy storage systems are crucial for new technology developments. With the growth of renewable energy deployment, stationary storage now plays a crucial role in addressing the challenges faced by renewables. Traditionally, lead-acid or aqueous batteries dominated this market; nevertheless, spent LIBs can meet this high demand and are getting ahead in the market. Therefore, the repurpose of LIBs in energy storage systems is getting more attention (Tan et al., 2020). Automotive leader Nissan and power management leader Eaton have collaborated to create "xStorage," utilizing retired Nissan Leaf batteries to offer reliable and affordable home energy storage solutions in Europe (Fan et al., 2020). For example, 280 of these batteries are used as backup power in Amsterdam Arena, home to the AFC Ajax football team (Chen et al., 2019).

## *3.4.2. Recycling*

Recycling is crucial for the future sustainability of batteries and is influenced by factors such as environmental impact and resource value. Recycling retired LIBs can be considered the new “urban mines”. By 2030, the global LIB recycling market is projected to reach 23.72 billion USD, indicating a significant economic impact (Fan et al., 2020). In European countries, by 2030, recycled resources should account for 15 % of the annual consumption (Jannesar Niri et al., 2024). Table 1 shows the different European countries that have battery recycling plants (Duarte Castro et al., 2022). European countries use an industrial alliance and vehicle distribution network to collect retired battery packs from EVs. European laws require companies to take back the batteries they sell and recycle them, with a minimum recovery rate of 50% of the total mass. New proposed regulations even aim to increase the minimum recovery rate to 65% (Blömeke et al., 2022).

However, collecting the batteries is not always an easy task, as second-hand cars can be exported to countries with other types of regulations, which do not include strict regulations or the abandonment of these electric cars by the EV owner, which does not allow the manufacturer to recycle them (Cong et al., 2021). The literature points out three main recycling methods: pyrometallurgy, hydrometallurgy, and direct recycling. These methods mainly focus on recovering the active part of the cathode, which is the electrode containing the main precious metals (Slattery et al., 2021). Nevertheless, a new method is currently being studied, biohydrometallurgy. Different steps should be considered before recycling, such as collection, transportation, discharging, and dismantling (Kotak et al., 2021).

| Company | Country | Process | Type of batteries treated | Capacity (tons/year) |
|---|---|---|---|---|
| RECUPYL S.A. | France | Hydrometallurgy | LIBs | 110 |
| G&P Batteries | UK | Hydro or Pyrometallurgy | Various | 145 |
| BATREC AG | Switzerland | Pyrometallurgy and mechanical treatment | LIBs | 200 |
| Euro Dieuze/SARP | France | Hydrometallurgy | LIBs | 200 |
| SNAM | France | Pyrometallurgy, mechanical separation and hydrometallurgy | NiCd, NiMH, LIBs | 300 |
| Duesenfeld | Germany | Combination of mechanical and hydrometallurgical | LIBs | 3000 |
| AKKUSER Ltd. | Finland | Mechanical treatment | NiCd, NiMH, LIBs, Zn alkaline | 4000 |
| ACCCUREC GmbH | Germany | Pyrolysis, mechanical treatment and hydro or Pyrometallurgy | NiCd, NiMH, LIBs | 6000 |
| UMICORE S.A. | Belgium | Pyrometallurgy followed by hydrometallurgy | LIBs | 7000 |
| Redux | Germany and Austria | Mechanical and hydrometallurgical | Various | 10,000 |
| ERAMET (Valdi) | France | Pyrometallurgy | Various | 20,000 |
| AEA Technology | UK | Hydrometallurgy | LIBs | - |
| uRecycle | Sweden | Mechanical | Various | - |

*Table 1. Battery recycling plants in Europe (Duarte Castro et al., 2022)*

### *Steps before recycling*

The transportation of the batteries to recycling centers is a relatively minor environmental factor compared to the production and use phases of LIBs (Ferrara et al., 2021). Nevertheless, this process must be handled with great care, as improper treatment can lead to accidents such as burning or explosions. Many international institutions have established numerous regulations. The standard for LIB transportation is generally UN38.3. (Cong et al., 2021).

