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An exploratory study on the End-Of-Life Batteries Supply Chain

The automotive sector perspective

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SUMMARY

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ABSTRACT

Demand for batteries is increasing at unprecedented rates, driven by the electrification of the transport sector. As a consequence of this, supply chains of companies all over the world will face challenges related to raw material supply chain, production and End-Of-Life (EOL) waste management.

In this regard, the thesis discusses all aspects involved in the EOL management of Lithium-ion batteries (LIBs), analyzing current and future perspectives. Starting from raw materials demand and supply, the work will try to determine the impact of remanufacture, reuse and recycle on batteries supply chain, providing also a complete picture of actors active in these fields in EU and US regions. Collection, transportation and disassembling are also an important part of the work.

Closed Loop Supply Chain models and Reverse Logistics processes are reviewed, corresponding research review related to these aspects and including future research directions. Furthermore, a Closed Loop Supply Chain processes model is theorized.

INTRODUCTION

The paradigm shift from Internal Combustion Engines (ICE) to electric propulsion systems puts the automotive industry at the forefront of a transformative era, driven by the imperative to reduce carbon emissions and combat climate change. At the heart of Electric Vehicles (EVs), lies the rechargeable battery, a critical component whose effective management throughout its lifecycle has numerous and profound implications.

As the global transition to electric mobility gains momentum, the End-Of-Life (EOL) batteries management is emerging as a pivotal challenge that demands rigorous attention. The formidable growth in the production and deployment of EVs has paved the way for a surge in spent batteries, necessitating a structured and sustainable approach to their collection, recycling, and reintegration into the supply chain. Neglecting this phase not only poses environmental risks but also hinders the realization of the full potential of EVs as a low-carbon alternative to traditional vehicles.

This thesis embarks on a comprehensive exploration of batteries EOL supply chain management within the automotive sector, recognizing it as a linchpin in the broader mission to create a more sustainable transportation ecosystem. The end-of-life journey of an automotive battery encompasses a complex web of processes, from the initial dismantling of vehicles to the final reincorporation of recovered materials into new battery production. Each juncture in this chain presents unique challenges and opportunities that necessitate a multidimensional perspective.

The research will be structured as follows.

- Chapter 1, following an introduction to the current battery sector (context, demand and challenges), proceeds to define the concepts of Closed Loop Supply Chain and Reverse Logistics, crucial to design a sustainable supply chain model. Finally, key concepts of Waste management are introduced, as well as Remanufacturing, Repurposing and Recycling definitions.
  Objective of the first chapter is to provide the right tools for the reader to be able to better understand the results that emerged.
- Chapter 2, sets out and describes in detail the methodology through which the results were achieved.
- Chapter 3, analyzes the supply chain of batteries EOL, examining the existing system starting from raw materials supply chain (demand, actors, geopolitical situation). After this, different

processes of the EOL management are discussed: Prevention, Remanufacturing, Repurposing, Recycling, Collection and Transportation.

Finally, after discussing all the different phases a Closed Loop Supply Chain model is proposed.

- Chapter 4, studies capacity volumes of facilities located in EU and US for Remanufacturing, Repurposing and Recycling, analyzing if current and future capacity can cover the volume of batteries coming to EOL.

  As a result of this chapter, is available the most up-to-date facilities map in Europe with related capacities.

1. BATTERY DEMAND AND KEY CONCEPTS DEFINITIONS

The chapter aims to provide to the reader the current context of battery industry, as well as the main notions regarding the dominant topics of this research thesis.

Firstly, the expected increase in battery demand is analyzed, with a focus on the related challenges.

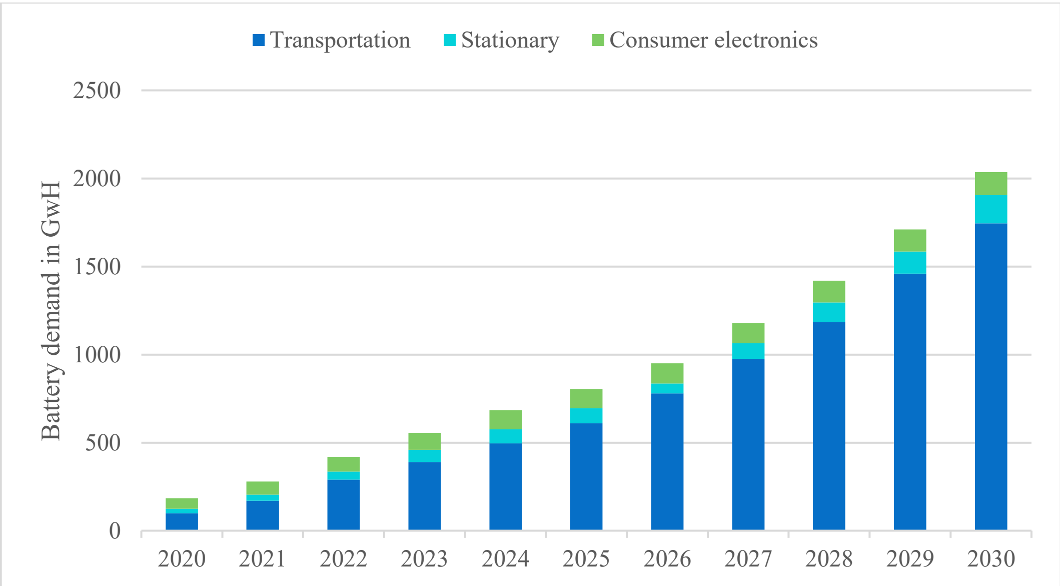
After this, concepts of Remanufacturing, Repurposing and Recycling will be elaborated, followed by an introduction on waste management.

Finally, a definition of closed loop supply chain and reverse logistics will be given. Being at early stages of product lifecycle, there's a huge opportunity to develop a circular, sustainable supply chain system for batteries End-of-Life management.

1.1. BATTERY DEMAND AND CHALLENGES IN THE SUPPLY CHAIN

The global demand for batteries has been growing rapidly, mainly for the electrification process of the mobility sector but also for an increase in renewable energy storage and consumer electronics. Table 1 shows the weight of different applications on battery demand, with transportation being the main driver:

Table 1: Projected global battery demand from 2020 to 2030, by application (in gigawatt hours), Statista 2021, [1]



According to Bernstein demand from EVs will grow to 2700 GW/h by 2030, with others estimates arriving to 4000 GW/h [2].

Climate targets will create business opportunities within electrification, mainly the Paris Agreement of 2015 is driving zero-carbon solutions in sectors that account for more than 70% of global emissions with particular focus on power and transport sectors. Another key legislation was voted in June 2022, when the EU parliament decided to ban sales of new internal combustions engines starting from 2035.

Electric vehicles will therefore drive demand for batteries to unprecedented levels. With EV advent, there'll be a radical shift in battery design and components. The automotive sector will not be any more based on fossil fuels, but on minerals, with the involvement of many new geopolitical actors (fig. 1).

Figure 1: Indicative Supply Chain of oil and gas and selected clean energy technologies (IEA, 2022)

This will lead to numerous challenges in the battery supply chain, which will be discussed in the following paragraphs:

- Production capacity;
- Social and environmental concerns;
- Technological advancements (in-depth analysis chapter 3);
- Raw materials supply chain (in-depth analysis chapter 3).

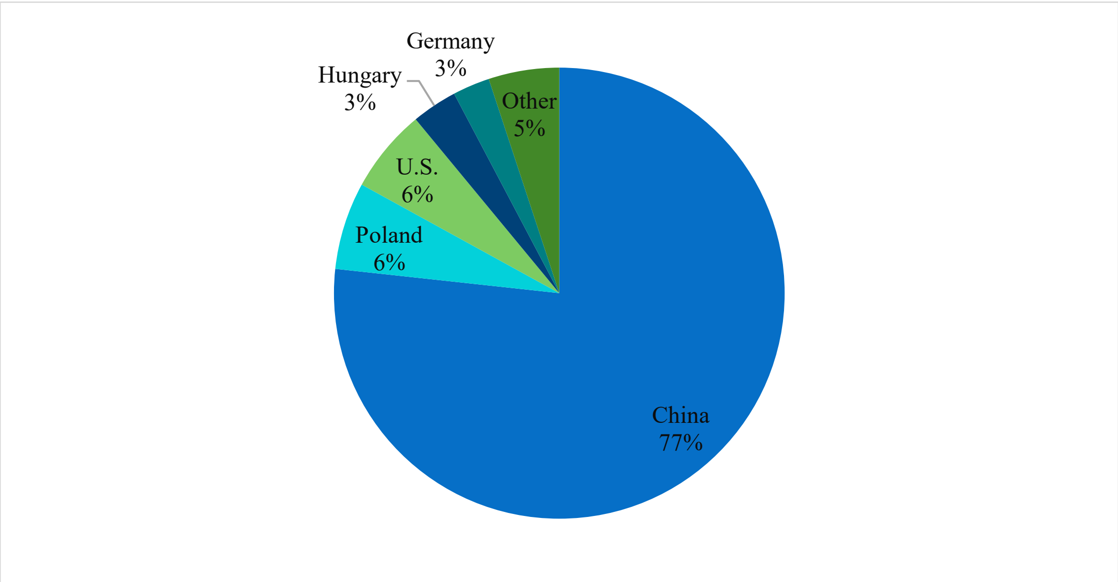
1.1.1. PRODUCTION CAPACITY

To meet the increasing demand is necessary a significant expansion of battery manufacturing facilities.

As things stand, China is the undisputed leader: in 2022 had more battery production capacity than the rest of the world combined. US Inflation Reduction Act is expected to inject almost USD 150 billion into clean energy, electric vehicles and batteries [3]. According to experts, these investments could lead to a challenge China's dominance in the long-term [4].
The situation for Europe looks grim, as it is currently far away both in manufacturing and investments: according to BloombergNEF Europe's share of investments dropped from 41% in 2021 to 2% in 2022, while in the US and China continued to grow. Moreover, potential battery production capacity in Europe is at risk of being delayed, scaled down or not realized if further action is not taken, since many of the announced battery gigafactories are at risk [5].

Table 2 shows the extent of China's dominance in manufacturing [6]:

Table 2: Battery Cell Manufacturing Capacity, GWh (% of total), 2022



Additionally, Chinese EV battery makers are dominant in the market having six companies in the world top 10 players (see table 3), with CATL being the largest global producer and accounting for almost a third (27,5%) of global sales. Considering all Chinese companies in the top ten, they sum up to 44,4% of market share. Another important manufacturer is South Korea, having three companies figuring in the top 10 (LG, SDI, SKI) and accounting for 22,9% of market share.

This list is also useful to understand how the biggest producers have factories located not necessarily in the country of origin. Most of the active multi-gigawatt-hour cell manufacturing facilities in the world are owned by a Chinese, Japanese or Korean company. Emblematic is the case of Poland, current European leader: this is due to the presence of LG Energy Solution gigafactory in Wroclaw, the largest in Europe. Current capacity of this single factory is 70 GWh and is expected to reach 115 GWh in 2025. [7] Same goes for Hungary, currently having a capacity of 38 GWh with investments from CATL and SK Innovation (SKI) coming further on, with an expected capacity to reach 207 GWh in 2031 [8], [9].

Table 3: Top 10 battery producers in 2022, [10]

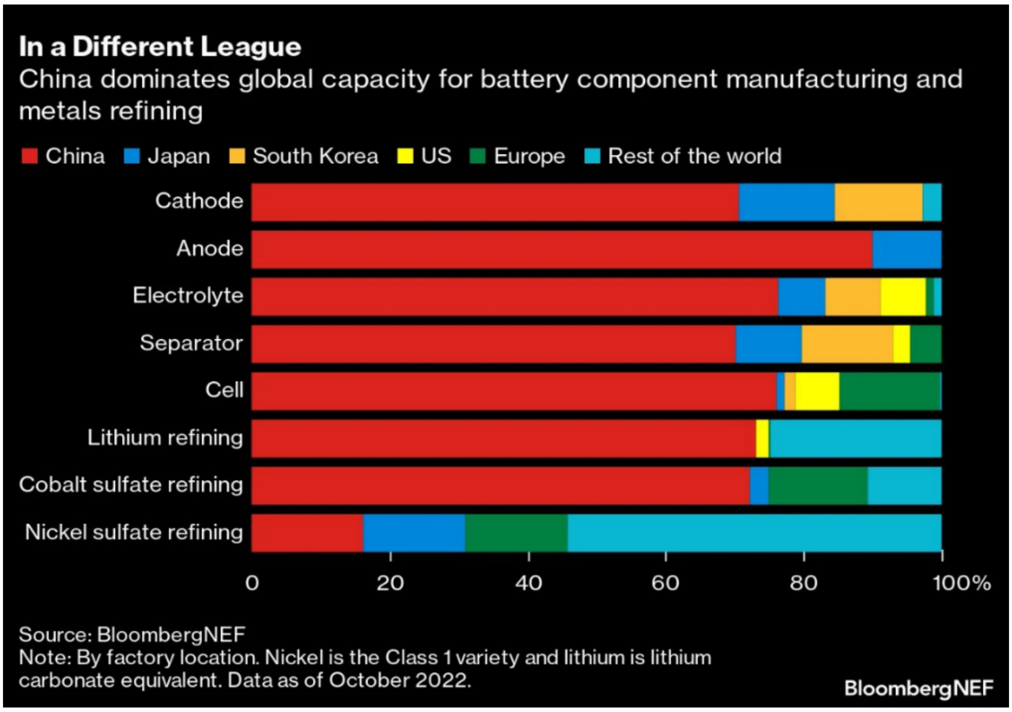
#	Company	Mkt Share (Sales)	Country
1	CATL	27.50%	China
2	LG	12.30%	South Korea
3	BYD	9.60%	China
4	SDI	6.00%	South Korea
5	SKI	4.60%	South Korea
6	Panasonic	3.60%	Japan
7	Guoxuan	2.80%	China
8	CALB	2.50%	China
9	EVE	1.10%	China
10	SVOLT	0.90%	China

Chinese battery producers dislocate factories in eastern Europe for a combination of factors: logistics, since countries are well positioned to serve both automaker and EV consumers; costs, thanks to cheaper labor and land rental cost; overcapacity, after aggressive expansion that expects to overcome internal demand. Battery companies have largely avoided the United States for geopolitical reasons, probably for fear of a political backlash.

China's dominance in all supply chain aspects is unmatched. The Asian country was ahead of times with investments and has strategic dominance in all the different stages of the production process, becoming therefore indispensable for other countries, as shown in figure 2.

Europe, Canada, and the United States are anticipated to assume increasingly important roles in shaping the dynamics of this supply chain in the foreseeable future. The surge in demand for electric vehicles in Europe is poised to propel cell production closer to home. This shift is particularly noteworthy in light of the COVID-19 pandemic, which has underscored the significance of localized supply chains and the facilitation of trade-free tariffs within the region. Consequently, countries in Europe, including Germany, Sweden, Finland, and Norway, have already secured positions among the top ten nations in the 2022 lithium-ion battery supply chain ranking, as indicated by the 2022 BNEF study.

Figure 2: Battery component manufacturing and refining by country (%), (BloombergNEF, 2022)



The US is trying to catch by with unprecedented investments. The Inflation Reduction Act (IRA) of 2022, introduces tax credits for eligible EVs to incentive their adoption (see paragraph 3.2.2).

Europe is currently in a fundamental phase for its future. With the European Green Deal, launched in 2019, the old continent has presented an ambitious plan to being a more sustainable, climate-neutral, and environmentally friendly society and economy. Main objective is to reach carbon-neutrality by 2050: this means reducing greenhouse gas emissions to net-zero levels, effectively balancing emissions with removals. This was a milestone in EU's climate policies, followed by ambitious and tempestive regulations specific for sustainable transportation: the "Clean Vehicles Directives" [11] and the updated "Battery Directives" [12] that will replace the existing battery directive from 2006 are just two examples.

These regulations have led to investments to increase overall battery production capacity. But the aforementioned IRA regulations are a serious threat for the EU, with many potential investors deciding to move their spending to the US, since regulations are simpler and faster. An emblematic example was given by Nortvolth, that had committed to build a plant in Germany, but is considering postponing its investment to prioritize creation of new US plants instead [13]. Also Volkswagen, Europe's largest carmaker, is considering whether to build new plants in US rather than the EU and have literally affirmed that the "right framework conditions" in the EU need to be developed in order to invest [14]. Adding that as things stand, building a factory in the US is faster compared to eastern Europe, thanks to the public subsidies. Right now there are just a few EU countries with operating plants. Meanwhile, numerous plants are expected to be built within 2030. Here following an elaboration of data taken from Reuters [15], to clearly explain the distribution and volume of the investments as of now:

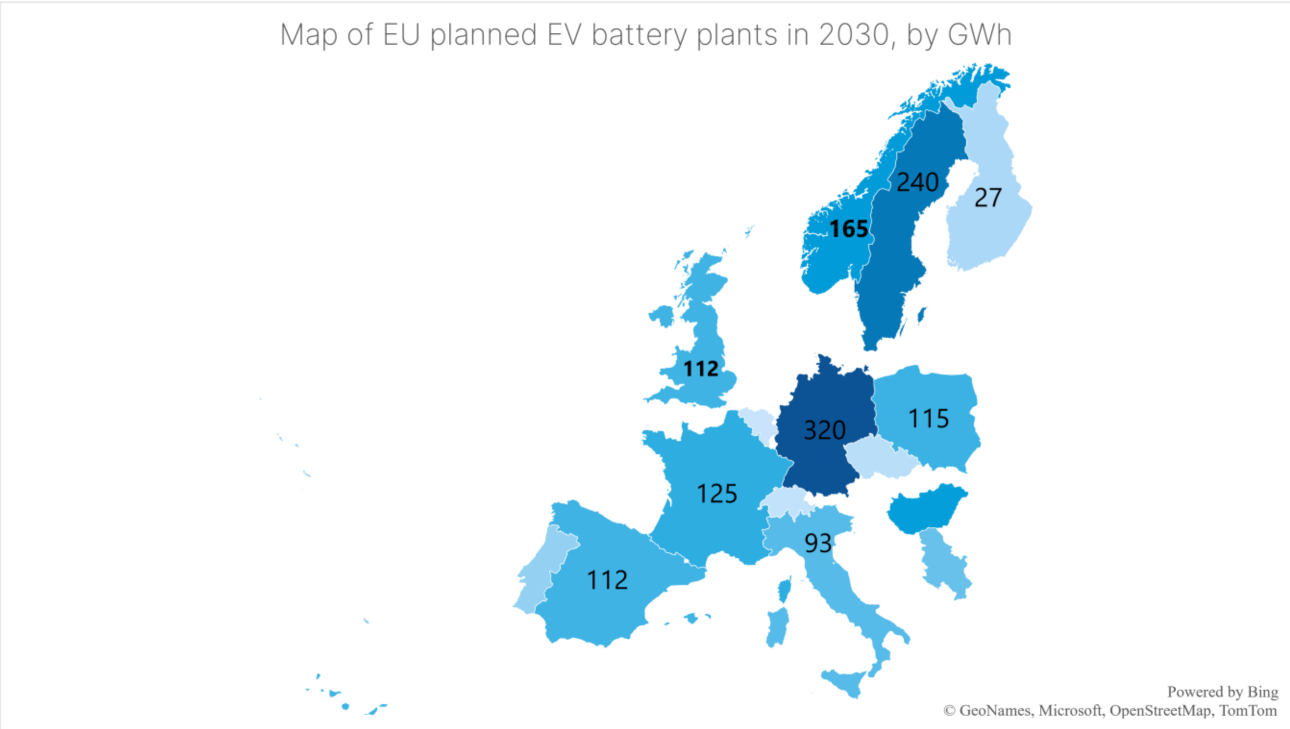
Table 4: Operating and Planned battery manufacturing plants in Europe, by capacity, (Reuters, 2023)

Where	Planned capacity (GWh)	Operating
Belgium	3	0
UK	112	0
Czechia	15	0,2
Finland	27	0
France	125	1
Germany	320,1	14,5
Hungary	158	30
Italy	93	0
Norway	165	0
Poland	115	70
Portugal	45	0
Serbia	80	0
Spain	112	0
Sweden	240	40
Switzerland	7,6	0

Many of these projects have not yet started construction, some even need to find financing or choose the battery chemistry. American IRA regulations will probably have an impact on some of these previously announced constructions, with many companies already announcing their intention to move the production of batteries in US due to more favorable political context (see paragraph EU and US regulations).

According to a Transport & Environment report, 68% of the planned projects (measured on GWh capacity) are at risk, with 16% of these being at high risk of being cancelled [5]. Tesla's Giga Berlin is the plant with the largest volumes at risk. The American automaker has already announced that is currently focusing on producing cells in the US thanks to the framework created by IRA [16].

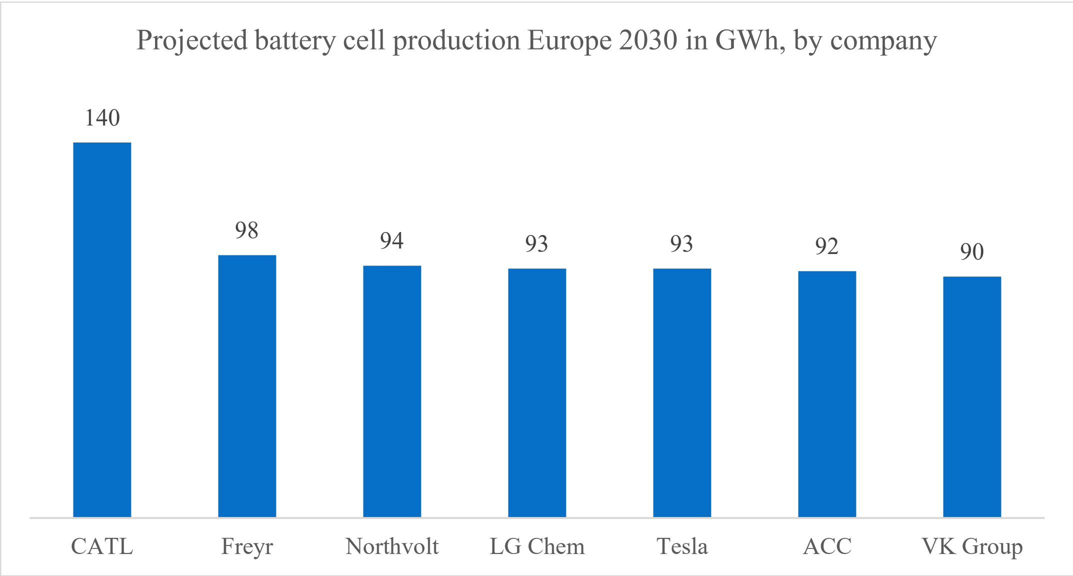
Table 5: Map of EU planned EV battery plants in 2030, by GWh



There could be many scenarios, with projects being delayed, scaled down or even cancelled that would lead to impactful consequences for the EU's supply chain. Europe would not satisfy its battery cell demand, being left ulteriorly behind China and US.