Spent LIBs undergo a discharging step. Without discharge, direct mechanical processing likely damages the cell, and direct contact between the anode and the cathode is likely to happen, causing short circuits and thermal explosions (Cong et al., 2021). This discharging process could also take place before transportation as it will reduce some problems (Tan et al., 2020). It is normally conducted in aqueous solutions, controlling the discharge rate and evaluating its performance based on discharge efficiency with time and corrosion of the battery (Cong et al., 2021). An alternative to discharging and being able to work with the battery with no risks from the high voltage and the high reactivity of components is freezing with liquid nitrogen or processing the batteries in an inert atmosphere. Nevertheless, because of the inconvenience and consumption of resources, these methods are not used during industrial-scale operations (Fan et al., 2020).

Disassembling materials during the recycling process has proven to be a significant challenge. In the disassembly process, the battery system will be dismantled into module level or cell level (Hua et al., 2020). This phase is particularly extensive and costly due to the manual labor involved, which significantly increases the overall cost of recycling (Kampker et al., 2023). The current battery pack design does not facilitate easy disassembly, making recycling more challenging and reducing the economic value of waste materials (El-Sherif et al., 2024). Until now, the automotive industry has not established a widely accepted standard for the configurations and structures of battery packs and modules in EVs. As a result, there can be substantial differences between various EV packs, including size, shape, capacity, and materials variations. This lack of standardization presents challenges for recycling, as the process of disassembling will take much more time (Hua et al., 2020).

For both pyrometallurgy and hydrometallurgy processes, after the battery is disassembled, it is shredded in an inert atmosphere and then crushed. The resulting product from shredding is a mixture rich in metal oxides, a dense portion of aluminum and copper from the non-magnetic current collectors, and other materials such as plastic (Kotak et al., 2021). Some of these products are separated and can be further recycled (Fan et al., 2020). Using sieving, centrifugation, floatation, magnetic, Eddy current, or pneumatic classifiers, among other methods. Another alternative is that all the shredded material can be processed within the pyrometallurgical or hydrometallurgical processes (Ferrara et al., 2021). The most important material from the shredding process is called “black mass, " made from mostly cathode and anode materials (Velázquez-Martínez et al., 2019).

### *Pyrometallurgy*

To recover the precious metals from the “black mass” metallurgical processes take place to recover and remanufacture the materials used in the LIB. Pyrometallurgy is simpler and requires fewer steps to process compared to hydrometallurgy (Tan et al., 2020). Pyrometallurgy involves exposing the "black mass" to high heat in a furnace. Different temperature combinations must be strategically selected to target the desired material's melting point, leaving behind slag with the remaining material and toxic gas emissions (Cong et al., 2021). This slag subproduct can later be used as additives in the construction industry (X. Zhang et al., 2018). As there are different types of batteries, we can adjust some parameters, such as the time spent in the furnace or the temperature, to recover specific materials (Cong et al., 2021). The pyrometallurgical process involves a series of stages to extract the valuable metal. These stages start with pre-heating the materials, subjecting them to high temperature to melt and separate the different components, the electrolyte evaporates slowly and can reduce the explosion risk. The second stage is plastic burning, where organic materials are burned; this helps maintaining the heat inside the furnace. Lastly, the remaining material is smelted. Lithium was defined as a critical element in the 2020 revision of the EU's list of critical raw materials together with cobalt, which has been on the list since the beginning (Rinne et al., 2021). Nevertheless, cobalt is the most important material to recover due to its strategic significance not only for aspects related to the critical supply chain and economic revenue but also for unethical labor practices (Ferrara et al., 2021). These processes require high energy consumption as temperatures range from 500-1000 ºC (Hua et al., 2020). Therefore, new methods, such as using plasma smelting technology to enhance the efficiency and environmental performance of LIBs, are being studied to reduce this large amount of energy (Rajaeifar et al., 2021).

### *Hydrometallurgy*

Hydrometallurgical processes mainly include leaching, purification and separation, and material precipitation (Tan et al., 2020). This recycling method draws attention from researchers due to its high recovery of metals with high purity, low energy consumption, and very low gas emissions. After the "black mass" is pre-treated with heat to remove all the organic material, leaching is the first step in hydrometallurgical recycling to dissolve the valuable metals into a solution, these metals then form metal salts. Various leaching agents are used for different cathode-active materials (Liu et al., 2023). The most widely leaching agents used are inorganic agents, such as sulfuric acid, hydrochloric acid, and nitric acid, which are the most cost-efficient. However, these chemicals have low pH, which generates large amounts of wastewater and affects the environment. Alternatives to this leaching method, such as organic leaching and bioleaching, have been studied but are still under development (Iturrondobeitia et al., 2022). Also, electrochemical leaching is an emerging technology that has the potential to replace traditional leaching methods, as it has been proven to reduce by 80% in terms of global warming potential (Adhikari et al., 2023).