In order to have the full picture, in table 6 are illustrated the biggest companies planned produced battery cell output in EU in 2030 [17]:

Table 6: Projected battery cell production Europe 2030 in GWh, by company (Statista, 2023)

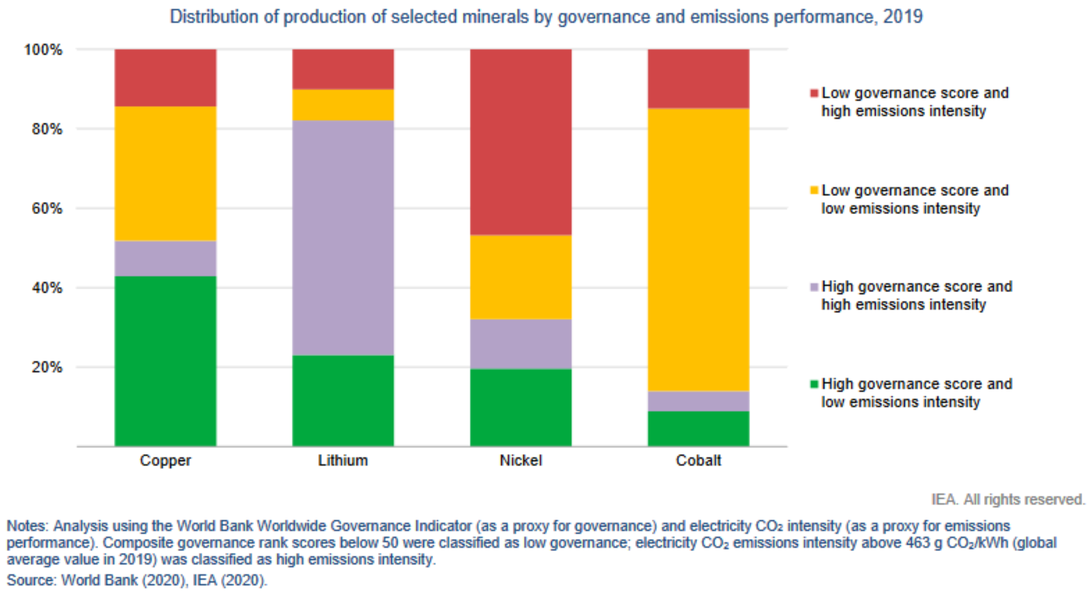


1.1.2. SOCIAL & ENVIROMENTAL CONCERNS

The mining of certain battery materials has raised concerns about poor labor conditions and environmental damage in some regions, which can affect the overall ethical and sustainable reputation of battery production, as anticipated in paragraph 3. In the near future Environmental Social and Governance (ESG) considerations will become significantly important to meet sustainability targets set by different countries and companies.

The majority of batteries nowadays are produced in countries which either have high emission intensity or low governance score, according to data from IEA based on The World Bank Worldwide Governance Indicator (fig. 3) [18].

Figure 3: Distribution of production of selected minerals by governance and emissions performance (IEA, 2020)

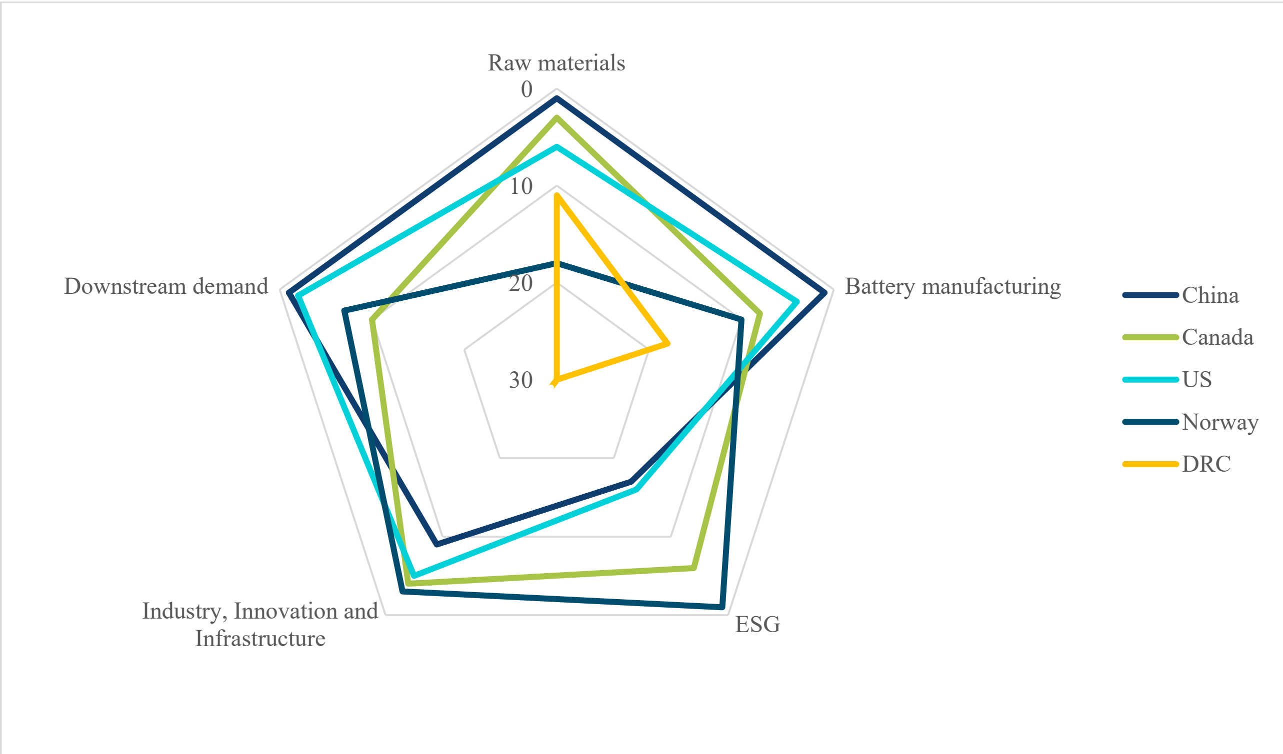


China's battery supply chain is excellent regarding many aspects of the supply chain but is lacking in Environmental Social and Governance metrics (table 7). European Union has a great opportunity to lead in this aspect, and currently North European countries like Norway, Finland and Sweden are considered the best. Nordic countries in particular are advantaged because of abundant availability of green energy at low cost, stable energy supply and cold climate and in general competence along the full battery value chain [19].

Many experts in the field agree in the fact currently battery industry is not "green" enough to and is something that needs to be addressed. Mining processes are fundamental and will not be substituted in the future, but the way mining is processed can be changed. This is mainly up to institutions and policymakers who will have to deal with these social and environmental issues as soon as possible, enforcing the law introduced.

As will be discussed in the thesis, 2nd life and recycling will be crucial process in making the industry sustainable both from an environmental and economic standpoint.

Table 7: BloombergNEF supply chain ranking scores for selected countries (BloombergNEF, 2022)



1.2. CLOSED LOOP (CIRCULAR) SUPPLY CHAIN AND REVERSE LOGISITCS

The switch to EVs from MCI is a huge opportunity for re-thinking the mass automotive industry. As thing stand, EV adoption is seeing exponential growth, with the share of electric cars in total sales seeing an increase from 4% in 2020 to 14% in 2022. This year, electric cars could account for 18% of total car sales. [20]

Applying Roger's Diffusion of Innovations theory to EV market, it can be stated that it's currently in the early stages of the adoption curve. Nordic countries are among the most mature market entering yet the early majority stage of the curve, with Norway having for instance 25% of EVs over the total of all cars on the road, followed by Iceland having a 9.9% share. Production is ramping up, and mass adoption is getting closer and closer.

For this exponentially growing demand, is therefore fundamental to pay attention to all stages of the product life, improving use of resources and environmental impact whenever possible.

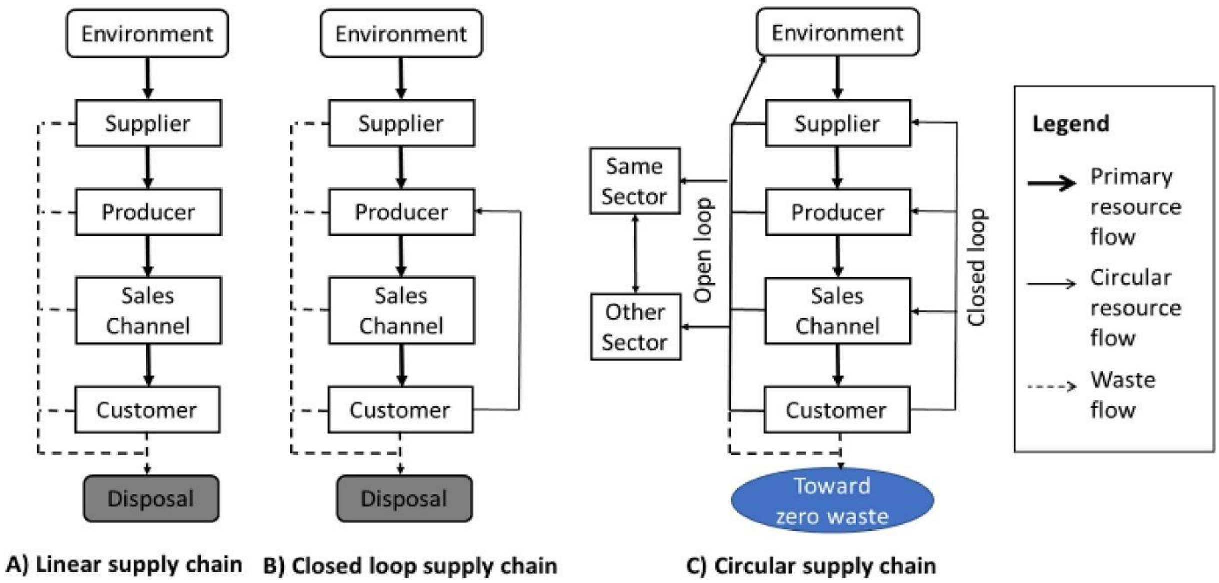
Supply Chain can be labelled as "a combination of processes to fulfill customers' requests and includes all possible entities like suppliers, manufacturers, transporters, warehouses, retailers, and customers themselves" [21]. Simchi-Levi and Kaminski refer to it also as the logistics network, that "consists of suppliers, manufacturing centers, warehouses, distribution centers and retail outlets, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities". [22]

Reverse logistics is defined by the American Reverse Logistics Executive Council as "The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal". [23] Simchi-Levi and Kaminski say it involves the movement of good from their "typical" final destination back in the Supply Chain. It's a growing aspect in the distribution network, due to increased attention to lifecycle environmental impact and increasing number of returned goods in e-commerce. [22]

A Closed Loop Supply Chain network comprises both forward and reverse logistics simultaneously. Batista et al. defined Circular Supply Chain Management as "the coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/ services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organizations". In the Supply Chain Management (SCM) literature on sustainability, different concepts have been used interchangeably like CLSC, sustainable supply chains, green supply chains and environmental supply chains. Guide and Van Wassenhove define CLSC Management as “the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time” [24]

Figure 4 reports a traditional linear, closed loop and circular supply chain model according to Farooque et al. It denotes the difference between closed loop and circular supply chain, since the latter recovers value from waste by collaborating with other organizations within the industrial sector (open loop, same sector), or with different industrial sectors (open loop, cross-sector). Circular Supply Chain Management is therefore defined as “the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholders in a product/service lifecycle including parts/product manufacturers, service providers, consumers, and users”. Others refer to the integration of CE and CLSC as circular supply chains. Both these concepts, focus on value recovery operations through reverse logistics. [25]

Figure 4: Linear, Closed Loop and Circular Supply Chains, ”, [25]



1.3. REMANUFACTURING, REPURPOSING, RECYCLING

Figure 5: 3R representation

Remanufacturing is "the rebuilding of a product to specifications of the original manufactured product using a combination of reused, repaired and new parts", focused on recovering a whole product and prolonging its useful lifetime with minimal additional cost [26]. It entails recovering the residual value of used products by bringing them to a new-like condition. Typically, this process is the preferred one for EOL products, since is more environmentally friendly, higher in quality, and has a longer extended life. [25]

In the context of electric vehicles (EVs) refers to the process of refurbishing EV batteries, bringing them as good as new and reutilizing their spare parts in older EVs. This procedure necessitates that the EV batteries possess a satisfactory State Of Health (SOH) and adhere to all Original Equipment Manufacturer (OEM)-specified criteria pertaining to power, energy, cycle life, among other parameters.

Many sources concord that a battery is unsuitable for continued use in a car when the energy or power density drops to 80% of its original value, some state also 70% [27], [28].

The process of identification of a new use for a product that can no longer be used in its original form, takes the name of repurposing or reusing [25]. When batteries are unable to hold a desired capacity (like the aforementioned 80%), to extract more value and extend their lifetime is also possible to use them in less stressful applications, such like stationary storage, peak shaving, back-up, frequency regulation, renewables integration, and EV charging.

Unlike remanufacturing, this process involves also a reconfiguration of modules and packs, inserting a new battery management system (BMS) to destine the battery to a non-vehicle application. Reuse of LIB in stationary applications will require battery classification and the determination of charge state and capacity. [29]

Taking into account different scenarios assumptions, Huster et al. [30] have demonstrated how battery remanufacturing will have a consistent demand. There are issues to be taken into account, that in my opinion stand also for repurposing:

- After remanufacturing process, it's possible a battery could not be reused in a car. This is due to possible future developments in battery technology that could lead to incompatibilities between batteries and vehicles of different technological generations. The study estimates that in different scenarios, returning batteries that could enter the remanufacturing process account from 65% to 85% of the total (depending on battery and vehicle life expectancies).
- Consumer acceptance of remanufactured batteries is not a guarantee. The transition towards circular economy models requires changes in consumer behaviors, with different studies affirming how consumers tend to reject remanufactured and repurposed products [25]
- It's not clear if scaling of business models is feasible yet. There need to be technological improvements, as the already discussed disassembling automation in order to decrease process costs. Also lack of standardization is a practical challenge.

To these considerations, McKinsey underlines how the original manufacturer has the responsibility to offer vehicle-use qualified LIBs. However, the risks and liability of using batteries in non-original functions are not well defined. If repurposing is to make a significant impact, liability standards need to be developed.

Recycling is the process of converting waste materials into new materials and objects. In the waste management hierarchy it precedes the dismantling process, but from a circular economy perspective it closes the loop in the battery manufacturing process.

This process is fundamental to make use of waste as a valuable resource, because EVs are made of elements and materials that make it difficult to ensure a stable supply on a local level (see paragraph Raw Materials Supply Chain). Demand for LIBs is expected to increase considerably in the future and recycling could be a key element to find a solution to reduce shortages of materials and components and in general dependance from producers of rare earth metals like lithium, cobalt, and nickel.

Moreover, it reduces manufacturing carbon emissions, environmental degradation and water pollution (e.g. from mining) [22].

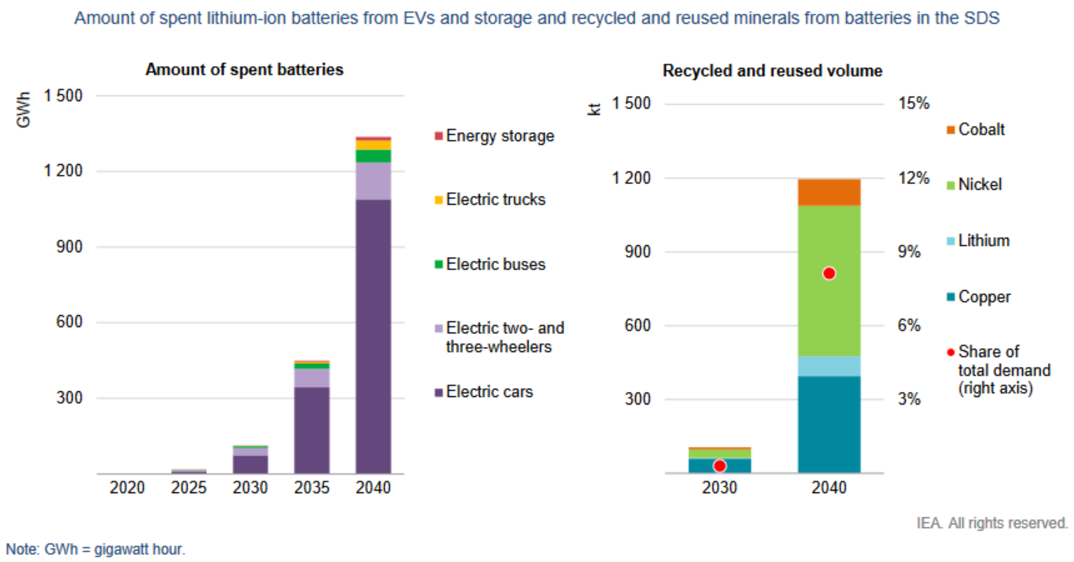
It should be clear though that recycling does not eliminate the need for continued investment in the primary supply of minerals. New investment in primary supply will still be needed even in the case that EOL recycling rates were to reach 100% by 2050, according to a World Bank study [31].

The lead-acid battery recycling industry has proved to be highly successful and should be looked at to improve recycling for LIBs. It has to be stated that the former is simpler and economically effective to recycle, having only one chemistry factor. A successful business model has been built over it, thanks also to governments regulations requiring recycling of lead due to its toxicity. Efficiency is very high, with recycling rates of 96% in North America [32] and ranging between 60%-95% in EU [33].

The number of spent battery volumes is expected to explode in the next few years, driven by EVs. There are numerous forecasts of EOL batteries in 2030, that suggest immense recycling possibilities (fig 6).

Kastanaki and Giannis have estimated that by 2030 between 0,82-1,3 million EOL batteries will be generated only in the European Union. By 2035, the number will grow to 1,14-3,3 million batteries. This number is reasonable and in accordance with Drabik and Rizos, who estimated 1,2 million EOL batteries in 2030 and 2,6 million in 2035. [34]

Figure 6: Amount of spent LIBs from EVs and storage; recycled and reused minerals from batteries in the SDS, (IEA, 2022) [18]



2. METHODOLOGY

As discussed in chapter 1, the electrification of the automotive process is happening with unprecedented pace, therefore there still are numerous literature gaps to be filled. Within the framework of this thesis, an exploratory investigation, grounded in existing literature, facilitates researchers in scrutinizing literature of particular interest. Moreover, this approach helps researchers to recognize conceptual contents and aims to contribute to development of publications.

As a search strategy for this work, a method similar to Snowballing research method was employed. It's a non-probabilistic method used to identify relevant sources by starting with a small set of known or foundational papers and then systematically expanding the search by examining the references cited in those papers, as well as any subsequent papers that cite them. This research diverges from the typical application of snowballing, which is commonly employed in social research. The distinction in application is, however, the very reason behind choosing this method for the present study. While snowballing is traditionally utilized by social scientists dealing with hard-to-reach or elusive populations, this research deviates by focusing not on individuals but on a collection of publications. This approach proves instrumental in addressing gaps in the literature and elucidating findings that remain relatively unknown due to the recent surge in attention towards batteries and their and EOL management, with particular focus on the potential supply chain impact. In essence, the adoption of snowball sampling in this study is deemed highly effective for conducting exploratory research.

In addition to the academical analysis, several interviews with actors involved in the field were conducted to address main issues in the industry and to gather insights for future prospects. The people involved in the interviews are from automotive companies, battery EOL logistics, battery makers and actors involved in remanufacturing, repurposing, and recycling.

Also the Battery Innovation Days 2023 event was attended (online), giving perspectives from key players and experts from the battery field like policy makers, industry players, research community and end-users. Moreover, key European Research & Innovation initiatives were discussed.

As an abstract and citation database was used Scopus, having provided availability of most of the articles in the database. To maintain the quality of content and to keep the selected articles to a manageable number, the search was restricted to "Articles", "Articles in press" and "Review articles" published in peer-reviewed journals. Although representing a limitation, only English sources were included in our review given the language limitations of the author team.

At the screening stage, articles were included/excluded based on the abstract, which was retrieved from the database and sorted by the highest number of citations to start from the most relevant papers in the field. Being based on abstract, selection process was conducted on a subjective basis with no specific inclusion/exclusion criteria, beyond whether a paper appeared to be incorporating a focus on Supply Chain of EOL batteries.

3. BATTERY END OF LIFE SUPPLY CHAIN

In this chapter all aspects related to the supply chain of batteries EOL will be analyzed, and as final output a closed loop supply chain model will be proposed.

In the first paragraph, to have a complete picture of battery supply chain, crucial to understand all topics treated in the work, metal content of a battery is analyzed and particularly raw materials supply chain is treated in depth, focusing on Lithium, Cobalt and Nickel.

In the second paragraph, an analysis of waste management policies across the globe is treated. Particular attention is paid to European and American regulations, Waste management Hierarchy and Circular Economy Models for the supply chain.

Prevention phase is then treated in depth, with focus on battery designs and chemistry, as well as emerging innovations and fields where research needs to be intensified.

After this, Remanufacturing and Reuse arguments are treated considering all relevant aspects.

Finally, Recycling is discussed, exploring its indicators, processes and costs from a theoretical and geopolitical perspective.

3.1. RAW MATERIALS SUPPLY CHAIN

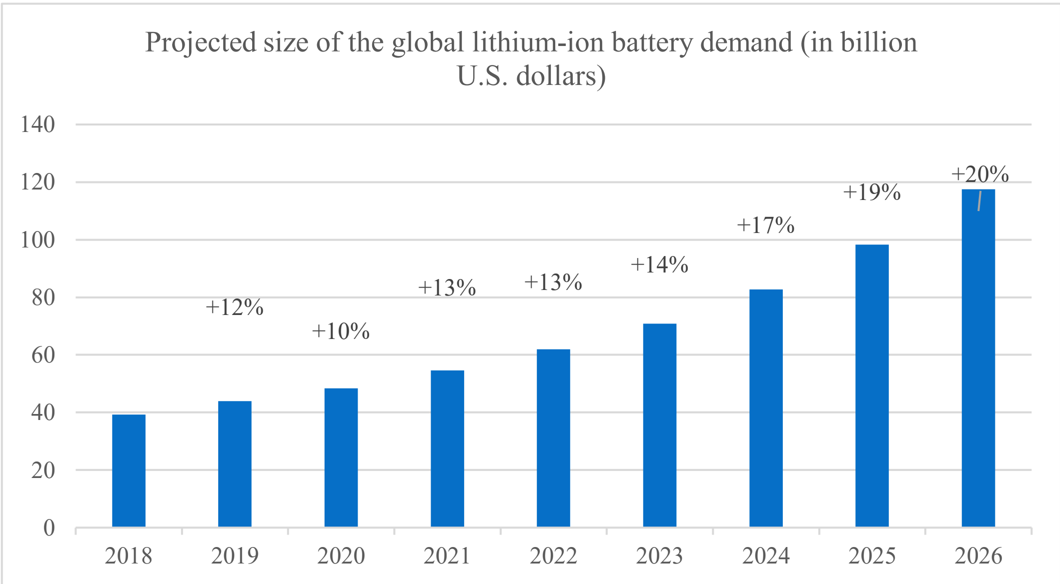
The production of batteries requires a mix of specific raw materials like lithium, cobalt, nickel and rare earth elements. Securing a stable supply of these materials can be challenging due to geopolitical issues, limited mining capacity, and concerns about ethical sourcing.

The increase in battery demand leads the demand for critical minerals to grow. As shown in table 8, the market for Li-ion batteries is constantly growing, with a size value of around 62 billion US dollars in 2022 (+57% over 2018), and a projected value of 117 billion in 2026, with a +89% growth over 2022. [35]

There are mixed opinions regarding the abundance of resources, with articles periodically popping up talking of possible global shortages due to demand. According to a recent Transport & Environment study [36], based on elaboration over the US Geological Survey data, the Earth's crust possesses ample mineral reserves for battery raw materials, indicating a theoretically abundant supply capable of meeting the demands of the industry. Moreover, the study shows how the shortage of resources to electrify passenger transport is a myth: mineral demand to reserves ratio in a scenario where there's an increase in demand, with no change in battery dimensions and habit in car utilization, would be equal to 11% for Lithium and Nickel, 10% for Cobalt and 0,9% for manganese.

The main issue, therefore, is not the quantity of minerals existent but the possibility of regional shortages for carmakers, in other words to have a reliable supply chain. Vertical integration might be a solution for automakers, with many companies already sealing deals [37] with mining companies to have enough of these battery materials on time. This strategy carries with it risks related to price volatility and environmental concerns, since as already mentioned many mines are in countries with lower standards in this sense.

Table 8: Projected size of the global lithium-ion battery demand (in billion U.S. dollars), (Statista, 2022)



Main risk factors in securing reliable supplies of critical minerals are:

1. Geographical concentration;
2. Project lead times (from discovery to development);
3. Monitoring of ESG issues.

Recycling, re-use, and in general the pursuit of a circular product life cycle, will be crucial in this aspect of the supply chain.

All things considered, recycling looks fundamental for strategic reasons, particularly for players that are trying to overcome incumbents like China, that even if does not top the charts for reserves and production, controls the refining market accounting for 60% of Lithium Chemical production.

Europe in particular would benefit from recycling since as discussed in the following paragraph many of the raw materials are imported from other countries, making the Old Continent particularly weak in this strategic aspect of the supply chain, being completely dependent from other countries. The Critical Raw Materials Act [38] published in March 2023, part of the Green Deal Industrial plan, is surely a good step in the direction to ensure a more resilient and sustainable supply of materials (see paragraph regulations in EU and US), In addition to this, procuring raw materials outside Europe has impact on greenhouse gas emissions also for logistics and transportation reasons.

Following a description of the metal content of electric vehicles, divided by main component. Finally, the geopolitical supply chain situation for Lithium, Cobalt, Nickel and Manganese is analyzed.

3.1.1. ELECTRIC VEHICLES BATTERIES: METAL CONTENT

Battery cells typically account for 70% to 85% of the total battery weight and include several minerals in every component. For example, the cathode could contain lithium, nickel, cobalt and manganese; the anode graphite and current collector like copper. The remaining modules and pack component consist mostly of aluminum, steel, coolants and electronic parts. The quantity necessary for each mineral varies considerably depending on the cathode and anode chemistries.

CATHODE CHEMISTRIES

Lithium-ion batteries are frequently categorized by the chemistry of their cathodes. Based on the combination of minerals, the batteries will have different characteristics. In table 10 are schematized the most common combinations, specifying the different characteristics [18].

For most manufacturers and countries, reducing cobalt and striving for higher energy density is becoming a concern. Therefore, cobalt-rich chemistries are expected to reduce in the future in favor of NCA and NMC variants with more nickel and manganese. Other technologies, like All-Solid-State-Batteries, should also enter the market.

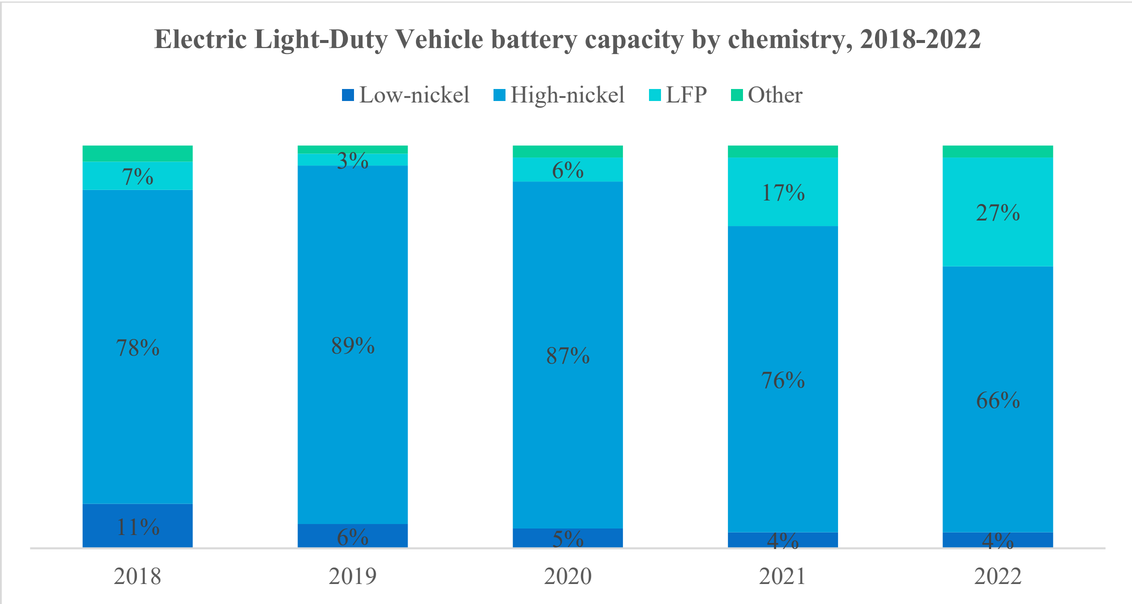
When talking about NMC variants, we refer to different metal composition (where the numbers refer to the Nickel:Manganese:Cobalt ratio) [39], [34]:

- NMC 111 (Nickel 33.3% – Manganese 33.3% – Cobalt 33.3%);
- NMC 622 (Nickel 60% – Manganese 20% – Cobalt 20%);
- NMC 811 (Nickel 80% – Manganese 10% – Cobalt 10%).

Data gathered from Internacional Energy Agency (IEA), [40] also underline the trend in cobalt reduction (see table 9). Manganese is also showing potential as a cathode component, being for this use cheaper and safer than nickel-rich chemistries, but with lower stability that could lead to lower performances in the long term.

In 2022, Lithium iron phosphate (LFP) cathode chemistries have reached their highest share in the past decade, due to an increase in use by Chinese OEM (BYD accounting for 50% of demand), but also Tesla.

Table 9: Electric Light-Duty Vehicle battery capacity by chemistry, 2018-2022



LFP can be considered a compromise between NCA and NMC for its lower energy density and contained dimensions suitable for buses and trucks. Moreover, it's appropriate for stationary applications, thanks to lower prices, safer chemical composition and absence of both cobalt and nickel. As a downside, energy density tends to be lower than NMC.

Figure 7 shows the batteries placed on the market in Europe by both chemistry and application [41].

Figure 7: Batteries in the EU market by application and chemistry, (IVL, 2022)

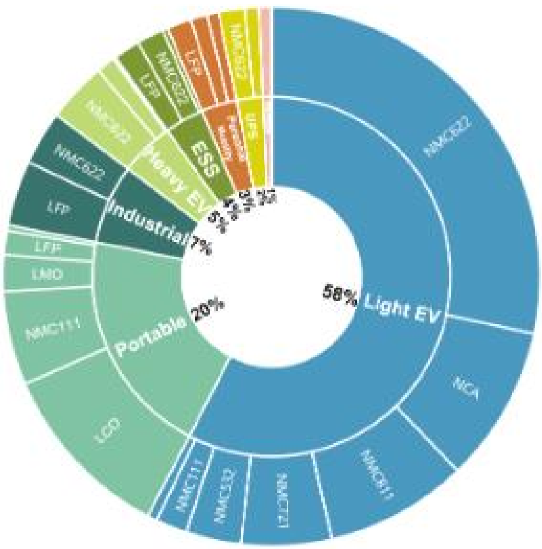


Table 10: Combination of Lithium-Ion cathodes

Name	Short name	Advantages	Disadvantages	Use
Lithium Cobalt Oxide	LCO	• Energy density (150-190 Wh/kg) • Technological Maturity	• Thermal instability • Short life cycle (500-1000 cycles) • Safety concerns	Portable electronics; Not favored in EV applications for safety concerns
Lithium Manganese Oxide	LMO	• Life cycle (1000-1500 cycles) • Thermal stability • Cobalt-free	• Energy density (100-140 Wh/kg)	Electric bikes; Commercial Vehicles
Lithium Iron Phosphate	LFP	• Thermal stability • Life cycle (2000 cycles) • Low cost	• Energy density (90-140 Wh/kg) • Size and weight	Stationary Energy Storage applications; EV (trucks included)
Lithium Nickel Cobalt Aluminum Oxide	NCA	• Highest specific energy range (200-250 Wh/kg) • Life cycle: 1000-1500 cycles	• Expensive	EV; Potential use in power systems in backup and load shifting applications
Lithium Nickel Manganese Cobalt Oxide	NMC	• Life cycle: 1000-2000	• Energy density (140-200 Wh/kg)	EV, particularly favored for PHEV

ANODE CHEMISTRIES AND ELECTROLYTE

Main criteria to select anode materials is the charge collection capability.

In most Lithium-ion batteries, Graphite is currently the dominant choice for the anode. Commercial alternatives are being developed, since the capability is proving to be not suitable for requirements of high-performance lithium batteries.

Main competition is arising from four categories of materials: Alloy Materials, Conversion-type Transition Metal compounds, Silicon-based compounds, and Carbon-based compounds [42].

The electrolyte heavily influences battery performance impacting on rate capability, cycle life, coulombic efficiency, operation temperature range and safety.

The two main components of a liquid electrolyte are salt and solvent. Most common salt is $LiPF_6$ used for commercial systems due to its non-toxicity and thermal stability. The solvent is composed of mixtures of alkyl carbonates. In addition, electrolyte additives are added to improve the cycle life and safety if LIBs [43].

3.1.2. LITHIUM

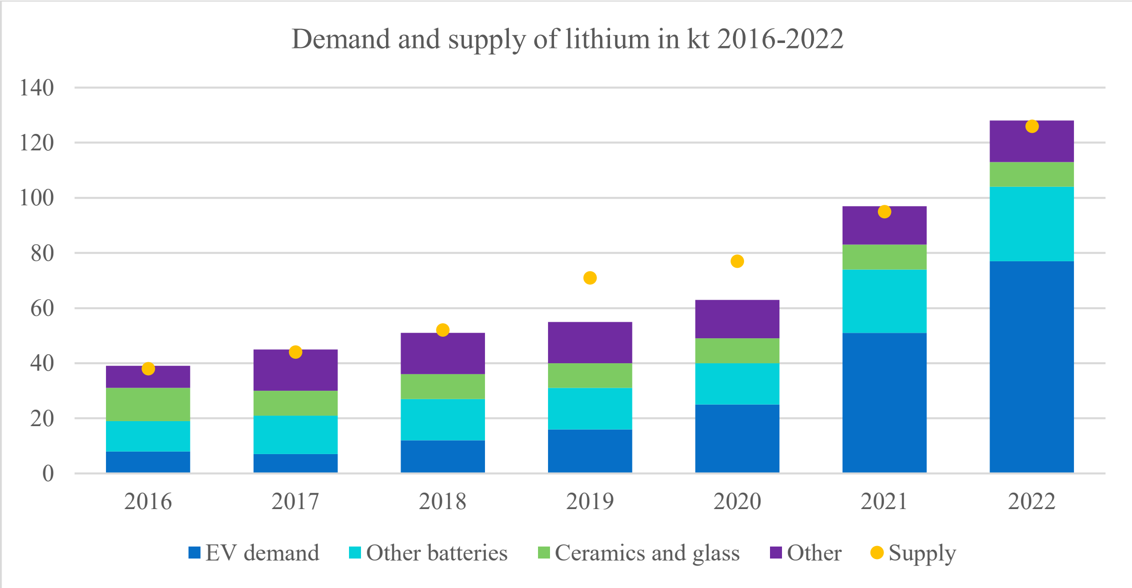
As things stand, the lithium supply is struggling to keep up to cover actual demand (see table 9), with batteries being the main driver accounting for more than 80%. According to IEA data, demand has exceeded supply both in 2021 and 2022, with significant increases being registered every year (YoY +54% in 2021 and +32% in 2022). The market for lithium is still immature, with supply showing ups and downs between deficit and surplus. Infrastructures need time and money to be properly developed and as a result of this, supply is growing at an insufficient rate, even if there's a continuing production increase (YoY +23% in 2021 and +33% in 2022) [40].

This metal is used all over the world, but its reserves and production are not distributed uniformly [44]. South American nations possess more than half the reserves available in the world (53%), followed by Australia with about 27% of the resources stocked (see table 10).

The main sources for lithium are ores and salt lakes, with the latter accounting for 87% of world lithium [45]. Main reason for this proportion is the process, because to extract lithium from salt lakes is used solar evaporation: cheap but time-consuming (18-24 months). Extracting lithium from ores ensures higher lithium concentration, but production cost is higher due to a more energy-intensive procedure [46].

The main output of production process is Lithium Carbonate, that is used as main material for battery cathodes (mainly for cathodes with low level of nickel). Another final product is lithium hydroxide.

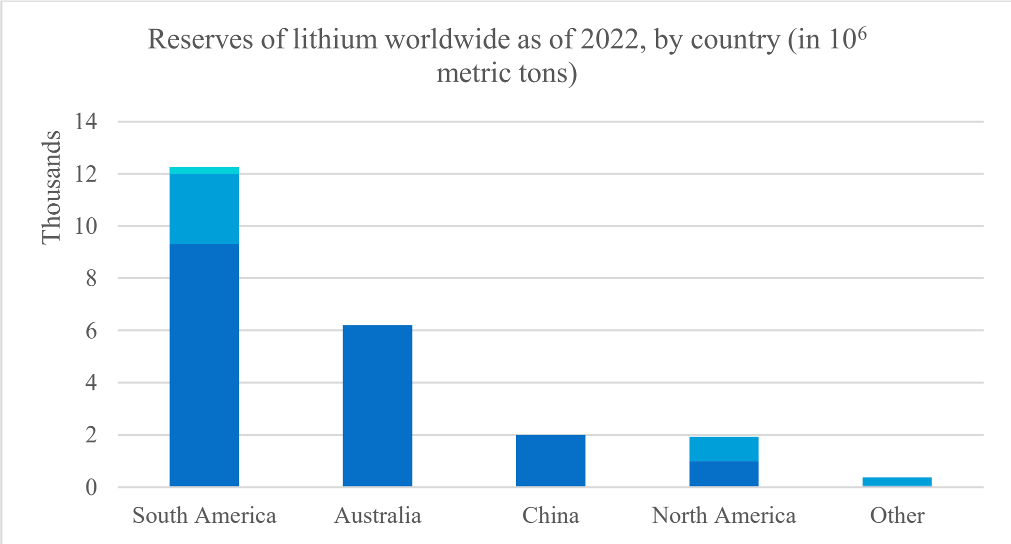
Table 9: Demand and supply of lithium in kt 2016-2022, (IEA, 2022)



The salars with the highest lithium concentration are in Bolivia, Argentina and Chile, but also are present in many other countries. Lithium-bearing minerals, like spodumene and petalite are mostly extracted from pegmatites in Australia, Zimbabwe and Brazil [47]. After being extracted with beneficiation processes, lithium concentrate is then exported to China where is then refined to lithium carbonate or lithium. Globally, Australia is the first producer, followed by Chile and China (see table 11) [48].

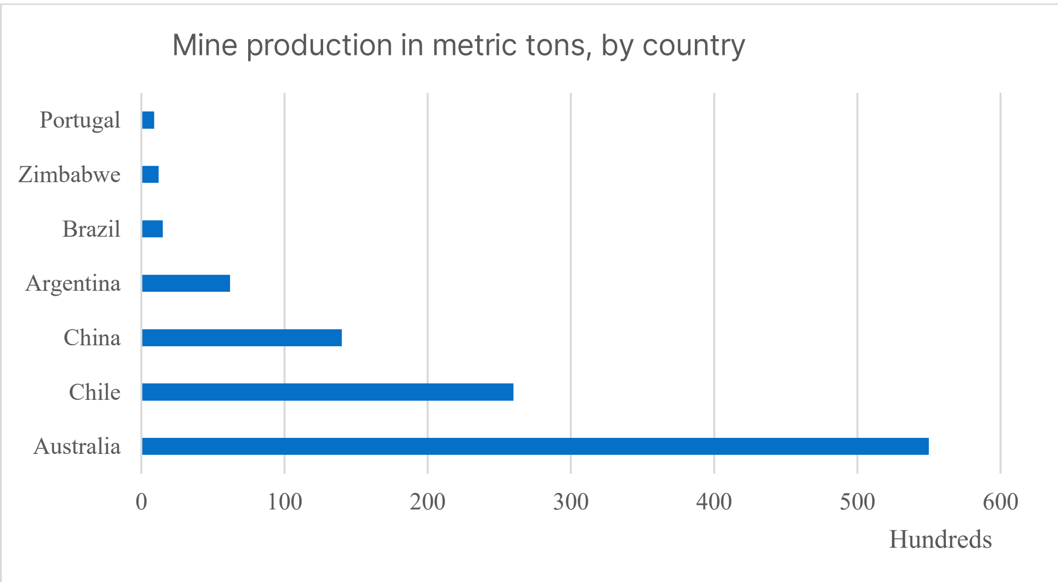
Many efforts are being conducted to reduce the costs of lithium extraction. While it exists in seawater, the concentration of Lithium is too low to be economical, but oilfield and geothermal brines are showing promise and may become an important source of lithium in the future. Latest research suggests that geothermal Li exploitation have a lot of potential regarding the quantity of Lithium that could be extracted, but it could vary from the sources of extraction, process and evaluation of economic conditions, all factors varying between different brines [49].

Table 10: Reserves of lithium worldwide as of 2022, by country (in 1,000 metric tons), (US Geological Survey, 2023)



Additional mining will be necessary to meet Europe's growing demand for raw materials in all scenarios in the long term. But bringing new supplies will take time and will require capital investments. The average lead times from discovery to production can be 4 to 7 years for lithium and 15 to 20 years for nickel [50]. Currently a production expansion is ongoing, with major producers planning to further increase the primary supply in the medium term, whether this will be enough will depend on demand evolution.

Table 11: Mine production in metric tons, by country

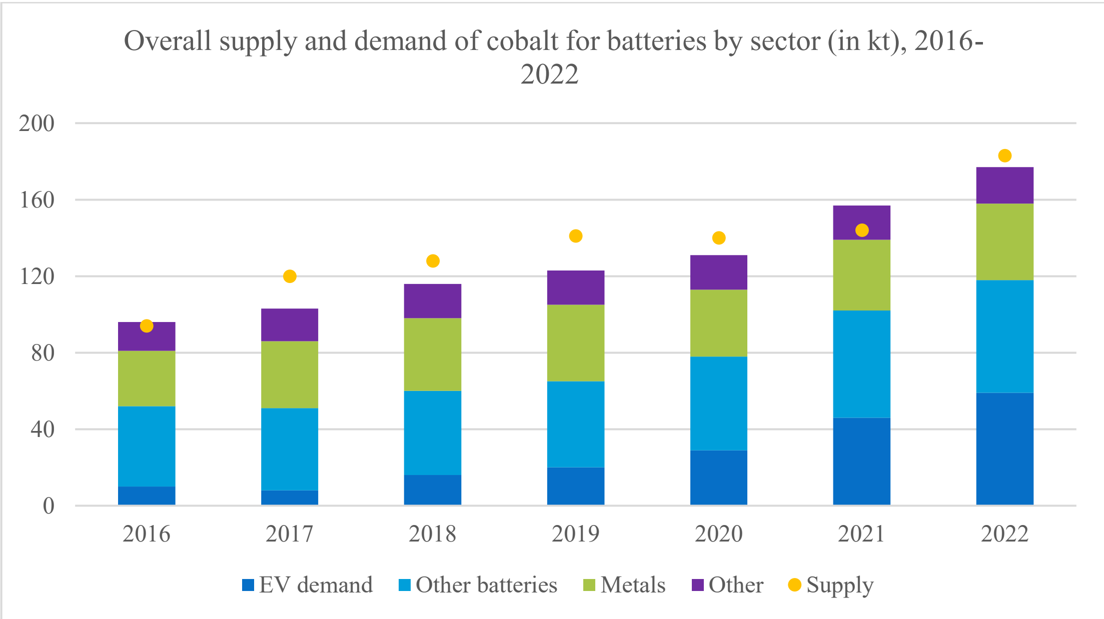


3.1.3. COBALT

Cobalt demand is constantly increasing in step with EV demand, being the main driver of the mineral's use (see table 12). Supply has been sufficiently developed over the years, with investments that helped to control price volatility, after an astonishing increase in prices between 2016 and 2018 (400% increase) [51].

Future demand will depend on developments in battery cathode chemistries. As already discussed, the market is shifting towards batteries with high-nickel content, like NMC 622 and NMC 811, therefore a demand increase is expected but with variability related to this factor.