The next step in this method is the solvent extraction, it is used to separate compounds according to their relative solubilities into two immiscible liquid phases. This process results in the formation of an organic phase and an aqueous phase, each containing specific components. The organic phase preferentially binds to certain metal ions, allowing the separation of different metals based on their chemical properties. Different organic solvents must be used when a particular ion wants to be extracted, selectively extracting the ion of your preference from the aqueous solution while coexisting metals remain in the aqueous phase. Then, the organic phase containing the desired metal is scrubbed to remove any remaining impurity metals and purified before further processing (Murphy & Haji, 2022). The scrubbing stage uses weak acid/weak base. Afterward, the solvent is cleaned and can be reused, while the solute is recovered through stripping (Saleem et al., 2023).

In the final step of the process, metal precipitation occurs as soluble metallic ions undergo a reaction with a precipitating agent, leading to their recovery as insoluble compounds. The solubility of metal salts is influenced by the pH levels. Metals such as copper, aluminum, and iron are typically precipitated at a low pH of less than 5, while nickel, manganese, and cobalt are co-precipitated at a moderate pH of approximately 10. Finally, lithium is recovered at a pH level of around 12 (Saleem et al., 2023). It is reported that high metal recovery efficiencies for this method are 100% for Cu, 99.2% for Mn, 97.8% for Co, 99.1% for Ni, and 95.8% for Li (Duarte Castro et al., 2022).

### *Direct recycling*

Direct recycling is a promising new method, where the cathode and anode chemistry is retained, which means that a separate process is required for each material and battery technology (Wesselkämper et al., 2024a). Compared to pyrometallurgy and hydrometallurgy, direct recycling has the advantage of avoiding demanding and time-consuming pretreatments (Ferrara et al., 2021). Recycling directly helps recover important materials without changing their basic structure or needing complicated chemical or physical processes. It has a low cost and low emissions because it does not require too many treatments. Figure 20 presents a comparison of the different recycling methods. The data illustrates the considerable potential of direct recycling; however, this technology needs further development and investigation as not many plants are developing this method.