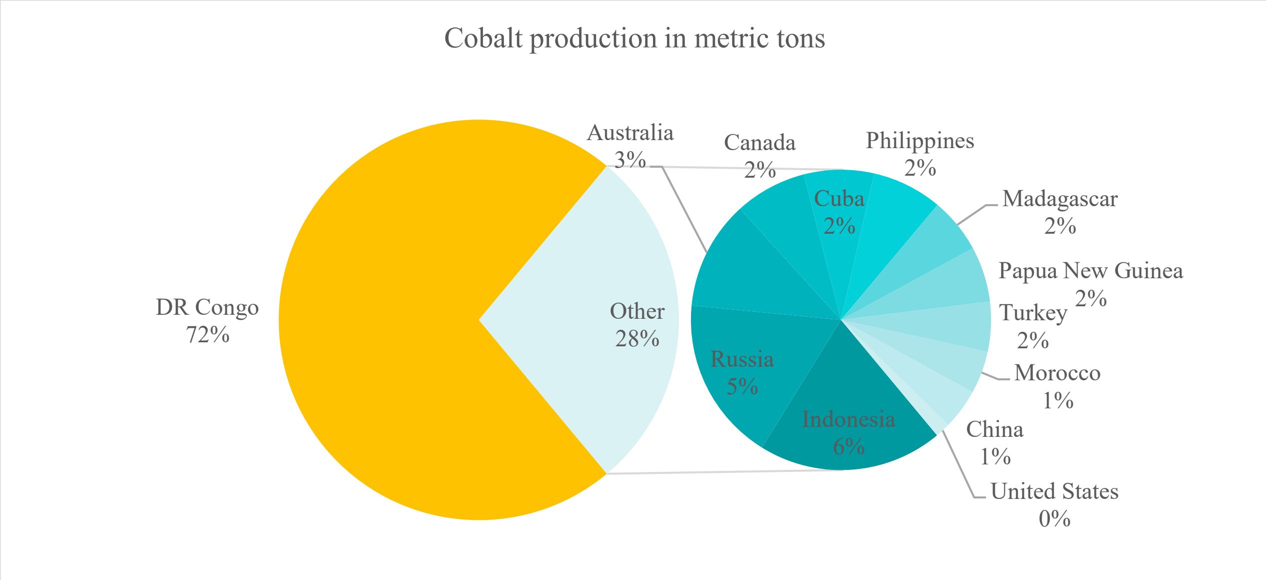
Table 12: Overall supply and demand of cobalt for batteries by sector (in kt), 2016-2022



Democratic Republic of the Congo (DRC) is by far the main cobalt producer (see table 15), accounting for 72% of global production, with rest of the world combined accounting for 28% of remaining quantity [52].

It's generally produced as a by-product of copper, and in some countries as nickel byproduct. After production, DRC generally exports cobalt hydroxide, an intermediate chemical product, to China, where it's converted into cobalt sulfate to be used in batteries. As for Lithium, China controls this sector of the value chain, processing 70% of cobalt to be converted globally [18].

Table 13: Cobalt mine production worldwide by major countries 2022



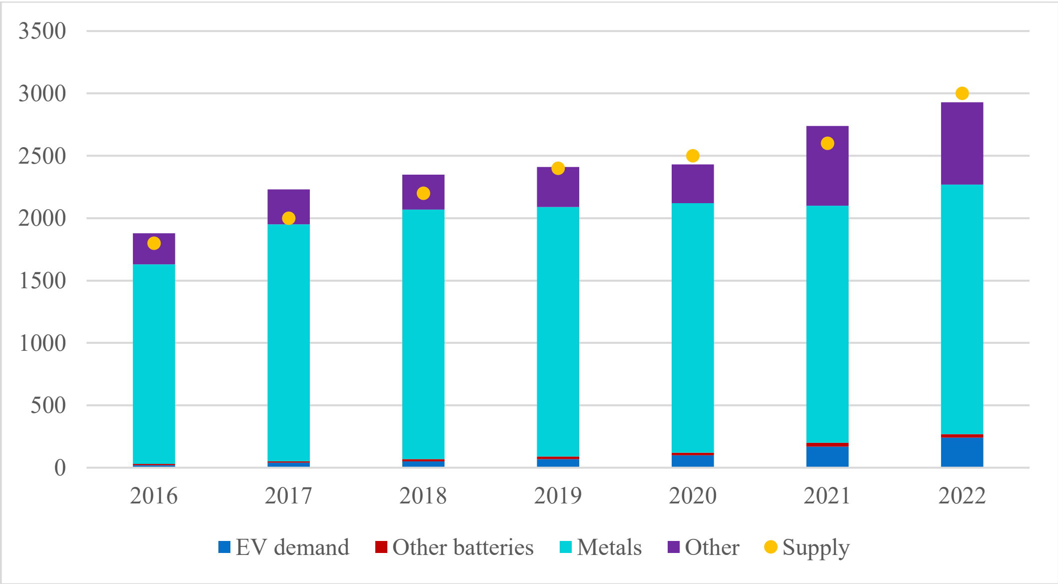
In DRC there's an important share of Artisanal and small-scale mining (ASM), with related environmental and social impact due to a complete lack of regulations. Child labor, unsafe work conditions and generally country corruption are risks companies are taking into account, also trying to mitigate them with programs like "Cobalt for development" [53], launched by BMW, BASF, Samsung SDI, Samsung Electronics and VK.

3.1.4. NICKEL

Nickel products are of two classes: high-purity class 1 (containing 99.8% nickel or above) and lower-purity class 2 (containing less than 99.8% nickel). Battery cathodes need nickel sulfate, that is synthesized from class 1 products.

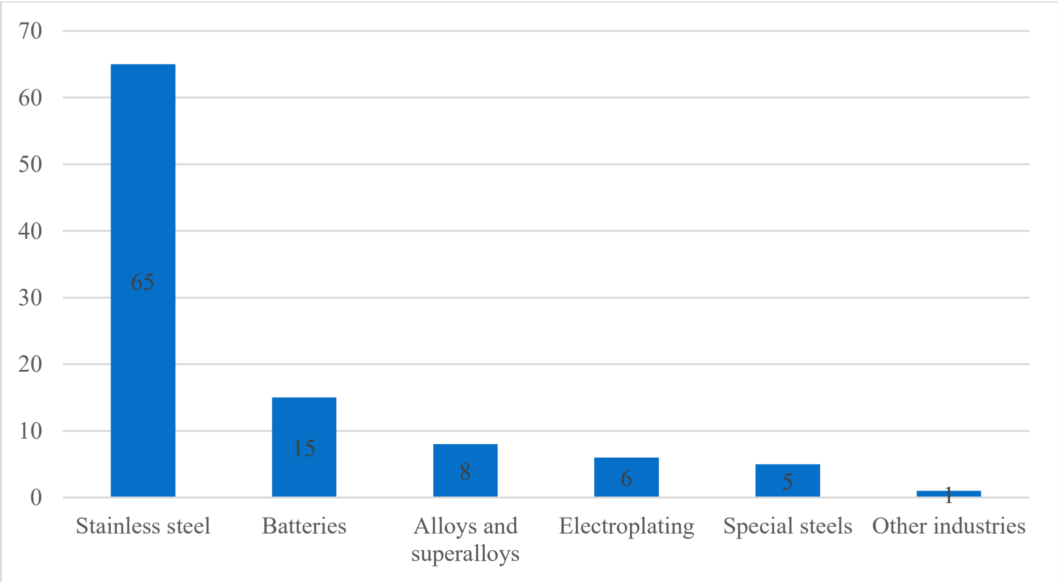
There has been a constant increase in nickel demand in recent years, mainly driven by the battery sector (see table 14).

Table 14: Overall supply and demand of nickel for batteries by sector (in kt), 2016-2022



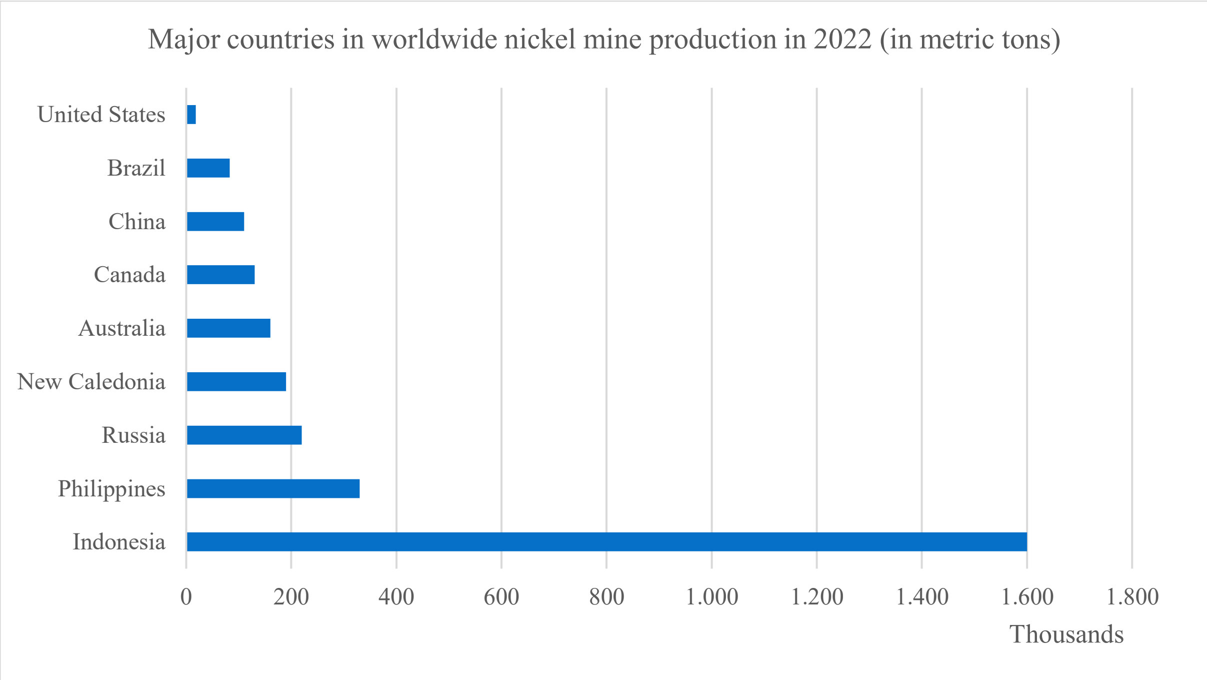
Stainless steel is the predominant use for nickel (see table 15), accounting for 65% of demand in 2022. The battery industry consumes 15% of demand, with an increase of 32% YoY [54].

Table 15: Nickel consumption by industry (%) in 2022



Indonesia and Philippines account for 45% of today's global output (see table 16) and are expected to furtherly increase their importance thanks to investments that will drive future supply growth. Indonesia in particular plays crucial role in nickel's supply chain, and consequently the country's future policies and events will have global repercussions [55].

Table 16: Major countries in worldwide nickel mine production in 2022 (in metric tons)



3.2. WASTE MANAGEMENT

Batteries are produced in different forms, sizes and for various applications. Basically all batteries are a threat to the environment and public health if not disposed in a correct and safe manner, but some types are more dangerous than others for their metal toxicity.

Generally speaking, the management of household and industrial waste comes at a financial and environmental cost irrespective of the use (may it be recycling, re-use, disposal or incineration). The waste management process comprehends collection, sortation and transportation, after all these phases it can be treated. It's easy to understand how all these different phases contribute to greenhouse gas emissions and pollution of air, soil, and water.

It's even more environmentally important to correctly collect, treat and recycle all materials of a battery: metals, non-metals, electrolytes, plastics and so on. In 1995 US Environmental Protection Act categorized batteries as universal and hazardous waste, and in May of 2023 US Environmental Protection Agency issued a memorandum stating the same for LIBs, for their ignitability and reactivity characteristics [56]. Also EU considers LIBs hazardous waste under directive 2008/98/EC [57]. Hazardous waste is more difficult to treat, because special processes are needed to deal with hazardous components.

Re-thinking battery design processes is crucial. As things stand, recovery and recycling are an afterthought, instead battery makers should consider from day one a circular process that takes into account how components should be disassembled. Manufacturing companies have responsibilities for sure, but also governments and in general public entities should be more incisive about making recycling and reuse mandatory in an effective way.

In accordance with this, also Simchi-Levi and Kaminsky in their "Designing and Managing the Supply Chain" sustain that in order to reduce the carbon footprint of a company or product, there are three opportunities to exploit (in the long term): recycling and waste prevention, product design for sustainability and emerging clean technologies.

In order to elaborate a possible model for battery recycling and re-use, main battery chemistries and metal content will be described and then will be analyzed two models for waste management: the waste management hierarchy and the circular economy model elaborated by Martinez et al.

3.2.1. REGULATIONS IN EU AND US

Main regulations for batteries to be analyzed in the following paragraphs are the European Batteries Directive introduced in 2022, the European Critical Raw Materials Act of March 2023, temporary crisis and transition framework of March 2023 and the US Inflation Reduction Act also introduced in 2022.

3.2.1.1. IRA

The US congress signed Inflation Reduction Act (IRA) in 2022, and as of September 2023 more than $110 billion have been spent in clean energy investments with $70 of them destined for the US battery supply chain. The measure has been heavily effective, with rapid increases in investments into battery factories [58], new metals processing plants and electric vehicles have increased drastically. TechCrunch data suggests that thanks to IRA automakers and battery manufacturers have collectively invested and promised to invest close to $100 billion in building domestic cell and module manufacturing. Together, these companies promise to deliver an annual capacity of over 1,200 gigawatt-hours before 2030, if each factory reaches maximum capacity [59].

Therefore, the main impact has been on cell supply. In addition to this, the cost curve was positively impacted with a consistent reduction over the last year.

According to Trost and Dunn [60], it's necessary to also take into account different issues with this measure:

- The market-value based target, subject to volatile market prices;
- Difficult to reach targets because relevant minerals such as cobalt and manganese are generally extracted outside US borders, as shown in figure xx.
- US infrastructure is not developed enough to recycle the expected increasing volume of minerals to reintroduce them in the supply chain.
- It has been determined that the target may be achievable for fully electric vehicles with nickel cobalt aluminum cathode batteries, but achieving the target with lithium iron phosphate and nickel cobalt manganese batteries would be challenging.

The paper suggests that greater support is needed in particular for recycling, that is an unqualified necessity.

3.2.1.2. EU BATTERY DIRECTIVE

The European Parliament in 2022 has introduced a new regulation replacing the existing Batteries Directive from 2006. This new cradle-to-grave regulatory framework for batteries will require a lot of more detailed rules (secondary legislation) to be adopted from 2024 to 2028 to be fully operational. The new Regulatory Framework for Batteries will introduce [61]:

- Extended Producer Responsibility (EPP);
- Targets for producers to collect waste;
- A minimum Recovery Rate of 90% in 2027 for Cobalt, Copper, Lead and Nickel and 50% for Lithium. In 2031, the minimum will be set at 95% for the former metals and 80% for Lithium;
- Mandatory minimum levels of recycled contents;
- Recycling efficiency target: for nickel-cadmium batteries at 80% by the end of 2025 and 50% by the end 2025 for other waste batteries.

In particular, it will be interesting to see how EPP will be implemented, since it could be very important to recover resources through EOL management.

3.2.1.3. CRITICAL RAW MATERIALS ACT

The Critical Raw Materials Act [38] published in March 2023, part of the Green Deal Industrial plan, sets the following benchmark for EU domestic capacity:

- at least 10% of the EU's annual consumption for extraction;
- at least 40% of the EU's annual consumption for processing;
- at least 15% of the EU's annual consumption for recycling (that according to unofficial news will be shifted to 25%);
- no more than 65% of the EU's annual consumption from a single third country.

The enforcement will be executed with Supply Chain risks audit.

This measure hopes to facilitate permitting process for strategic projects, since project applications are not very smooth across European countries, taking as examples installing an electric car charger to building battery or recycling factories. Often, it's due to a lack of expertise and personnel in local authorities.

The commission aims to resolve this issue by encouraging governments to tackle capacity constraints, which may involve providing financial assistance, and by imposing strict timelines for permit approvals. For processing and recycling projects, the deadline for permit approval is set at one year [62].

The recycling issue is also treated adding that "Member States will need to adopt and implement national measures to improve the collection of critical raw materials rich waste and ensure its recycling into secondary critical raw materials. Member States and private operators will have to investigate the potential for recovery of critical raw materials from extractive waste in current mining activities but also from historical mining waste sites. Products containing permanent magnets will need to meet circularity requirements and provide information on the recyclability and recycled content." While being a step forward, it's still a vague measure that needs more specifications yet..

Main issues reported from expert on the field for the law as it has been announced are different:

- Missing specific targets for raw materials;
- Financial support for refining and mining projects is not yet defined;
- Lack of incentives to use locally produced raw materials;
- Lack of clear elaboration of how permitting processes can be accelerated;
- Recycling capacities are often limited to the production of black mass;
- Possibly overcapacity in China and consequent competition for the EU.

3.2.1.4. TEMPORARY CRISIS AND TRANSITION FRAMEWORK (TCTF)

European response to Inflation Reduction Act didn't take long to arrive. With the aforementioned policy, the USA can produce batteries at a price level similar to Cina. European production costs compared are 40% higher, according to European Battery Alliance. In addition to this, high electricity prices need to be considered in a very energy-intensive industry.

With Temporary Crisis And Transition Framework (TCTF), section 2.8 TCTF, recital 85: MS can set up schemes to accelerate the transition towards a net-zero economy. Eligible investments are:

I. Production of batteries, solar panels, wind turbines, heat-pumps, electrolysers, and equipment for carbon capture usage and storage (CCUS);
II. Production of key components designed and primarily used as direct input for the production of the equipment defined under (i);
III. Production or recovery of related critical raw materials necessary for the production of the equipment and key components defined under (i) and (ii).

As discussed in Battery Innovation Days event, schemes according to rec. 85 applicable to or solely focused on batteries have been implemented in:

- Spain (May 2023): volume 837 mil. Euros, up to 300 mil. Euro per beneficiary;
- France (May 2023): “Green Industry Investment” tax credit, volume 500 mil. Euros p.a. (all TCTF sectors);
- Germany (July 2023): volume 3 bln. Euros (all TCTF sectors), up to 200 mil. Euro per beneficiary;
- Hungary (August 2023): volume 2.36 bln. Euros (all TCTF sectors), up to 350 mil. Euro per beneficiary;
- Austria (November 2023): volume 60 mil. Euro

This regulation is still active and aid will be granted until 31st December 2025.

3.2.2. THE WASTE MANAGEMENT HIERARCHY

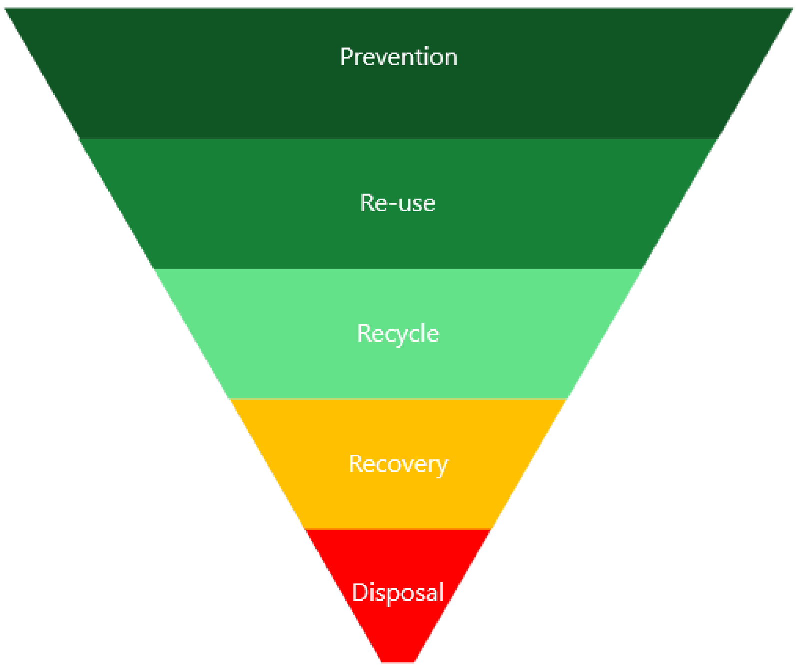
The Waste Management Hierarchy is a well diffused concept in environmental literature, introduced for the first time in 1975 into European waste policy. Is a concept of waste management which incorporates practices relevant to the circular economy, widely applied in many countries. In some cases is part of waste legislation, like in European Union [63], ranking waste and materials management options. According to den Hollander et al. it is one of the guiding principles of eco-design. [25]

Figure 9 illustrates the waste hierarchy as legislated by EU in 2008 with directive 2008/98/EC [64]. The key factor in all waste management strategies is waste prevention. Reducing waste amount and its hazardousness (by reducing the use of dangerous substances in products) will have immediate impact on disposal, making it simpler. Prevention is linked with improving manufacturing processes and influencing consumers towards greener products.
Re-use and recycling come into play when products are reaching or have reached end-of life. Finally, waste that can not be recycled or reused should be safely incinerated, with landfill being used as a last resort. Both these last two methods need close monitoring because of their potential for causing severe environmental damage [65].

Applying these concepts to batteries:

- Prevention: LIB's need to be designed to use less-critical materials, should be lighter and have smaller batteries, incorporate self-healing solutions and be easy to disassemble.
- Re-use: electric-vehicle batteries should have a second use, or be re-purposed or reconditioned.
- Recycling: batteries should be recycled, recovering as much material as possible and preserving any structural value and quality (for example, preventing contamination).
- Recovery: using some battery materials as energy for processes such as fuel for pyrometallurgy.
- Disposal: means that no value is recovered and the waste goes to landfill.

Figure 8: Waste management Hierarchy

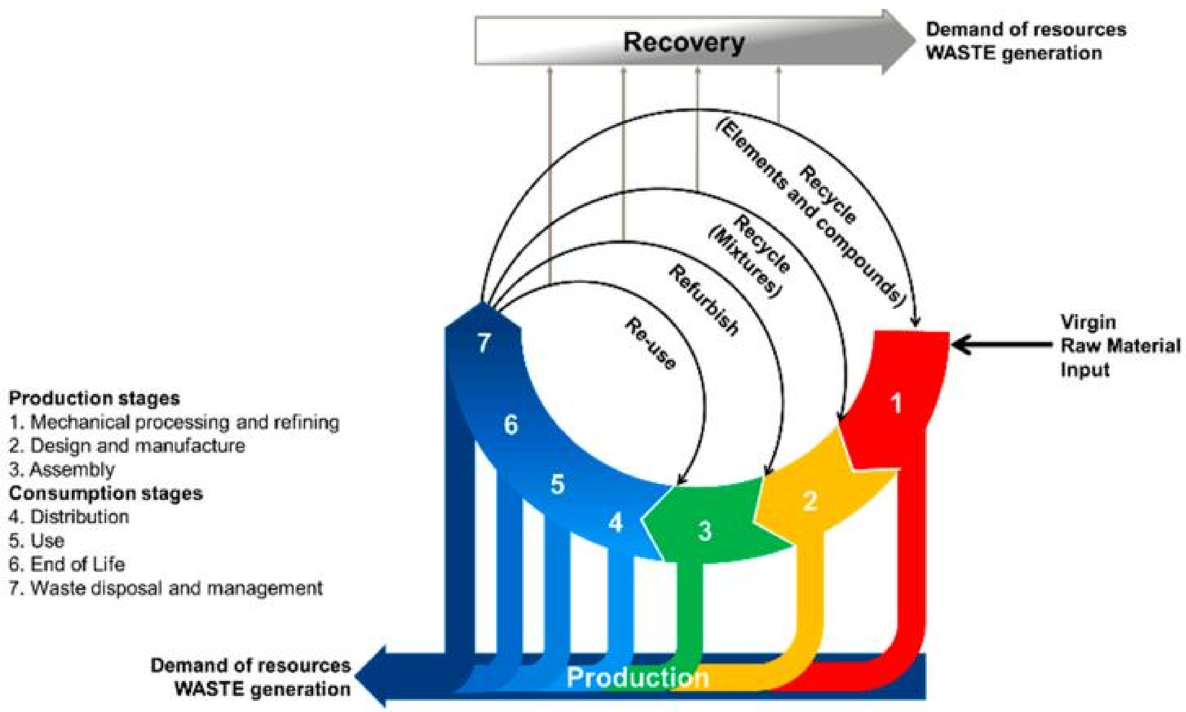


3.2.3. CIRCULAR ECONOMY MODEL FROM A MATERIAL-CENTRIC PERSPECTIVE

In 2019 Martinez et al. proposed a Circular Economy model that accounts for the losses of material inherent to the production and recovery phases.
The model integrates the 4Rs (Remanufacture, Refurbish/Repair, Reuse, Recycle) of circular economy to life span of the product.

In the loops (see Fig. 9), the material moves from the input stage (1) towards the EOL of the product (6), where recovery systems (7) take action and reintroduce elements into the value generation chain. The model shows different reintroduction points relative to the recovery process and their energy intensiveness. That is, the further the reinsertion point is from the waste disposal and management (7) point, the more resource-intensive the recovery process will be. It is well known that both economic and technological feasibility are bound to the market trends, which decide whether LIBs will be processed down to level of elements and compounds. Indirectly, these drivers also define the usability of the recovered materials. In other words, materials on the level of elements and compounds have a potentially broader field of application than those obtained through refurbishment. In reality, industrial-scale LIB recycling processes present inefficiencies, resulting in inevitable material losses. [66]

Figure 9: Circular Economy Model from a Material-Centric Perspective (Martinez et al., 2019) [66]



3.3. PREVENTION

Daniel Etsy in its book "Green to gold: how smart companies use environmental strategy to innovate, create value and build competitive advantage" calls the different efforts to reduce resource uses and cut wastes as eco-efficiency. Redesigning a process or a product can lower both financial and operational risks, and the constant pursuing of eco-efficiency can therefore bring numerous advantages to companies [67].

In accordance with this, Simchi-Levi and Kaminski sustain that recycling and waste prevention reduce carbon emissions in two stages during the product life cycle: product manufacturing and at product EOL. Furthermore, waste prevention saves energy and reduces greenhouse gas emissions. Therefore, Corporate Social Responsibility offers an opportunity for new revenue streams and additional efficiencies. But for this to become a reality, it's necessary for firms to make these principles part of their business vision. [22]

These concepts can be applied starting from the top of the waste management hierarchy, with the prevention phase, with particular focus on battery design, size, chemistries and possible innovations like sensing and self healing.

3.3.1. BATTERY DESIGN AND CHEMISTRY

With the increasing number of batteries that are going to circulate in the future, it should be noted how battery size and chemistry influence demand, future waste management and reliance on primary production.

Furthermore, in order to reduce emissions it's crucial consider product life cycle, including EOL since design stage. This is useful to reduce waste, improve utilization of transportation capacity and increase the use of recycled materials.

A report from Transport and Environment [36], published in July 2023, has developed an analysis of three different scenarios from 2022 to 2050:

- Business as usual follows the current status quo of the industry trends on technology and transport activity;
- Accelerated scenario involves optimized batteries and chemistry technologies as well as lower car activity;
- Aggressive scenario entails drastic technology changes and lower car activities.

In figure 10 are shown the expected results on demand of batteries and raw materials in the different scenarios. The analysis estimates that decreasing battery dimensions, improving chemistry and reducing car usage could lead to a decrease in battery demand from 31% to 48%.

Figure 10: Battery demand from passenger transport in Europe (Transport and Environment, 2023)

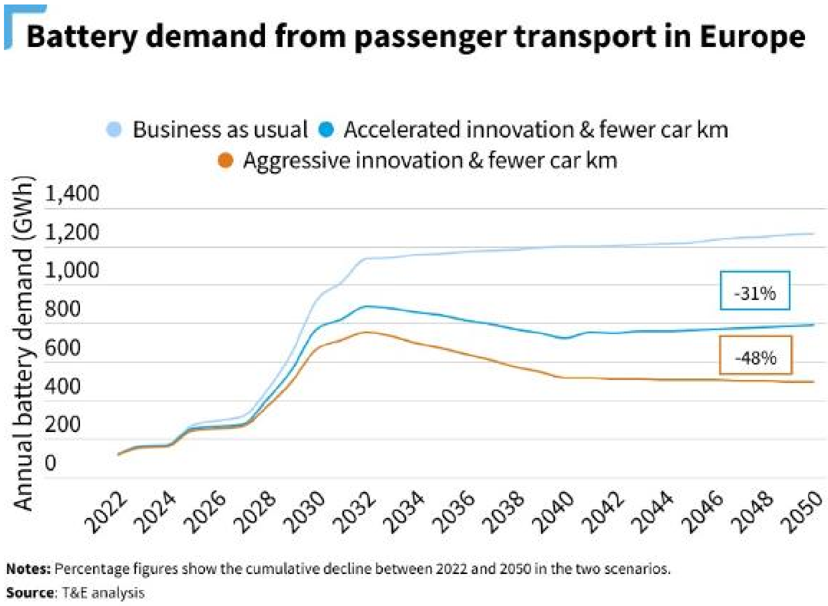
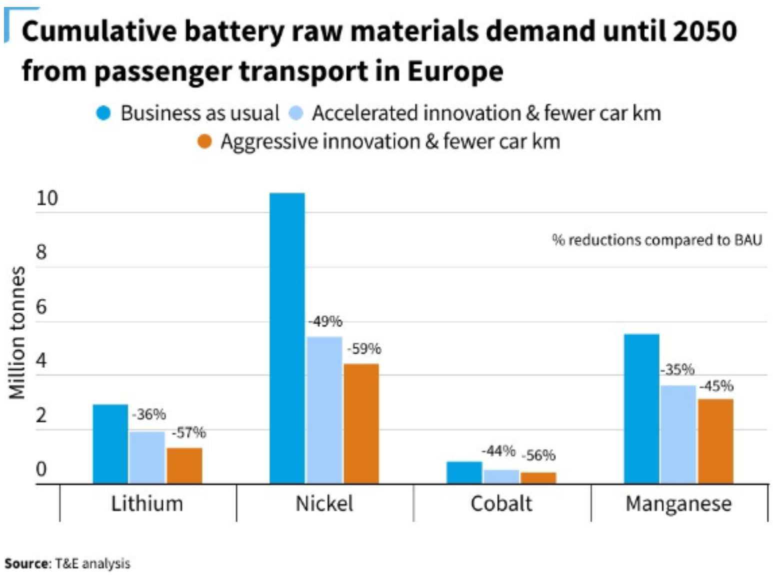


Figure 11 shows the impact of the aforementioned variables on raw materials. In particular, it's interesting to note that keeping things as of now, Nickel will be the most demanded metal but acting on the variables would lead to a much lower quantity needed, with a reduction that could account to 59% of business as usual.

Figure 11: Cumulative battery raw materials demand until 2050 from passenger transport in Europe (Transport and Environment, 2023)



Another fundamental aspect to take into account for all actors involved in the battery market is the importance of designing batteries taking into account future disassembly, recycling and dismantling of the product. In the previous chapter (future technological advancements paragraph) was already mentioned the importance of automation and standardization of battery design for safety, economic and environmental reasons.

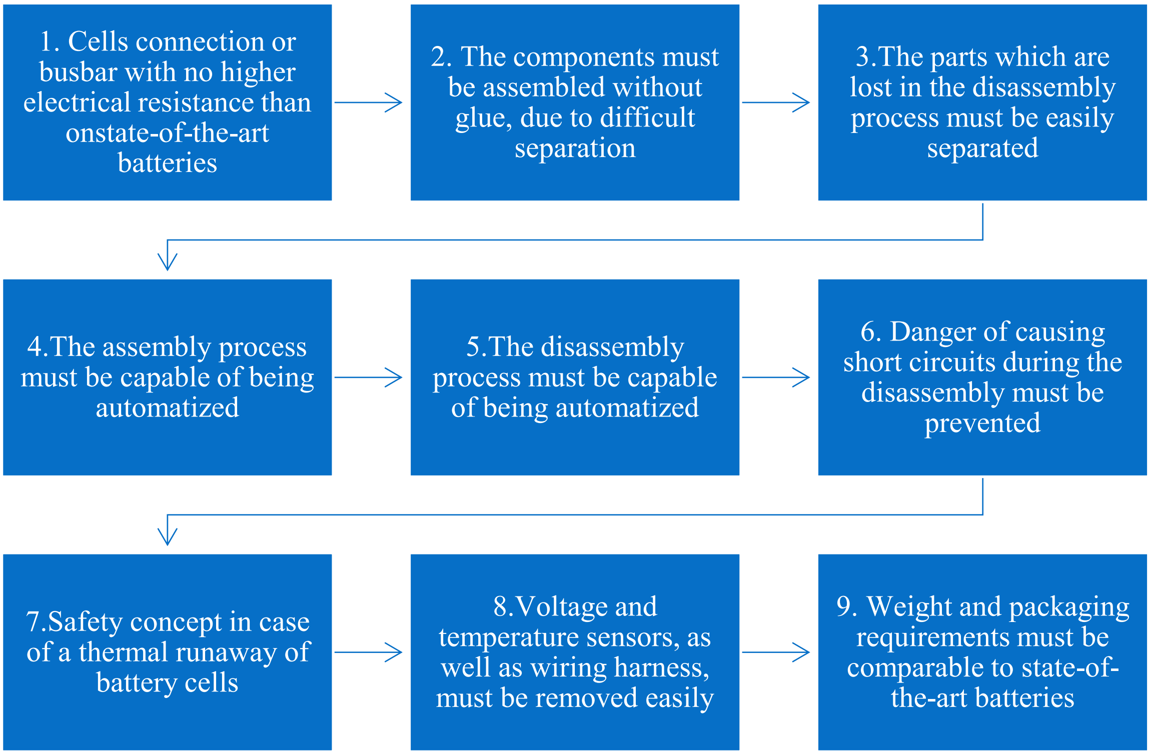
Pack disassembling into modules or cells is the first step towards recycling, and separation and sortation is fundamental in the process. Battery packs are an integrated system containing different components with different geometrical forms.

As things stand, due to different designs and layout, there is not a standardized, or universally applicable method for disassembly, making it a complex and variable activity. A reasonable disassembly sequence could potentially reduce process times and costs and improve overall efficiency. Furthermore, the capacity of manually disassembly cannot match the rapid growth of the number of LIBs consumed, making it fundamental to shift to an automated process. [68], [69] Currently, semi-automatic disassembly is the most optimal solution [68].

Even if there are numerous publications discussing this topic, the implementation of it is still lacking and is imperative to furtherly push in this direction.

Probably the most advanced system in this field so far, has been developed by Comau, an Italian multinational company in the automation field based in Turin. It's called Flex-BD and is a "robotized system that automates the entire process of dismantling worn-out electric batteries using a highly flexible, repeatable and standardizable process. Now, having validated the proof-of-concept, Comau has expanded the scope to include second life repurposing of automotive batteries." [70] Comau's system use advanced vision systems and IA to recognize the battery pack type and therefore define the needed tools to disassemble the pack to the module level, not arriving to cell. In this way modules can be re-used (and probably due to increasing complexity in arriving to cell level, see remanufacturing paragraph)
The system is designed in a flexible way, meaning it can adapt to different applications, sizes and shapes of batteries, making it theoretically scalable for different type of automotive batteries [71].

According to Kampker et al. there are nine fundamental requirements on product design that need to be diffused to achieve battery cells recovery (from used modules) [26]:



3.3.2. INNOVATIONS: SMART BATTERIES, SENSING AND SELF HEALING

Over the past years battery performances have improved and costs decreased (see paragraph technological advancements). It's important to keep improving accelerating discovery of new materials with higher energy density and/or power performance that also exhibit high stability towards unwanted degradation reactions.

It will also be important to improve the lifetime, reliability and safety of future batteries. In the roadmap Battery 2030+, developed by cross-sectoral stakeholders in the field of battery R&D, there are interesting themes useful to this purpose. It is suggested to develop smart-batteries able with high sensitivity and the use of self-healing functionalities. These two functionalities should be connected via the Battery Management System (BMS), which will trigger self-healing based on information from the sensors. In figure 12, are summarized goals to introduce these kinds of technologies and their importance in a short, medium and long term. [69] It's important to note these technologies would impact the first life cycle of the battery, not second-life, recycling or dismantling.

Concurrently to these new technologies, investments and effort to develop shared data systems are needed. For example, in 2019 the Global Battery Alliance (GBA) conceptualized a framework to increase transparency across the battery value chain, called Battery Passport. In 2022 a proof-of-concept was developed, covering the entire value chain, divided into four sections:

Figure 12: Short-, medium-, and long-term goals for Sensing and Self-healing, (Battery 2030+)

<table>
<tr><th>Research Areas</th><th>Short-term (3 years)</th><th>Medium-term (6 years)</th><th>Long-term (10-years)</th></tr>
<tr><td rowspan="3">Sensing</td><td>Apply non-invasive multi-sensing approaches</td><td rowspan="2">Miniaturise and integrate the identified (electro)chemically stable sensing technologies with multifunctions at the cell level and in real battery modules, in a cost-effective way compatible with industrial manufacturing processes.</td><td rowspan="3">Master sensor communication with an advanced BMS relying on new AI protocols by wireless means to achieve a fully operational smart battery pack.</td></tr>
<tr><td>Integrating sensors into existing battery components (e.g., separator, current collector, and electrode composite</td></tr>
<tr><td>Deploy sensors capable of detecting various relevant phenomena (e.g., interface dynamics, electrolyte degradation, dendritic growth, metals dissolution, and materials structure change)</td><td>Deliver proof of concept of higher quality, reliability, and lifetime on the cell and module levels.</td></tr>
<tr><td rowspan="2">Self-healing</td><td>Establishing a new research community that includes a wide range of R&D disciplines to develop self-healing functionalities for batteries.</td><td>Integrating self-healing functionalities into battery components (e.g., separator or electrode composite).</td><td>Established efficient feedback loops between cell sensing, BMS, and/or AI modules to appropriately trigger, by external stimulus, the self-healing functions already implanted in the cell.</td></tr>
<tr><td>Developing autonomous and non-autonomous (on demand) self-healing functionalities for specific battery chemistries, targeting loss of capacity and loss of power.</td><td>Electrochemically stable non-autonomous self-healing functionalities triggered via an external stimulus obtained from an advanced BMS.</td><td>Designing and manufacturing low-cost biosourced and/or biomimetic membranes with controlled functionalities and structure as autonomous self healing functionalities</td></tr>
</table>

battery, materials, ESG and data. It reports all data and descriptions needed to track provenance, manufacturing, ESG performances, battery life extension and recycling [72].

If something like the battery passport would be used on a global level would be a game changer for the industry since it would assure transparency and benchmarking of different types of batteries. To make it happen though, there would need to be a strong belief from governments and institutions, because many actors could not collaborate due to possibility of being exposed as poor performer in one or more of the sections analyzed.

European Union has introduced the obligation of a digital passport with the New Battery Regulation starting from May 2026. In the passport will be recorded: battery details, raw materials used, ESG assessment and supply chain data. These will be also accessible to consumers or other stakeholders through a QR code the will be apposed on the battery.

3.3.3. TECHNOLOGICAL ADVANCEMENTS

As battery technology continues to advance, manufacturers face challenges in rapidly adapting their production processes to reduce costs, incorporate new materials and designs.

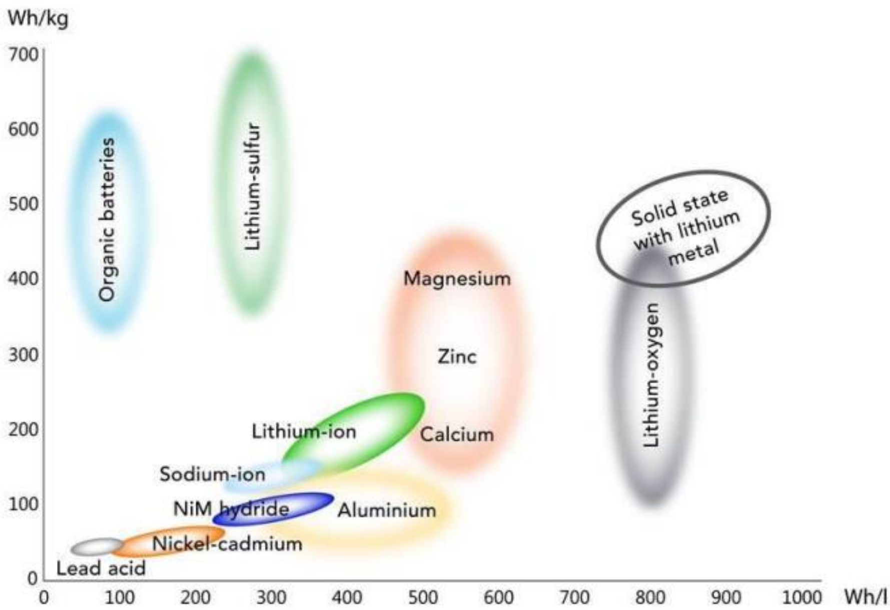
Further technology innovation is needed to continue cost reductions, with the average cost of lithium-ion batteries declining almost 90% over the past decade [18] while energy density has increased, and generally Battery Energy Storage Systems seeing a continuous price decline [73].

New pack designs and decreasing manufacturing costs can lead to further cost reductions in the near term. As of now, standardization of design for battery packs, modules and cells is lacking, and looks far from happening in the future. Also, assembly and disassembly is done by human operators, and in the future these process need to be automated both for costs, safety and environmental reasons. In 2018, Apple for example has created an automated disassembly line as R&D project, "Liam", that works just for iPhone 6 models that cannot be repaired, having therefore still a minimal impact over total production. With this solution, Apple produced different material streams that can be sent for targeted material recovery, yielding a more diverse set of materials compared to the standard shredding process of metals [74].

Beside these aspects, other factors already discussed in previous paragraphs influence battery costs. First, maintaining a steady supply to meet the increasing demand and preserve the drop in costs is likely to be increasingly challenging. Second, the sources and supply chains of the various critical minerals that are needed to bring these energy density improvements are often geographically concentrated in certain regions, and an uninterrupted supply cannot be taken for granted.

Finally, with current technology and materials are reaching their physical limits of improvement, notable cost reductions can only be achieved by the disruption of the current technology – for example in the form of All Solid-State Batteries (ASSB) with lithium anodes or increased used of silicon in graphite anodes for existing chemistries. Therefore, the continued cost decline at a pace observed during the past decade cannot be taken for granted without a further acceleration in technology innovation. Other Battery technologies based on novel chemistries are far from being commercially viable. While sodium ion batteries have recently been commercialized and also Li-metal systems have reached maturity in some applications, batteries based on alternative mono- and multivalent ions, such as potassium, magnesium, aluminum, calcium and other chemical elements are still the subject of intense research and development efforts. In figure 13 are represented the energy performance characteristics of major rechargeable battery types [69]:

Figure 13: Energy performance of major rechargeable battery types (Battery 2030+, 2022)



3.3.3.1. ASSB

Most state-of-the-art commercial batteries with NCA, NMC or LFP cathodes require a liquid electrolyte for ion transfer and a graphite-based anode. These two components fundamentally limit the functionality and energy density of lithium-ion batteries today. ASSBs equipped with lithium metal anodes could achieve a higher volumetric energy density than LIBs, making them the ideal batteries for EVs of the future. Research is being conducted on improving energy and power, but results are still far from being commercially viable to overcome LIBs dominance [75], since a scale-up process from laboratory to industrial production is not always successful.

3.3.3.2. FLOW BATTERIES

Besides lithium-ion batteries, flow batteries could emerge as a breakthrough technology for stationary storage as they do not show performance degradation for 25–30 years and are capable of being sized according to energy storage needs with limited investment. It has to be stated though, that compared to LIBs Flow Batteries are still in an early stage of development, are currently costly and their scalability needs to be furtherly investigated [76].

Rongke Power, a Chinese company, after six years since the announcement completed the biggest project on flow batteries in May 2022. A 100 MW power and 400 MWh energy Redox Flow battery storage was connected to a grid in Dalian (northeast China). This is the first phase of the project, that can be scaled-up to 200 MW/800MWh [77].

3.3.3.3. SODIUM-ION BATTERIES

Sodium-ion batteries offer a promising alternative to lithium-ion batteries, primarily due to sodium's widespread availability and affordability as the one of the most abundant element on Earth. These batteries possess several advantages, including being non-flammable (enhancing safety), boasting extended cycle life, exhibiting good performance in low temperatures, and demonstrating potential for greater sustainability by reducing the reliance on critical materials. Currently, their main limitation is a comparatively lower energy density compared to lithium-ion batteries, resulting in shorter driving ranges for batteries of the same mass. Nevertheless, ongoing research and development efforts are focused on enhancing their performance, with expectations of achieving energy densities comparable to LFP batteries at a lower cost once production is scaled up.

3.4. LIFE EXTENSION: REMANUFACTURING AND REUSE (2ND LIFE)

After prevention phase, we enter in battery End-Of-Life (EOL). Like recycling, re-manufacturing and re-using are important from a circular economy perspective since they allow to recover residual battery value. Therefore, re-use and recycling should not be seen as alternatives, but as different phases of a battery EOL, with the former being an extension of battery life and the latter returning material to the production process. From a logistics management perspective, these are considered reverse logistics processes.

Unlike the materials recovery and recycling process, in which the battery is completely discharged and destroyed, second-life battery repurposing is done while maintaining a low but active battery charge. Batteries are removed from vehicles, tested, remanufactured if needed and, after being certified for performance and safety, repurposed as-is or in parts.

Remanufacturing is the most desirable EOL scenario in terms of maximizing the value and minimizing life-cycle energy consumption and emissions; however, this option is the most stringent in terms of battery quality requirements [27], [26].