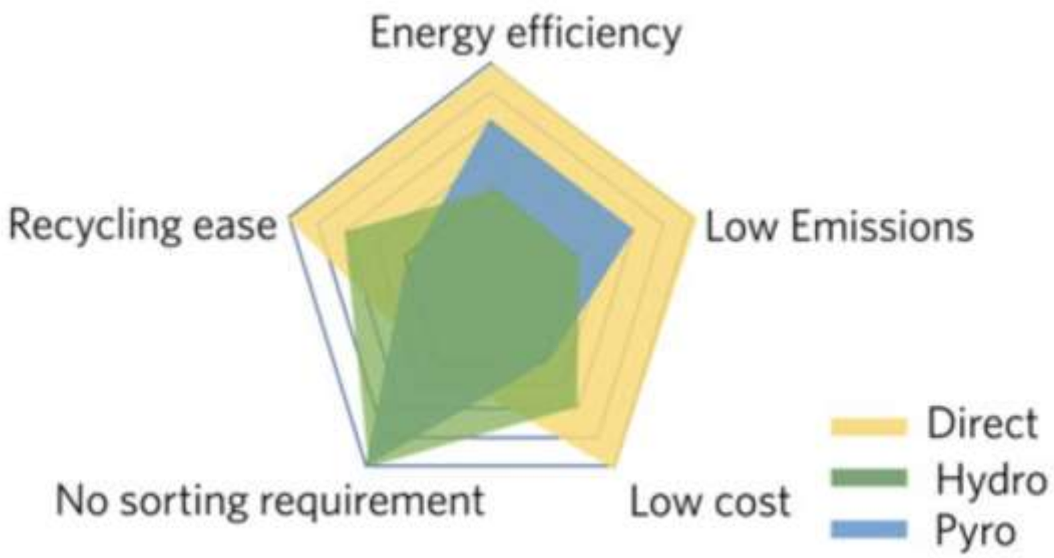


*Figure 20. Comparison between different recycling methods (Tan et al., 2020)*

### *Biohydrometallurgy*

This emerging method presents a more sustainable approach with reduced energy consumption, minimized environmental impact, lower investment costs, and improved metal recovery rates. Biohydrometallurgy has shown successful results in treating waste electrical and electronic equipment, allowing for the recovery of critical metals from printed circuit boards and other electronic products (Ferrara et al., 2021). This method is primarily employed for bioleaching on an industrial scale, utilizing various microorganisms, including autotropic bacteria, heterotrophic bacteria, and fungi. This method also needs pre-treatments to obtain the “black mass” and all the steps mentioned in the hydrometallurgical method (Duarte Castro et al., 2022).

### *3.4.1. Design for Recycling*

Design for recycling often involves minor changes to product structures but can help to establish a circular economy if it returns raw materials to the manufacturing process at a significantly reduced cost compared with primary sources. During a product’s development, there is an initial phase where performance improvements are essential, focusing on costs, and a second phase where the environmental impact is taken into consideration (Thompson et al., 2020). A proper design for recycling takes into consideration the design for disassembling and the design of chemists.

#### *Design for Disassembly*

Compared to the various battery recycling methods reported, relatively little attention has been paid to modifying existing battery designs to facilitate ease of recycling. At the module level, LIBs are fabricated using permanent assembly designs or very complicated batteries to be disassembled. Due to the market characteristics, there are many different types of batteries where the number, shape, and position of the individual components significantly vary, making it challenging for automated dismantling and often requiring specialized technicians to disassemble manually (Hua et al., 2020). For example, disassembling a Nissan Leaf battery up to the cell level will take 468.1 min, which is very long and costly (Klohs et al., 2023). Standardizing the cell design and labeling materials can reduce pretreatment costs during recycling. Labeling battery chemistries in a standard way and classifying different batteries during recycling would also maximize environmental benefits (Z. Yang et al., 2022). Currently, the disassembly process is taken manually. Therefore, there is a high-voltage risk to the workers, especially at the beginning of the process, because all the modules are connected and there are higher voltages. Sometimes, the disassembly process starts without knowing if the battery is charged, as some batteries can only be discharged after the housing cover has been removed. (Klohs et al., 2023). Also, the deficit of data is a major problem when dismantling the battery. Open data for EV-LIBs isn't common due to business confidentiality and intellectual property. Therefore, most collected end-of-life battery packs have little information about their cell compositions, making it very difficult to plan a disassembly strategy without sufficient information (Meng et al., 2022). Figure 21 shows the sequence of the individual disassembly activities that take place for a single battery. It shows that the most challenging process steps are opening the housing cover, detaching the cables, and removing the modules.