Consequently as what said in sensing and self-healing chapter, there is still a lack of information about battery health and safety. Battery sensing or more generally diagnostic systems would make it easy to assess a battery's performance after its first life, supported by battery management systems that describe battery state of health data and chemistry. A comprehensive assessment of the entire battery pack may reveal that only a small fraction of cells exhibits a deficiency in retaining the requisite capacity, since cells do not age evenly because exposed to different temperatures. Consequently, discarding the entire battery pack would signify an inefficient utilization of resources. The core concept behind remanufacturing entails the substitution of substandard cells or modules within the packs, thereby facilitating the restoration of these remanufactured battery packs for subsequent use in EVs, or other non-automotive applications like stationary storage [27], [30].

The possibility to extend the LIBs lifetime and to restore SOH to almost 100% by exchanging a low number of cells (5-30% of total) has been demonstrated by simulating the reliability properties of battery cells and by virtually replacing the worst aged cells of a battery pack. According to Kampker et al. Modules can be individually tested by capacity measurement, internal resistance and self-discharge current then accordingly classified, but it is important to identify if there're cells showing deterioration signs. The test of single cells before the module disassembly is a complicated process, that leads to detection of degraded cells in the module under load, but the SOH cannot be estimated.

There's still a lack of literature and investments on cells deterioration identification in module and a standardized method needs to be identified yet. [26]

It's easy to understand how remanufacturing is strictly related to disassembling operations, and therefore improvements on the latter field would heavily affect the former, impacting on its diffusion and scalability, as well as its integration in already existing manufacturing lines.

A typical remanufacturing process would be as follows:

Within the waste management hierarchy, prioritizing re-use over recycling is advocated. The utilization of manufactured lithium-ion batteries (LIBs) is proposed to follow a hierarchical approach to optimize material utilization and minimize life-cycle impacts. This entails cascading their use through various applications. With the ongoing transition to cleaner energy sources by energy regulators in different regions, markets for energy storage are emerging. Energy storage is especially in demand in areas with weak grids necessitating reinforcement, a high penetration of renewables requiring supply-demand balance, opportunities for energy trading with the grid, and in off-grid applications.

The Energy Stored over Energy Invested (ESOI) metric, which quantifies the ratio between the energy invested in manufacturing a battery and the electrical energy it stores throughout its useful lifespan, serves as a key metric for comparing the efficiency of various energy-storage technologies. Notably, improvements in ESOI metrics can be achieved by repurposing end-of-life electric-vehicle batteries for second-use applications where stringent performance requirements are less critical.

The inception of second-use battery projects is underway in regions where regulatory and market conditions align. However, the concentration of waste, whether for refurbishment, re-manufacture, dismantling, or final disposal, poses significant challenges.

For batteries intended to be repurposed in second-life applications, such as ESSs, it needs to be taken into account that will have to compete, at the end of their first life, with improved battery technologies that are likely produced at lower costs. This increases the risk of some potential use cases for second-life batteries. A battery pack that is in good condition could be reused in another vehicle, meanwhile a pack that has a degradation level up the aforementioned 80% is suitable for stationary repurposing. For example, due to the decreased performance requirements, Abdalla et al. suggest "Energy Storage Systems for renewable foundations, network load control or spare producers may be ideal; scrubbing and agronomic equipment, construction machinery, forklifts, e-bikes and other items are also available" [78].

Battery Energy Storage System market is kicking up and beating predictions. BESS installed capacity has reached 76,4 GWh in 2022, with this number being 400% higher than estimated .

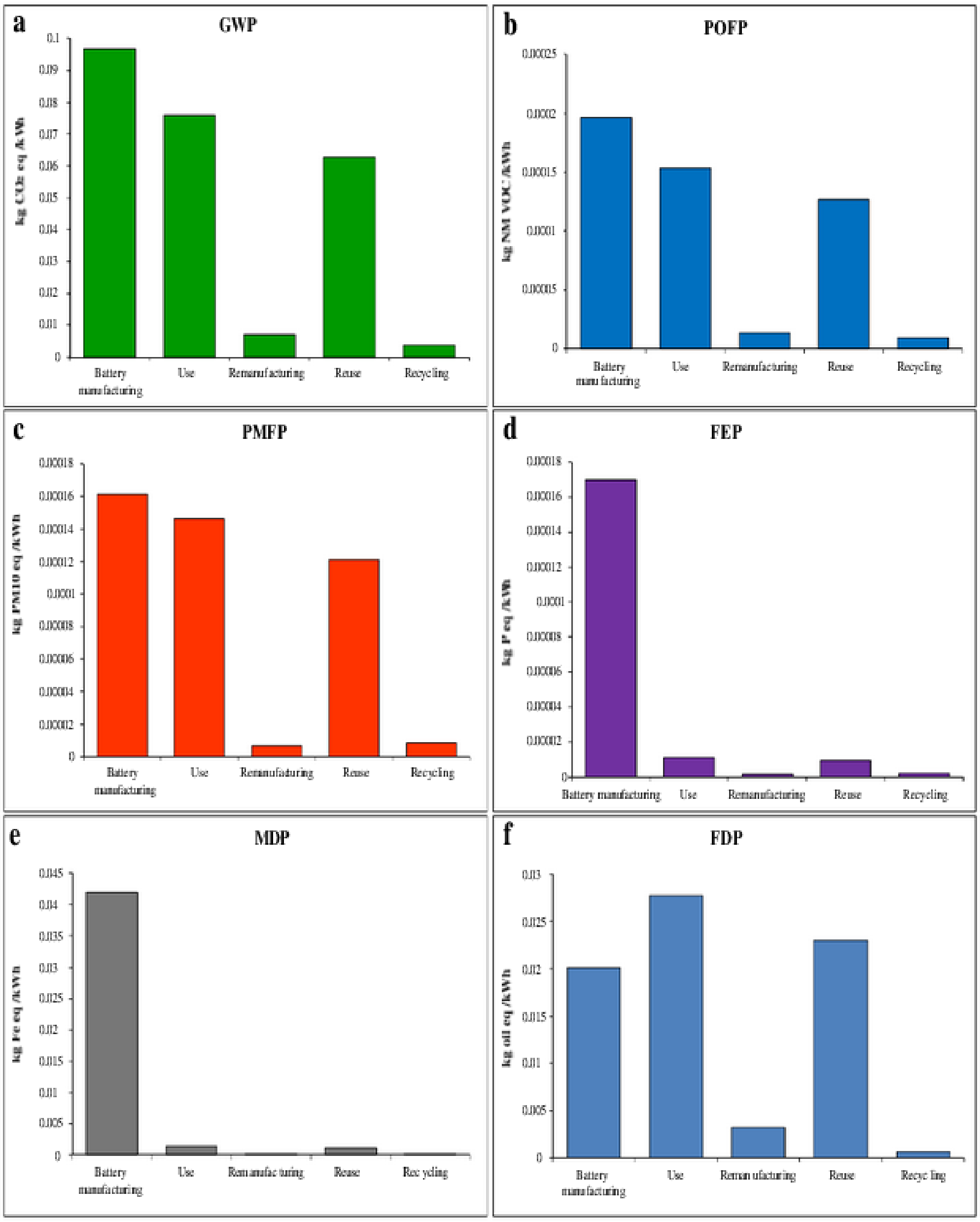
Life Cycle Assessment studies of batteries conducted by Ahmadi et al. reveal how potential environmental impacts of LIBs vary between the lifecycle phases. It's clear though that manufacturing is the most impacting phase according to all different impact indicator results, except for one:

- Global Warming Potential (GWP);
- Photochemical Oxidation Formation Potential (POFP);
- Particulate Matter Formation Potential (PMFP);
- Freshwater Eutrophication Potential (FEP);
- Metal Depletion Potential (MDP);
- Fossil Resource Depletion Potential (FDP).

Energy sources in electricity generation are crucial variables. In areas using coal power electricity, emissions and fossil depletion increases in both first use and reuse. On contrary, if clean wind electricity is used to recharge the battery packs in vehicles and reuse phases, the phases more impactful on energy and environmental emissions become manufacturing and re-manufacturing. Therefore, a green electricity mix, associated with processes that extend battery lifecycle are crucial in the automotive electrification transition, reducing impacts and emissions. [79]

Despite the fact that for an industry process model the 3R solution would be the most appropriate, there are cases when one or more of the three processes could be avoided for technical, environmental or economical reasons.

Figure 14: Impact Indicator Results for battery LCA (Ahmadi et al., 2019)



Regarding economical considerations, different research are concordant on costs savings. There are variable numbers circulating, for example the reutilization in buildings and utilities could lead on average to a reduction of 13-57% of costs and 7-32% in GHG emissions [80]. According to Harper et al. refurbishing is currently a preferable option over recycling, and this will change only when the second-use price will fall below the sum of refurbishment costs and recycling credit.

Xiong et al. have estimated that compared to virgin production of batteries, remanufacturing process combined with recycled material usage in production could save respectively 8,55% of energy consumption, 6,62% of GHG emissions and 8,17% in costs ($1,87 kg^{-1}). Results are based on hydrometallurgy process of NMC 111 batteries. [81]

In a closed loop supply chain model (where remanufacturing is considered), Li et al. have demonstrated a 9,81-30,93% increase in profit, if remanufacturing process is integrated into battery LIBs supply chain. Of course, these results are based on specific parameters and model proposed by the authors. [82]
It has to be noted how there exists research efforts on remanufacturing at the laboratory scale, but research is lacking that investigates Lithium-ion battery remanufacturing at the enterprise scale.

McKinsey estimates that refurbishment in the long term will be limited to the 5% of EOL EVs and ESS batteries [83]. Kastanaki and Giannis [34] have estimated the number of batteries available for remanufacturing and repurposing (see table 17 and 18). In their model, for remanufacturing were considered BEV with a SOH>90% (no PHEV), discarded in within 5 years of the first usage. In addition to these considerations, only 50% of batteries respecting these criteria were considered for various reasons.

Table 17: Number of batteries to be remanufactured in 2030 and 2033, (Kastanaki and Giannis, 2022)

Year	Number of batteries that will be remanufactured	% of new EV sales	Destination
2030	8-47 thousand	0,14-0,45%	Remanufacturing
2033	10-76 thousand	Not specified	Remanufacturing
2030	450 - 550 thousand	Not specified	Reuse
2035	490 - 1900 thousand	Not specified	Reuse

3.5. RECYCLING

Implementation of a recycling program will be fundamental for the automotive industry future. There are several advantages for it to happen, coming from various perspectives.

Fan et al. defined a 4H strategy for battery recycling, constituted as "high efficiency, high economic return, high environmental benefits and high safety".

Recycling can therefore have a huge impact on the environment, reducing reliance on primary resources like metals, preserving the environment and its natural resources and reduce the mining activities having an harmful impact on the planet.

It would also be beneficial to corporations, enlarging the options for raw materials, improve the resilience of the supply chain and obtain economical benefits by extracting value from waste.

To have an exhaustive picture of the recycling issue in EVs, different topics will be assessed in the next paragraphs:

- LIBs recycling indicators;
- Recycling Processes;
- Costs (comprising collection and transportation of EOL batteries);

3.5.1. LITHIUM ION BATTERIES RECYCLING INDICATORS

One of the major differences between oil and minerals lies in the way that they are used and recovered in the energy system. Unlike oil, which is combusted on an ongoing basis, minerals and metals are permanent materials that can be reused and recycled continuously with the right infrastructure and technologies in place.

Compared with oil, this offers an additional lever to ensure reliable supplies of minerals by keeping them in circulation as long as possible. The level of recycling is typically measured by two indicators [31].

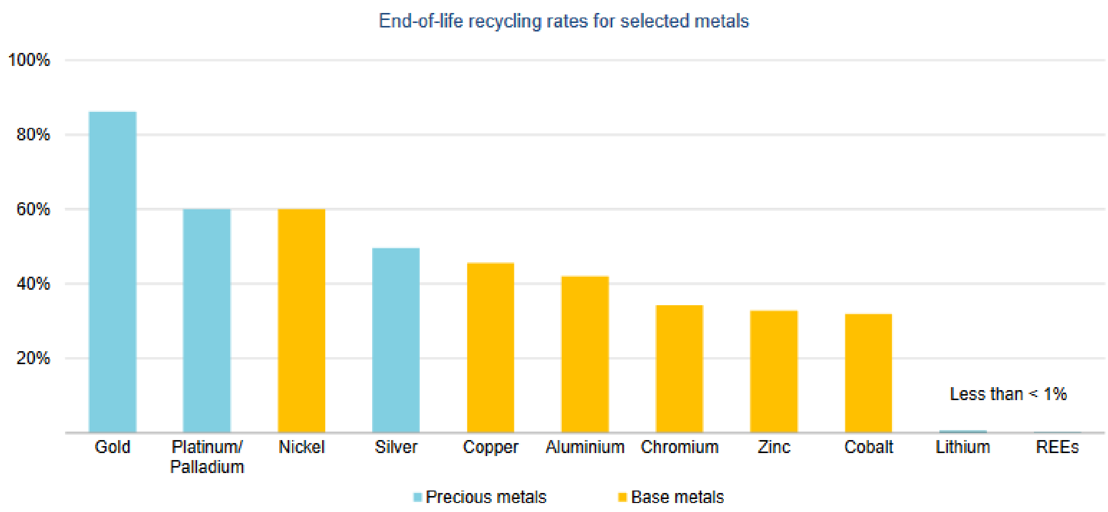
1. EOL recycling rates: measures how much of a material is recycled at the end of its use in a product. Another way to define it is the share of material in waste flow that is actually recycled.
2. Recycling input rates (or recycled content rates): measures the percentage of secondary sources in total supply.

These two indicators are not equal, with the former being higher than the latter (see table 18 [31]). The difference in these indicators is due to:

- Ease of collection, price levels and market maturity. Precious metals such as platinum, palladium and gold have also achieved higher rates of recycling due to very high global prices encouraging both collection and product recycling [18].
- Scrap availability. Aluminum for example has very high recycling rates, since it has a well-developed industry allowing to recycle between 42 and 70 percent of it, having also a solid scrap recycling industry. The recycled content rates instead are estimated between 34 and 36 percent. This important difference tells us the availability of scraps is simply not enough to meet the demand for aluminum.

  Losses in the recycling process. LIBs are a fitting case for this, having complex and expensive recycling processes leading to low recycling rates. Lithium, has almost no global recycling capabilities due in part to limited collection and technical constraints (e.g. lithium reactivity in thermodynamic and metallurgic recycling), with a similar picture for REEs (see fig.15). There are also regional variances: around 50% of total base metal production in the European Union is supplied via secondary production, using recycled metals, as opposed to 18% in the rest of the world.

Figure 15: EOL recycling rates for selected metals, (IEA, 2022) [18]



- Suboptimal performance by recycled material. For instance, Cobalt used in batteries needs to be extremely pure, limiting its recycled material use in that kind of applications.

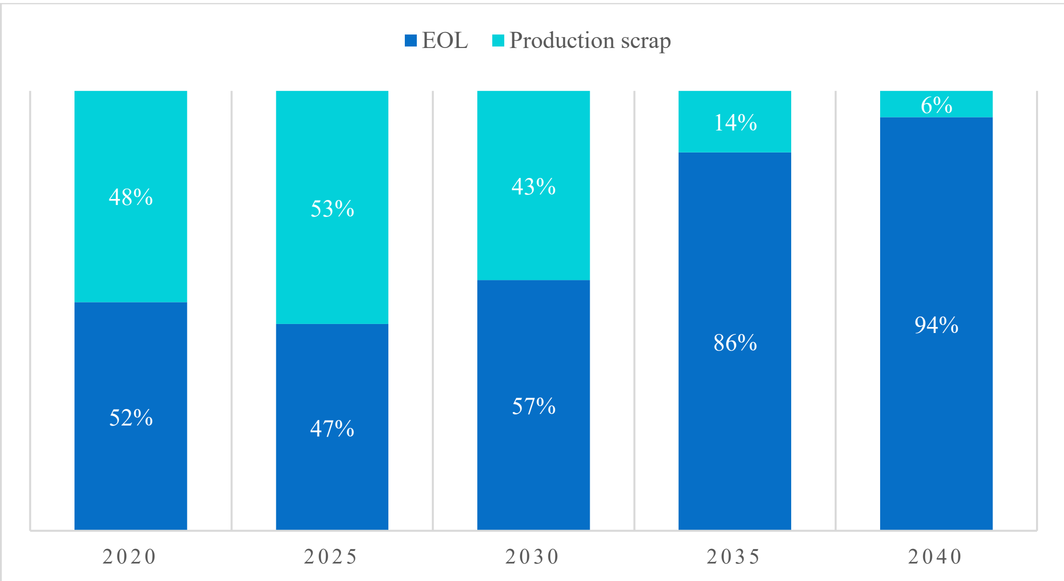
Table 18: EOL recycling and recycled rates by mineral, (World Bank, 2020)

Mineral	EOL recycling rates	Recycled content rates
Aluminum	42% - 70%	34% - 36%
Cobalt	68%	32%
Copper	43% - 53%	20% - 37%
Lithium	<1%	<1%
Nickel	57% - 63%	29% - 41%

Therefore, even if EOL rates could reach 100 percent (implying that all possible scrap was captured, recycled, and could be reused), Recycled rates are unlikely to reach 100 percent without significant reductions in overall demand for these minerals.

According to McKinsey [84], in 2020 roughly half of the global supply of EV batteries available for recycling originated from production scrap from factories, with the other half being supplied by cells reaching EOL. A paradigmatic change is expected in the next years, with EOL batteries that will account for the largest share of supply (see table 19).

Table 19: Distribution of EV batteries supply for recycling worldwide in 2020, with a forecast from 2025 to 2040, by source (Statista, 2023)



The recycling effort is still lacking worldwide. As of now, the recycling rate for batteries remains low mainly for costs related to the establishment of a battery collection system and related operational costs.

According to the US Department of Energy (DOE), in 2019 only 5% of LIBs were collected and recycled. [85] These numbers are even in European Union, and a little higher in China where about 10% of spent LIBs are recycled and reused [86].

According to McKinsey estimates, with investments into high-quality recycling processes currently in early-stage development, would raise recovery rates in all major markets and recycling could provide 13% of the global battery demand for cobalt, 5% of nickel and 9% of lithium in 2030. [83]

3.5.2. RECYCLING PROCESSES

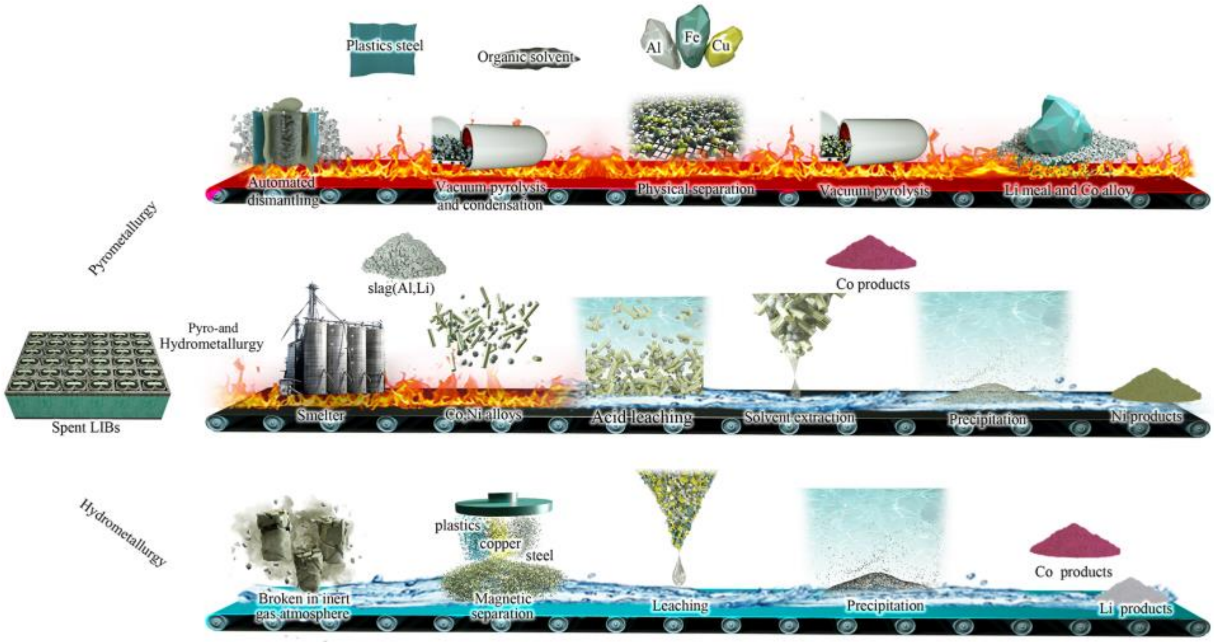
As discussed earlier in this thesis work, LIBs are composed of multiple modules, with cells having varying sizes, shapes and chemical chemistries among different manufacturers. Being complex structures, there needs to be various stages for recycling [66], [29], [87]:

- Pre-processing and mechanical processes.
  - The former is intended as any process that does not alter the structure of the cells. to be classified, and usually treated with processes of stabilization (discharge or inactivation), disassembly (also called opening) and separation which may be carried out separately or together.
  - The latter focuses on the use of different techniques to liberate, classify and concentrate materials without altering their chemistry.
- Hydrometallurgical, Pyrometallurgical (or a combination of both) and Direct Recycling methodologies.
  - Hydrometallurgy refers to "the leaching of valuable elements from a solid matrix and their subsequent precipitation through modification of the solvent-phase chemistry".
  - Pyrometallurgy process consists of operations at elevated temperatures where "redox reactions are activated to smelt and purify valuable metals".
  - Direct Recycling is the "removal of cathode or anode material from the electrode for reconditioning and re-use in a remanufactured LIB".

In figure 16 is reported a flow chart representation of processes used by Accurec (Pyrometallurgical), Recupyl (Hydrometallurgical), Umicore (combination of both). See paragraph "Outlook for LIBs facilities" to have a complete picture of processes used by different companies.

Baum et al. in their article "Lithium-Ion Battery Recycling─Overview of Techniques and Trends" have further described the economical recycling methods based on the cathode materials, according to academic and patent literature sources. According to this work: LCO, NCA and NCM can go through all the three previously mentioned recycling techniques. For LFP and LMO the economical effective recycling pathway is direct recycling [29].

Figure 16: Flow chart of spent LIB industrial recycling processes, [88]



It needs to be underlined how these different recycling methods present different levels of maturity, costs, complexity and environmental impact. Following a comparison of different processes, developed by Harper et al. [87]:

Figure 17: Comparison of different LiB recycling methods (Harper et al., 2019)

Comparison of different LiB recycling methods Best ••••• •••• ••• •• • Worst

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost
Pyrometallurgy	•••••	•••••	•	•••	••	•	•	•••••
Hydrometallurgy	••••	•••	•••	••••	•••	•••	•••	•••
Direct recycling	••	•	••	•••••	••••	•••	•••	•

	Presorting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	•••••	No	No	•••••	•••••	•••••	••	No	•
Hydrometallurgy	••••	No	No	•••••	•••••	••••	•••	•••••	•••
Direct recycling	•	•••••	••••	•••••	•••••	•••••	•••••	•••••	•••••

3.5.2.1. PRE-TREATMENT PROCESSES

Pre-treatment processes are used to separate plastics and polymer, also denominated peripheral parts, from cathode and anode.

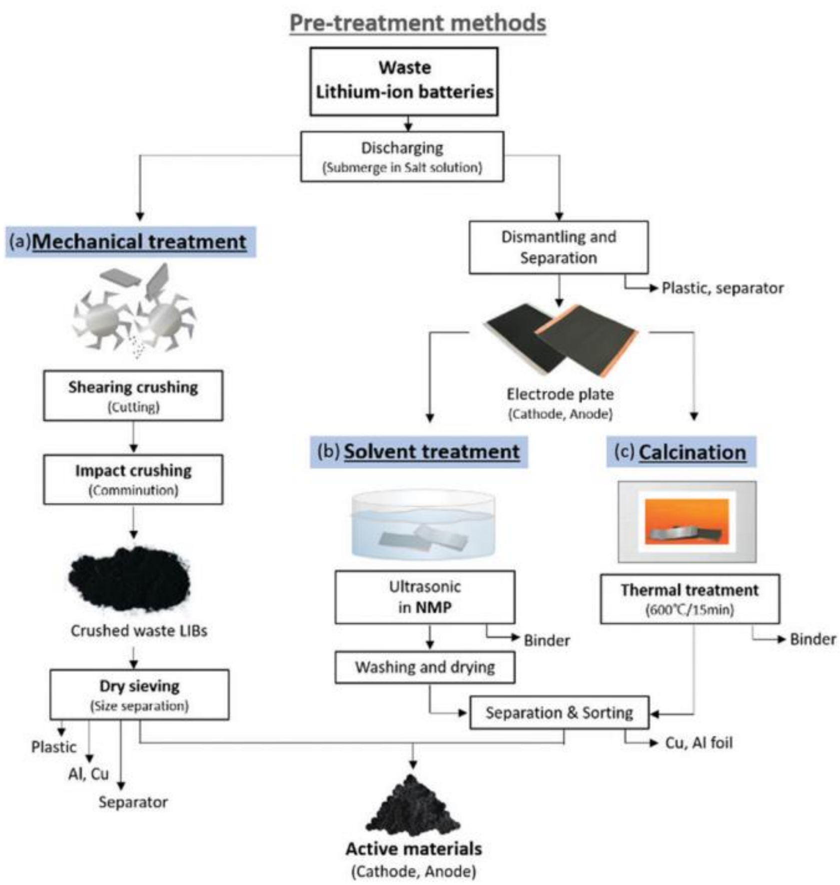
The first step of pre-treatment process is battery discharging. This is done to remove any power from the battery to ensure an efficient and safe process. Otherwise, the battery risks to explode or emit toxic gases due to short-circuiting.

There are three main pre-treatment method (see fig. 18):

- Mechanical pre-treatment involves "physically grinding the discharged lithium-ion batteries".
- Solvent pre-treatment utilizes "solutions and solvents to separate the active materials from the Al and Cu foils in the lithium-ion battery".
- Calcination pre-treatment "occurs in the temperature range of 150–500 1C to remove carbon and organic material from the discarded lithium-ion battery".

Each of the aforementioned methods has its pros and cons, with a standardized one that has to impose on the market yet.

Figure 18: Pre-treatment methods, [46]



3.5.2.2. PYROMETALLURGY

Simplicity and the possibility to recover high-value metals like cobalt allowed the diffusion of pyrometallurgical method. Lithium, though, is lost in the slag and only Nickel, Cobalt and Copper can be recovered.

Traditional pyrometallurgy technology is based on pyrolysis recycling. In the advanced technique of vacuum pyrolysis recycling, the process hinges on exploiting the disparate melting points of metals and organic solvents. Automated dismantling machinery is employed to extract electronics, plastics, and steel structures. The organic solvent undergoes a controlled vacuum heating, typically below 250°C, and is subsequently condensed based on the solvent's electrolyte melting point. The remaining battery components are introduced into an impact mill, where copper foil, aluminum foil, and iron-based alloy are methodically segregated through physical means. The residual electrode materials are subjected to a vacuum-induced evaporation and subsequent condensation to retrieve lithium.

The remaining metals are then concentrated and reclaimed through well-established industrial procedures. [66], [88]

Initially, many companies used the pyrometallurgical method to recycle spent LIBs because of its simple operation; however, this process was not intended for use in recycling of spent LIBs during their initial design. Only Ni, Co, and Cu can be recovered as alloys, and Li is lost in the slag.

There are many advantages for using Pyrometallurgical processes. As thing stand is the most mature and simple. Furthermore, sorting and size reduction are not necessary, with a mixture of LIBs and NiMh batteries that can be recycled. Also, this process as clear advantages regarding water consumption. Finally, the output can be used in synthesizing new cathode materials of many different chemistries. [43], [83]

Compared to virgin production, pyrometallurgical recycling processes can reduce the primary energy consumption in a range estimated within 6%-56% and GHG emissions by 23%. [28]

The disadvantages in this process are also numerous. First of all, as discussed earlier, cobalt is being reduced in battery composition ad the aim is to eliminate it, therefore the business model could not be effective for EVs. The alloy needs to be furtherly processed, therefore there are other costs to take into account. In addition, is a process energy intensive compared to others and with many materials in LIB that are not recovered (like lithium and aluminum). [28], [43], [83]

3.5.2.3. HYDROMETALLURGY

In this method, material retrieval is accomplished through aqueous chemistry, employing leaching in acids or bases, followed by concentration and purification. In the case of Lithium-ion Batteries (LIBs), ions in solution are segregated using a range of technologies such as ion exchange, solvent extraction, chemical precipitation, and electrolysis, ultimately resulting in their precipitation as distinct compounds.

Looking for example at Recupyl Hydrometallurgical process, it starts by including pre-treatment stages. Batteries undergo an initial stage where are destroyed within a protected environment of inert gas. Post this, a process of magnetic separation ensues, enabling the direct recycling of plastics, steel, and copper. The residual materials undergo a sequential leaching process with LiOH and H2SO4. Following this, precipitates are employed to remove impurities like copper, aluminum, and others. Through a strategic combination of NaClO and an inert gas like CO2, cobalt and lithium are effectively reclaimed in the form of Co(OH)2 and Li2CO3, respectively. [66], [88]

Hydrometallurgical process has several advantages. In particular, with this process materials recovered register an high purity and most of them can be recovered. Furthermore, its process require low temperature and lower CO2 emissions compared to pyrometallurgical process.

In contrast, this recycling process have higher costs compared to other ones, with water consumption and treatments for this kind of waste accounting for a good part of the economic expenses. In addition to this, sorting is necessary and therefore complexity is higher adding the need for storage space and related costs. As things stand, the primary emphasis lies on recuperating cathode material, owing to its considerable intrinsic worth. Conversely, materials of lesser value are often left unrecovered and unrecycled. Pioneering technologies aimed at extracting high-value substances like the electrolyte and graphite anode would not only mark a significant stride forward but also amplify the economic viability of the recycling endeavor. [28], [43], [83]

3.5.2.4. DIRECT RECYCLING

Direct recycling involves the retrieval of Lithium-ion Battery's active materials while preserving their original compound structure intact.

First step is battery discharging. Following discharge, spent batteries are carefully placed within a sealed container in a supercritical atmosphere. This crucial step facilitates the extraction of the electrolyte from the Lithium-ion Battery (LIB) cell. To streamline this process, alky lester, Lewis base, and the lithium-rich compound are introduced. Subsequently, a controlled reduction in pressure and temperature leads to the separation of the electrolytic compounds. Further processing is then carried out to recycle the electrolyte. Additionally, a subsequent relithiation process is imperative to enable the reuse of cathodic materials in subsequent battery cycles. [89]

This process is therefore very useful to recover most of the battery components. Regarding the cathode, it may be directly reused after this process, and therefore prove to be a useful solution for chemistries that have lower value, like LFPs.

It's also the lowest polluting process compared to Pyro and Hydro, since it does not contain acid-leaching or energy-consuming processes.

Main issue is Direct Recycling requires further development and is not commercially viable yet. This is clearly shown by the fact that none of the planned plants to be built in Europe will have this recycling process (see paragraph Outlook for LIBs facilities).

3.5.3. RECYCLING COSTS AND VALUE

To evaluate different battery recycling processes, Fan et al. [28] have developed the following equations that take into account all variables in play in different processes. The analysis can start from the simplest of equation:

$$E = \mathrm{R} - \mathrm{C_T} \quad (1)$$

Where E is the profit, R the revenues and C_T is the recycling process total cost. The recycling process total cost should include all processes needed and expense related to materials and capital: Collection and transportation process costs, electric power consumption, cost of equipment maintenance, water consumption, labor costs and chemical reagent costs. In addition to this, the battery scrap stream needs to be considered (cathode, size, purity).

Wang et al. focus on the difference between Variable and fixed costs for recycling, where variable costs are expenses that scale proportionately with the volume and fixed are not dependent on the volume of batteries being recycled.

In particular, a crucial parameter to determine fixed costs is the maximum recycling capacity, but is not a linear relationship between the two, since there are many variables to be considered like geographical location (and consequently labor and energy costs). The equation theorized to determine fixed costs is the following, according to Wang et al. [90]:

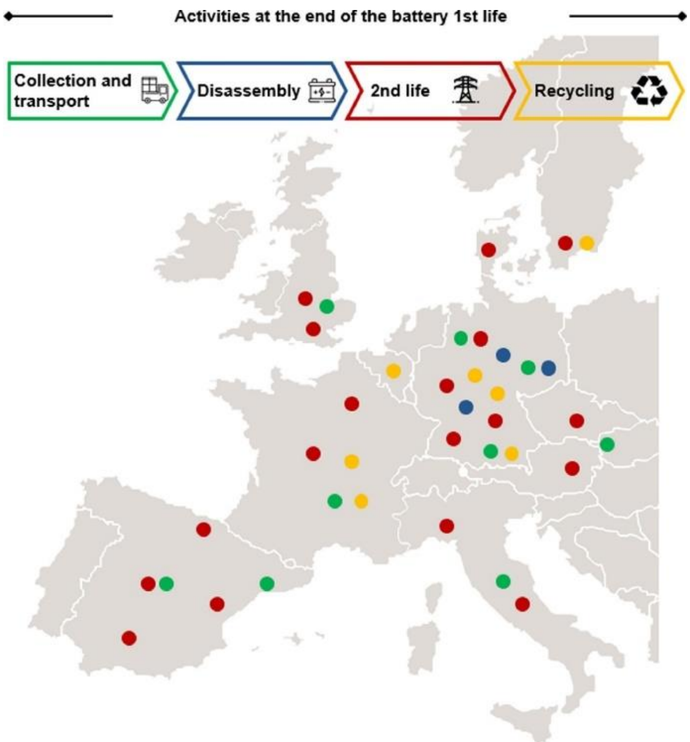
$$\frac{I_2}{I_1} = \left(\frac{Q_2}{Q_1}\right)^x \quad (2)$$

Where I_1 refers to the known investment for capacity Q_1 ; I_2 refers to the investment desired for capacity Q_1 and x is the investment capacity factor (empirically derived, varying depending on the type of industry and products, assumed with the 0.6 rule for LIBs).

Differently to Environmental costs, for the economic perspective, collection costs have an impact that can be estimated equal to 40% of variable costs. According to Redwood materials, logistics has the heaviest impact on battery pack collection and recycling costs. The key to reducing these costs is to achieve economies of scale through increased collection volume.

To estimate logistics costs, Rallo et al. have analyzed EU situation for battery management facilities. Currently, Germany is the only country in Europe having companies working in all battery supply chain different processes (see fig. 19). The results of their studies has resulted in a comparison between a centralized scenario (transportation of EOL batteries to Germany) and a decentralized scenario (creation of a Battery Management facility in Spain), with the former having costs 200% higher than the latter, and higher CO2 emissions. Of course, Logistics costs are higher in countries located at major distance from the facility dismantling centers. [91]

Figure 19: Companies operating in battery SC processes in Europe, (Rallo et al., 2022)



After collection and transportation processes, these gathered depleted LIBs have two potential destinations: they can either be relegated to designated landfills, provided local legislation permits, or they can undergo regulated recycling processes. In the event that batteries end up in landfills, manufacturers would incur a tipping fee, contingent on the landfill's geographical location.

Recycling costs are currently higher than landfill disposal one, but as stated in equation (1), there also are revenues to take into account.

Main value of recycling is retrieved from the cathode (see paragraph battery design and chemistry), therefore recycling business models needs to be analyzed carefully. Manufacturers are shifting towards higher quantities of Nickel and reducing Cobalt chemistries, clearly this is an issue since both pyrometallurgical and hydrometallurgical recycling process retrieve worth from the recovery of high-value cobalt. Among the metal in the cathodic active layers currently, copper, steel, nickel, aluminum and the aforementioned cobalt are recycled, based on the combined impact of recycling feasibility and ultimate gain (see table 20). Plastics are burned for vigor retrieval, but lithium, manganese, and graphite are rarely explored.
Cathode usually accounts for 40% of the material value in typical LIB. [27]

In figure 20 are reported the profit of recycling process as calculated by Fan et al. taking into account all the costs previously described ($C_{C\&T}$ = collection and transport costs, C_P = Electric power consumption, M_C = cost of equipment maintenance, C_W = water consumption, C_L = Labor Costs, C_C = Chemical reagents costs, C_D = Depreciation cost of equipment) and revenues given by different recycling chemistries.

Figure 20: Economic assessment of recycling processes (Fan et al, 2020)

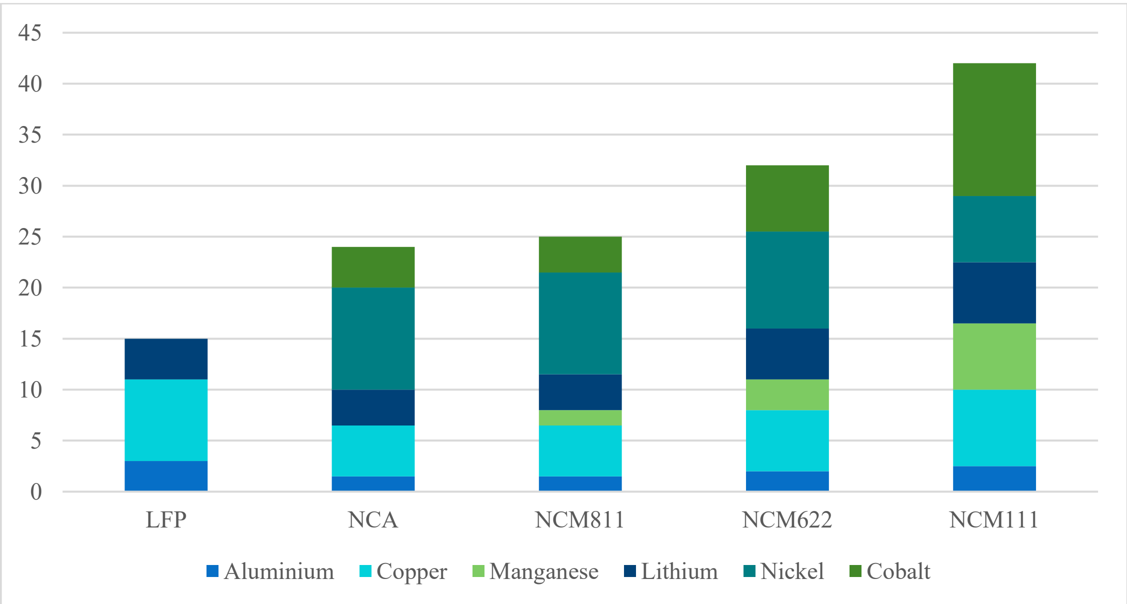
		C_T							R		
	Recycling processes	C_D	M_C	C_P	C_W	C_L	C_C	C_T	Products	Prices(/t)	E
10 t Spent LMO batteries	NaCl-discharging	$3.38	$0.67	$3.0	$100	$78	$290	$475.05	345.76 kg Li_2CO_3	$12,514	$4315.83
	Crushing and Screening	$12.16	$2.4	$4.4	$0	$79	$0	$97.96			
	Vacuum pyrolysis	$730	$144	$176	$0	$72	$0	$1122			
	leaching and evaporation	$152	$27.87	$160	$113.6	$156	$0	$609.47	1.76 t Mn_3O_4	$1430	
	purifying	$68	$13.33	$64	$0	$78	$0	$223.33			
1 t Spent LFP batteries	NaCl-discharging and dismantling	$1.69	$0.33	$41.5	$0	$39	$0	$82.52	260.7 kg $FePO_4$	$1000	$196.03
	Leaching	$3.34	$0.66	$40.5	$5	$39	$254.28	$342.78			
	Filtering, Drying and Sieving	$20.92	$4.16	$46	$2	$117	$0	$190.08	49.5 kg Li_2CO_3	$12,514	
	Purification	$30.38	$6	$24	$0	$39	$0.7	$100.08			
	Precipitation	$1.65	$0.33	$20	$4	$39	$19.24	$84.22	56.1 kg Waste Al foil	$2060	
1 t Spent LCO powders	Drying	$12.81	$2.53	$192	$0.4	$39	$35	$281.74	741 kg of Co_3O_4	$32021.63	$28016.19
	High temperature roasting	$546	$108	$264	$0	$39	$0	$957			
	Leaching and filtering	$7.05	$1.42	$2	$3.65	$39	$0	$53.12	456 kg of Li_2CO_3	$12,514	
	Precipitation and purification	$32.03	$6.33	$44	$5	$39	$0	$126.36			

Cobalt oxide (Co_3O_4) returns by far the highest revenues when recycled, having an average price in the period 2018-2023 of EUR/ton 31352. Since Cobalt presence in battery is being reduced, recycling process needs to be carefully evaluated from an economic standpoint.

At the time the analysis was conducted, Lithium Carbonate (Li_2CO_3) was at $/ton 12514, one of the lowest prices registered in the last 10 years in the market. But the prices have skyrocketed in the last few years in conjunction with COVID-19 pandemic, reaching $47000 in Europe and the astonishing $82000 (from $8000) in China. In 2023, prices have decreased consistently (-50% in EU, -70% in China). It needs to be taken into account how Chinese companies control the market and therefore Lithium price is subject to these companies policies [92]. These prices show once more the importance of recycling in the supply chain, useful to reduce raw materials market volatility impact on the supply chain.

Hence, when comparing recycling and disposal, surely the latter requires investments but overall can bring financial gains.

Table 20: Value of recycled electric vehicle (EV) batteries in 2020, by cathode chemistry (in U.S. dollars per kilowatt hour)



Transportation costs to recycling centers is a minor environmental contribution when compared with other stages of battery life cycle, like production and use phases (see fig. 21). Of course, transportation can not be overviewed. Surely this metric varies by country, but as of now, there is a lack of infrastructures for efficient, economical and safe transportation of the spent LIBs. This is strictly related to collection rates (see paragraph lithium-ion batteries recycling indicators).

Appropriate transport choice needs to be taken to reduce impact of the recycling process. The ideal solution from an environmental stand point for medium to long distances is train, followed by car, sea freight and airfreight as less preferred option. Specifically, Fan et al. indicate that transport by rail and truck can reduce transportation-related GHG emissions by 23%-45%. [28]

In logistics management, collection and transportation are part of the reverse logistics process. Collection is among the major challenges of recycling, and depends on the contribution and support of many stakeholders like the government, business and private organizations active in the social field.

As things stand, only 29.5% of the users properly collects LIBs, associated with 59.6% who keep them at home and 15.9% who disposed of them in dustbins [78].

Figure 21: Environmetal impacts and Energy consumption comparison

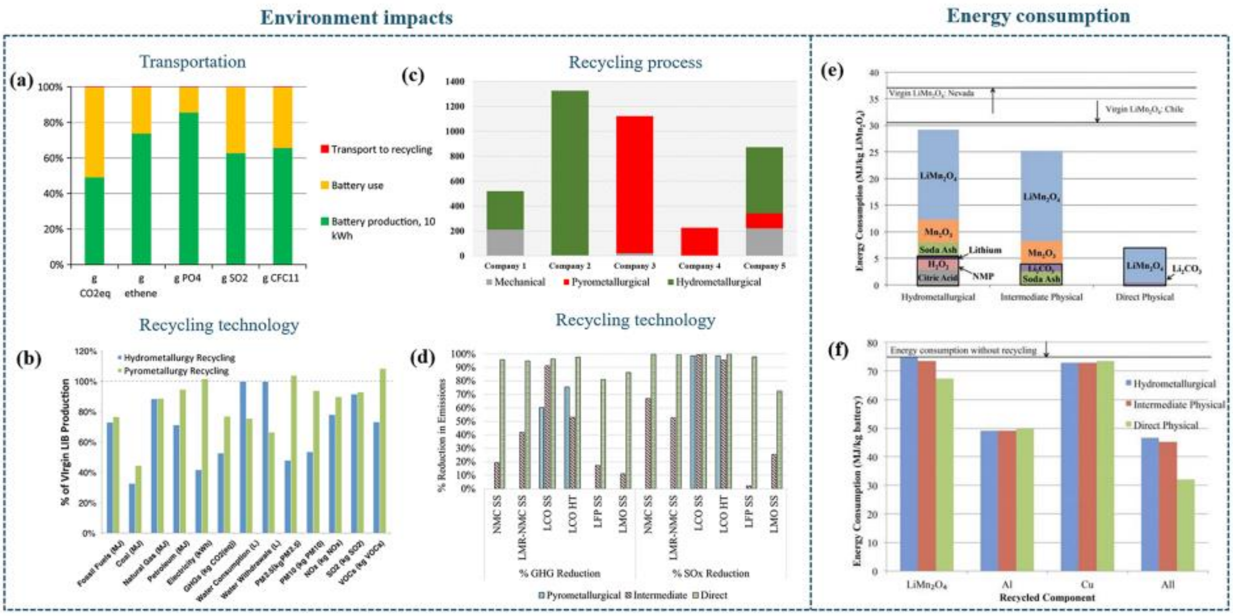


Figure 12. (a) Global warming, photochemical smog, eutrophication, acidification, and ozone depletion of a 10 kWh PHEV battery life cycle when the car is used in Scandinavia. Reprinted with permission from ref 80. Copyright 2010 Elsevier. (b) Resource use and environmental emissions of battery production and recycling (using hydrometallurgy and pyrometallurgy), compared to virgin battery production, for the LMO battery design. Reprinted with permission from ref 81. Copyright 2015 IOP Publishing Ltd. (c) Global Warming Potential (GWP/kg CO_2) of five companies' recycling processes. Data derived from ref 82. (d) GHG and SO_x reductions for different cathode materials recovered from pyrometallurgical, indirect physical, and direct physical materials as compared to producing them from virgin materials. Reprinted with permission from ref 85. Copyright 2015 Royal Society of Chemistry. (e) Estimated energy consumption for $LiMn_2O_4$ production via automotive battery recycling. (f) Total estimated energy consumption (MJ/kg battery) of BEV batteries made from virgin materials; with recycled cathode materials; with recycled Al; with recycled Cu; and with recycled cathode material, Cu, and Al by different recycling processes. (e and f) Reprinted from ref 86. Copyright 2012 American Chemical Society.