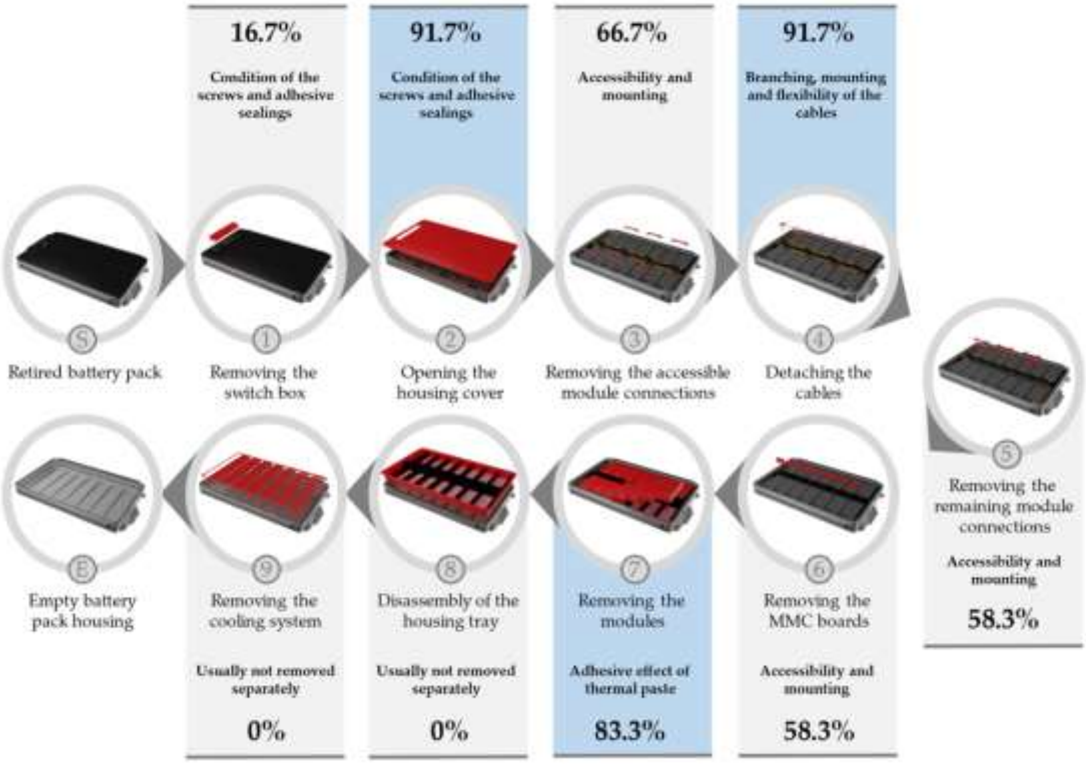


*Figure 21. General sequence of the individual disassembly activities and their potential challenges for battery systems (Klohs et al., 2023)*

To automatize the disassembly process, Meng et al. (2022) studied the implementation of artificial intelligence into the strategy of disassembly, which is more complex than the assembly strategy. They studied the human-robot collaborative disassembly system to determine the best process route and allocate tasks between robots and humans, reducing human risk while maximizing the economic and environmental benefits. The study shows that the EV-LIB pack is difficult for robotic disassembly because of adhesive bondings, thermal and welding joints, and tough and complex connections.

To facilitate the disassembly process, some improvements are expected from manufacturers, such as the adoption of common quick-release locking mechanisms instead of conventional metal–metal welding. Removable screw-off caps or incorporating perforated grooves within plastic casing might be an option (Tan et al., 2020). Also, a good approach would be having a pack configuration with solid busbars instead of flexible cables, where large cells could be easily disassembled from the structure (Thompson et al., 2020).

### *Design of chemists*

Designing new, environmentally friendly batteries is a focus for researchers. The main solution is redesigning the cathodes with lower cobalt content. Two different alternatives are in the scope of the studies: Lithium manganese oxide and lithium iron phosphate, which have zero cobalt content (Mayyas et al., 2019). Also, using solid-state batteries, eliminating the traditional liquid electrolyte, has a more environmentally friendly design and improves recycling safety by eliminating fire hazards. This enhances the ease of material separation and recovery (Tan et al., 2020).

# 4. Limitations and Future Research

During the literature review, different gaps have been identified. A brief chapter regarding the limitations and future research is presented.

## 4.1. Mineral-dependent Countries.

Developed countries participating in global supply chains gain substantial benefits from efficient mines. This is due to advanced information and communication technologies, which makes selling their raw materials easier in the global market. By joining global supply chains, these countries can enhance their productivity by focusing on specific tasks, exchanging knowledge with other nations, and developing healthy competence. Nevertheless, the source curse is introduced. This refers to countries rich in minerals or natural resources that perform worse economically. This idea suggests that relying too much on resources like minerals can harm a country's development. It can lead to problems such as unstable exchange rates, reduced innovation in other industries, and issues with how money is spent and borrowed (Jones et al., 2023).

A clear example is DRC, in which the whole country’s economy relies on the extraction of Cobalt and suffers all the consequences. Some countries like Bolivia or Chile, which have a lot of raw minerals, could benefit by not only exporting the ores but also by processing the materials within their own borders. This could help improve their economy and create new industries. However, there are challenges, such as limited local demand, lack of technical expertise, and inadequate infrastructure.

## 4.2. Use of Blockchain and Mining Transparency

Irresponsible raw materials sourcing means resource shortage and significant environmental impacts, which have an irreversible impact on the local and natural environment (Bonsu, 2020). Also, the non-traceability of raw materials negatively affects the market. Blockchain could be used as an auxiliary technological tool to guarantee traceability in sourcing raw minerals, building trust, and improving value chain responsible business practices. This technology can be very beneficial for the global value chain, but tackling raw minerals issues with Blockchain will not be sufficient for changing these problems, especially issues stemming from artisanal and illegal mining activities. To ensure responsible and ethical sourcing of raw minerals, it is essential to understand the social structures, unemployment, and livelihood challenges in resource-rich mining communities such as DRC.

## 4.3. Cybersecurity

As mentioned in the thesis, the BMS is the brain of the EV and the one in charge of controlling every aspect of it. As it uses electronic components, it can be susceptible to hacking. A great concern has been developed as if this battery gets hacked, they can start a fire or explosion by manipulating the BMS (Massaoudi et al., 2024). This technology must be reliable, and cybersecurity is an important aspect to take into consideration for the future development of BMS technologies.

## 4.4. Battery Range

The literature emphasizes the necessity for new technologies that can meet the needs of customers. LIBs typically have a limited lifespan and require frequent recharging when traveling long distances. It is essential to implement new technologies to enable batteries to have a longer range and travel greater distances. This will boost the adoption of electric vehicles and contribute to achieving the European goal.

## 4.5. Charging Infrastructure

The constant growth of EVs requires the development of charging infrastructures to be adjusted to this expansion. Widespread implementation of these infrastructures can increase the confidence of EV consumers and boost EV manufacturing. As a result, the availability of charging infrastructures significantly impacts the potential market for EVs. Countries with the highest EV sales also heavily invest in charging infrastructures; as there is more product, more demand for chargers is needed to satisfy this need. Strategic placement, concept development, and integration into cities are at the scope for better utilization of EVs (Z. Yang et al., 2022). The target of 1 million publicly accessible chargers was set for 2025, and Europe is currently behind this goal (Z. Yang et al., 2022).

## 4.6. Trackability of Batteries

After the EoL, the collected batteries must be labeled for identification. Unfortunately, there are no standardized concepts for this identification process. Since the batteries are not always clearly labeled, it may be necessary to contact the manufacturer, making the recycling process very time-consuming. It is important to consider implementing a battery passport to improve the entire life cycle of the battery (Kampker et al., 2023). The battery passport works as a digital information storage for products. It can be used as a product ID to track essential product lifecycle information. This innovative system will offer more transparency across the entire value chain, providing crucial information about the battery's production, usage, and recycling. Manufacturers will produce more sustainable batteries. Users will make more informed decisions about their battery usage, and recyclers will more effectively manage the recycling process. However, due to the large number of stakeholders involved during the life cycle of the battery, data storage becomes a challenge. Also, open data for EV-LIBs isn't common due to business confidentiality and intellectual property; this information should be available to benefit the whole value chain, informing consumers about their real product and enabling recycling plants and maintenance centers to work better.

## 4.7. Recycling Infrastructure

As the demand for EVs continues to increase, there will be a growing need to properly manage spent LIBs, as discussed in the findings. Europe currently needs more infrastructure to handle the significant amount of valuable material contained in spent LIBs. Many batteries go untreated due to the absence of facilities capable of recycling them. Just as megafactories are being constructed for the battery manufacturing process, a similar approach could be taken for the EoL stage of the batteries. This could lead to reduced recycling costs and make the process much more profitable while recovering all the crucial materials used in LIBs.

# 5. Conclusion

In the last decades, there has been great interest in researching LIBs for EVs due to the role that these vehicles comprise in the automobilist industry to shift towards a greener future. Despite the increasing trend in the development of LIBs, there are limitations and fragmented areas in the existing literature. Through Scopus research, the literature indicates that while there is a significant body of work on various aspects of the LIB value chain, there is still room for improvement in different life cycle stages.

The thesis summarizes the value chain from a circular economy perspective, enhancing the importance of every life cycle stage. The extraction and refining of key raw materials such as lithium, cobalt, and nickel come paired with considerable environmental challenges and ethical concerns, especially in DRC. In the assembly phase, advancements in battery design, management systems, and cooling technologies have enhanced the performance and lifespan of LIBs, nevertheless, further research must be done to meet customer’s needs. The EoL offers great opportunities for this industry. However, the diverse designs and lack of standardization present challenges for recycling and reusability. The EoL presents significant challenges; as the global demand for EVs grows, so does the volume of spent LIBs, necessitating efficient and sustainable EoL management strategies.

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