3.6. CLOSED LOOP MODEL PROPOSAL FOR BATTERY END OF LIFE MANAGEMENT

Here following (see fig. 23) a proposed closed loop model, which encompasses all battery production and recovery phases. All the previously analyzed phases are considered, taking as a starting point the waste management hierarchy and circular economy models by Velazquez et al. [66] and Kampker et al. [26].

Moving from a linear business model to a closed loop model would be beneficial from a macroeconomic and societal point of view. Of course, at a microeconomic level, companies need to take into account consumer behavior, legislation and profitability, making it complex to make this transition.

As previously stated, remanufacturing, repurposing and recycling should not be treated as alternatives, but as part of the same process. The ideal model for battery usage, should therefore encompass a 1st life usage, followed by a remanufacturing process whenever possible and a 2nd life to extend the battery lifecycle, with finally a recycling process to close the loop. This can be intended as an ideal process, since it's clear in reality recycling processes present inefficiencies and further scrap generation, leading to material losses.

The main reason for recycling being the final process of batteries end-of-life management is due to the fact storing a huge amount of batteries is neither safe or environmentally friendly. This process would have economic and strategic benefits, providing resilience in the supply chain and reducing impact of primary raw materials.

Differently from other models available in all publications consulted, this model comprises the prevention phase, that as described in paragraph "Prevention" of this work, is crucial in the management of EOL batteries.

As discussed in previous paragraphs, many aspects need to be developed to arrive to a model that resembles the one proposed. There are many bottlenecks in the industry as of now, related to technology, costs and scalability of the processes.

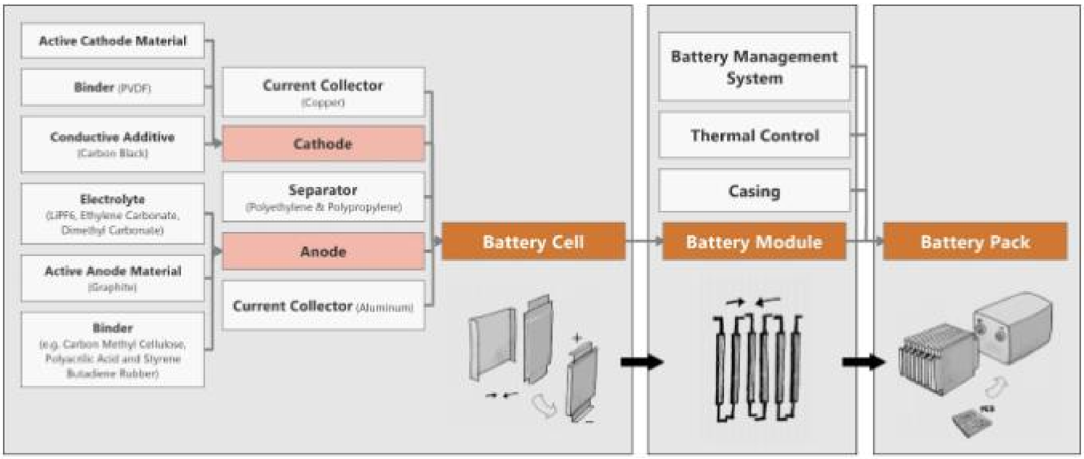
The battery manufacturing phases have been represented starting with raw materials processing and refining followed by cells design and manufacturing.

In figure 22 is represented a schematic diagram of the different components arriving to the cell level [41]. There are modules responsible for specific functions like Battery Management, Safety

Connection and disconnection, as well as cooling. As well as these, there are modules containing battery cells where energy is stored. [26]

The design and manufacturing phase is highlighted in red, since design is a crucial process in the prevention phase (see paragraph prevention).

Figure 22: Battery Product Architecture



After the different battery manufacturing processes, the battery is ready to be used in the automotive sector and therefore first life usage is depicted. As recalled in the introduction, a battery lasts on average 8-10 years or does not to be substituted until its capacity reach 75-80% of the original.

Batteries need then to be recollected and go towards the next process: remanufacturing. Here the model is still far to reach actual industrial realization since remanufacturing is strictly related to bottleneck processes like disassembling and State-Of-Health diagnostics (see prevention paragraph). The former has yet to be automatized and therefore is neither scalable nor safe. The latter needs to be improved, having yet weak results and high costs.

If battery modules do not result being suitable for EV usage, and most of its cells are still in good condition, those are replaced and finally the battery gets reassembled. The orange line following this process indicates that this is a reverse logistics process, encompassing life extension of the battery.

When the majority of cells are compromised, remanufacturing is not a suitable option and repurposing is the best one, from an environmental and economical standpoint. Batteries are then converted to be used in other usage.

Finally, if battery can not go towards the remanufacturing and then the repurposing path, only in that case recycling comes into place, recovering materials and reinstating them in the processes, according to what is being recycled. Elements and compounds will be recovered as raw materials, having a different reintroduction point from mixtures, that will be used during the manufacturing process.

RECYCLING AND 2ND LIFE: A DOG CHASING ITS TAIL?

In the model presented, both recycling and battery 2nd life are considered. Since beginning, in the work has been underlined the importance of considering these processes as consequential and never as alternatives.

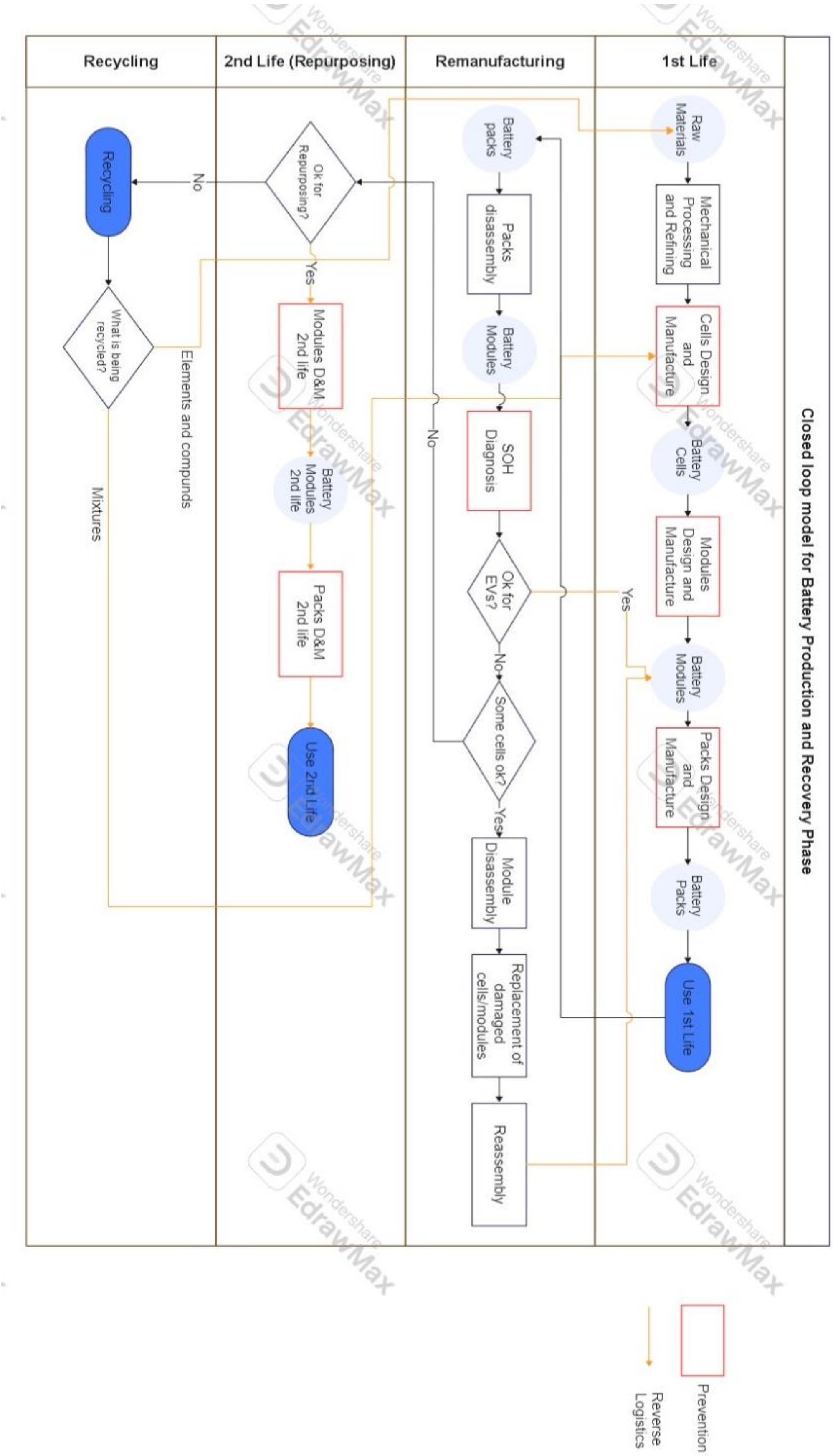
On the other hand, it's important to consider the trade-off between these two processes, also in the light of the following paragraph where recycling facilities capacities are analyzed taking into account the expected inflow of waste materials.

2nd life activities like repurposing and remanufacturing, by extending the battery life take away the input of the battery recycling process, creating a material efficiency problem. This would not be an issue if materials inflow is very prominent and enough to cover capacity of different facilities established (and planned).

Energy efficiency issue though can not be left apart. As discussed, cell production and consequently battery manufacturing are very energy intensive processes, therefore 2nd life is key to better spread their impact on a more extended life, reducing total emissions and environmental impact.

Therefore it's a problem of energy efficiency versus material efficiency that needs to be considered carefully.

Figure 23: Closed Loop Model for Battery End Of Life Management



4. FACILITIES AND ACTORS OUTLOOK FOR REMANUFACTURING, REPURPOSING AND RECYCLING

In this chapter will be described the main companies involved in remanufacturing and repurposing business.

Recycling companies will also be enumerated, with the purpose to analyze capacity and estimate whether European industry will be able to bear the influx of EOL batteries.

4.1. REMANUFACTURING AND REPURPOSING

In this paragraph the most relevant information regarding the companies active in this field for EV applications have been recouped and inserted. According to NAATBatt and NREL database [92] for battery supply chain in North America, there currently are 11 major companies active in this field, all located in the US. Data from the source was integrated to have a complete picture.

In Europe, most of the companies retrieved were responsible for the recycling of batteries and not necessarily of refurbishment for a consequent re-use. Of the companies analyzed, there are a few major companies active in the remanufacturing business as things stand. Stena Recycling is a key actor in the Nordic Battery supply chain, that as stated before has great potential and be fundamental in the future European battery strategy.

China is well positioned also in this aspect, having many companies that try to capture full value, starting from manufacturing arriving to recycling.

Following a description for major repurposing and remanufacturing companies. Will be reported the name of the company, some available information about it, facility country and HQ country.

- ATC Drivetrain: Remanufactures packs, including addition of new cells for automotive industry; other work is conducted here besides rebuilding electric drive trains (US,US).
- B2U Storage Solutions Inc: Repurposes EOL EV batteries in large-scale energy storage applications in their original pack casing; Have developed a patented EV Pack Storage (EPS) technology (US,US).
- Battery M.D. Inc.: HV EV Battery Pack Remanufacturing; Exclusive battery repair company of GM, Ford, Chrysler from 1999 to present; Workforce range 11-50; Full-service battery pack recycling (US,US).

- Element Energy, Inc.: Developer of a battery management system designed to improve the safety, energy throughput, and lifetime of lithium-ion battery packs. The company's system helps with the repurposing of retired EV batteries into grid-scale ESS (US,US).
- Global Battery Solutions: Acquired by ATC drivetrain in 2022; Addresses the 4-R of battery management (US,US). RePurpose Energy, Inc.: Licenses technology developed at UC Davis to repurpose car batteries for stationary applications (US,US).
- Smartville Inc.: Reuse/repurpose of LFP and NMC batteries to ESS applications (US,US).
- Spiers New Technologies (SNT) / Cox Automotive: Provides patented battery health diagnostic tool; 4R services for electric and hybrid vehicle battery packs (US,US).
- Sybesma's Electronics: Recycling/repurposing link goes to Global Battery Solutions; also includes EOL batteries as a feedstock; Workforce range 25-34 (US,US).
- Redwood materials: Offers solutions for all supply chain necessities. Remanufacturing of anode & cathode battery components; Hydrometallurgical metal refining; Collection, storage & material-specific recycling (Global, US).
- Denso: Works on B2B market with manufacturers. Battery monitoring and repurposing (EU,JP).
- Saft Groupe Sa: Preventive maintenance; Corrective maintenance; Mid-life refurbishment (Global).
- Stena Recycling: Remanufacturing when possible, otherwise recycling and dismantling (EU,SW).
- Phenix Batteries: SNAM subsidiary specialized in repurposing. End-Product are ESS (N.A.,FR).
- BatX Energies: Sourcing and transporting EOL batteries. Provides materials for remanufacturing: Currently sourcing is limited to India (India, India).
- NEU Battery Materials: Recycle of redox batteries; modular and scalable system(Singapore, Singapore).
- EXELx: Developed a multi-stage loop charging technology for battery restoration (UAE,UAE).
- GEM Co.: Has built a circular value chain for EV batteries which includes collection, refurbishment for second-life, recycling, material circulation, and battery pack remanufacture. besides product and material recycling, GEM has also developed battery management software (CHN,CHN).
- CATL: Remanufacture of batteries in good condition, Recycling when the former not feasible (CHN,CHN).
- LG Energy Solutions: Collection, Transportation, Reconditioning, Refurbishing, Recycling (SK; CHN, South Korea).

- Evyon AS: Provides a modular DC battery energy storage solution based on repurposed EV batteries for system integrators to integrate into a range of solutions (NO ,NO).
- Cirba Solutions: Retriev Tech, Battery Solutions and Heritage Battery Recycling combined to form Cirba Solutions (US,US).

Regarding OEMs, Nissan is presently engaged in the large-scale production of remanufactured Lithium-Ion batteries tailored for its Leaf model, after a factory was launched in Eastern Japan in collaboration with 4R Energy Corp [93].

Additionally, Toyota started in 2022 a collaboration with Redwood Materials to create a closed-loop battery ecosystem, starting from collection, testing and recycling. In future years the companies intend to expand to remanufacturing and other services [94].

Redwood is a key player in the field, having also purchased a 100 acres land near Tesla's Gigafactory in Sparks, Nevada, and intends to expand its current 150,000-square-foot facility in the state by more than 400,000-square-feet [95]. The company was created by JB Straubel, Tesla's co-founder therefore it's easy to understand the links between the two companies. Tesla on its website assesses a 100% recycling rate, meaning with all probability that a battery after being retrieved is sent to external recyclers (like it could be Redwood) who then recovers the material. Furthermore, Tesla has publicized its intention to engage in the remanufacturing of the battery pack for the Model 3 at the level of individual modules. Adding to these companies, also Volkswagen Group of America (VWGoA) started a collaboration with Redwood in 2022 to remanufacture battery materials in a domestic supply chain [96].

Starting from 2011, Renault has started a project to transform a growing number of factories making them entirely dedicated to circular economy. It takes the name "Refactory" and as of now there are about twenty factories located in 17 different European countries. Flins plant was the first established, and is expected to reach a capacity of 20 thousand reparations within 2030. [97] [98]

4.2. RECYCLING

To elaborate the following facilities database, data were taken from Lithium-Ion Battery Recycling Overview of Techniques and Trends [29] and integrated with NAATBAT database [92], as well as online research using Companies websites whenever available. Data was also integrated with battery-news.de website, which yearly updates the recycling facilities in Europe [99]. The capacity was reported when clearly stated on company website, online articles or as stated by the preciously mentioned sources. Facilities with capacity lower than 1 kilotons/year were not considered for the analysis.

The database that resulted from the research is the most updated and complete of information currently available for European countries. It reports company name, facility location and volume capacity, facility type (H=Hydrometallurgical, P=Pyrometallurgical; P&H = combo of Pyrometallurgical and Hydrometallurgical processes; U = Unknown).

In table 22 are reported the facilities currently up and running in Europe. Total capacity is currently of 395,45 kilotons/year, and the most common process is Hydrometallurgical, present in 11 facilities and accounting for 227,6 kilotons/year, followed by Pyrometallurgical (5 facilities, 98 kilotons/year) and P&H (4 facilities, 21,25 kilotons/year). For 6 plants was not possible to establish the process which was utilized.

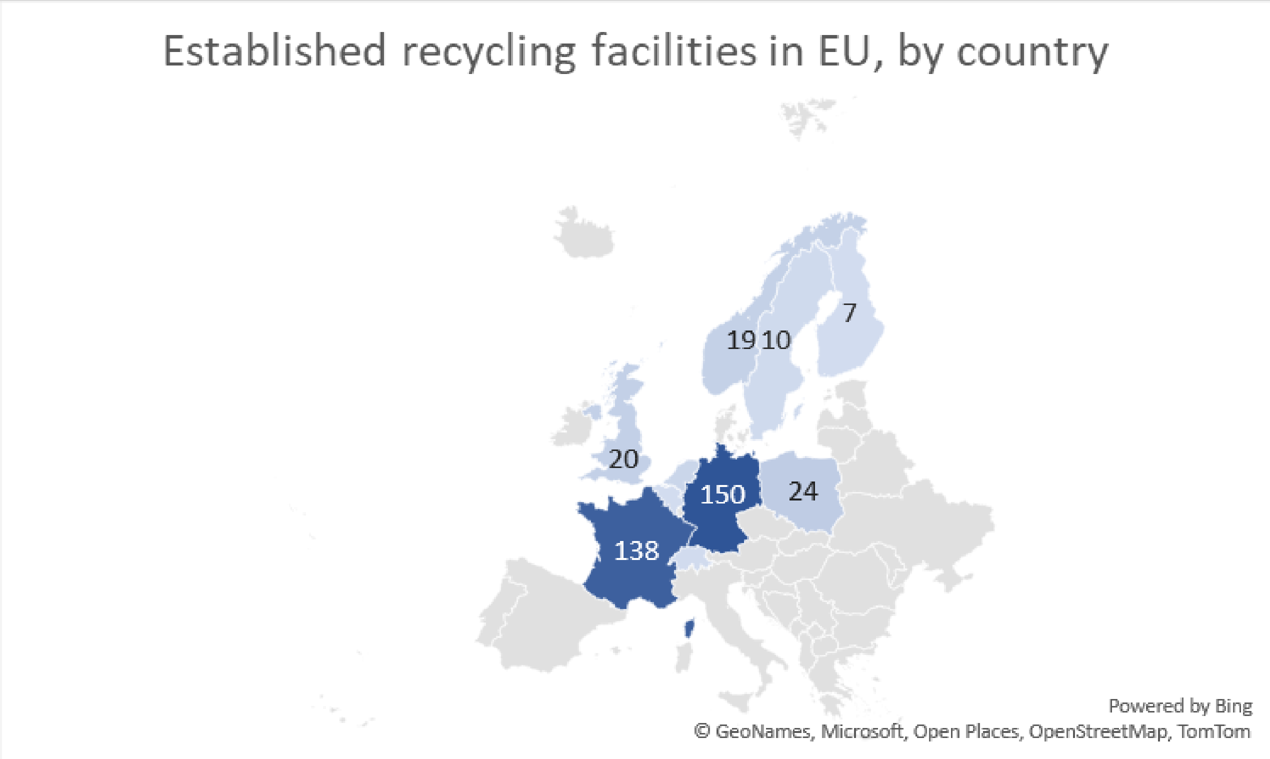
Germany and France are by far the current leader in the European Recycling Market, accounting for the 72,5% of current European Recycling capacity. Facilities are distributed all over the countries with the former having a capacity of 149,65 kilotons/year and the latter of 137,2 kilotons/year.

It has to be noted that in Grenoble, France there's the biggest European facility for the purpose, built for Recupyl. It's capable to manage 110 kilotons/year of End-of-Life batteries to be recycled. Redux has instead built the second biggest facility, currently located in Offenbach and able to process 50 kilotons/year.

Following there are Nordic Countries, accounting for 36 kilotons/year between Finland, Norway and Sweden.

The batteries collected in the BENELUX area are mainly recycled by Umicore in Antwerp, Belgium (7 kilotons/year). In 2021 TES announced the project for a new facility located in the port of Rotterdam, that will therefore expand capacity in the region (5 kilotons/year).

Figure 24: Established Recycling facilities in EU, by country



UK and Ireland used to export most of their spent LIBs to mainland Europe, but existing facilities are being upscaled and as of September 2023 the existing ones already reach 20 kilotons of recycling capacity per year, between Ecobat and Altilium metals.

Another notable mention is Poland, where almost totality of the capacity is driven by the SungEel HiTech facility located in Bukowice, one of the first to be built in Europe.

Table 21: Established Recycling European facilities

Company	Location	Country	Volume (kilotons/year)	Facility Type	Notes
Umicore Valeas	Hoboken, BE	BE	7	P&H	
Accurec	Krefeld, DE	DE	3,25	P&H	
Duesenfeld	Wendeburf, DE	DE	2,9	H	LitoRec process is based on its patents
Fortum	Kirchaot, DE	DE	3	U	
Ecobat	Hettstedt, DE	DE	20	U	Indicated capacity will be reached by end of 2023
Li-Cycle	Saxony-Anhalt, DE	DE	30	H	
Primobius Gmbh	Hilchenbach, DE	DE	20	H	
Redux (Redwood)	Bremerhaven, DE	DE	10	P	

Redux (Redwood)	Offenbach, DE	DE	50	P	
Roth	Wernberg-Koblitz, DE	DE	9	U	
Volkswagen	Saltzigtter, DE	DE	1,5	H	VK Group components
Akkuser	Nivala, FI	FI	4	P&H	
Fortum	Ikaalinen, FI	FI	3	U	
Recupyl	Grenoble, FR	FR	110	H	
TES	Grenoble, FR	FR	2,2	H	
Valdi	Commentry, FR	FR	20	P	
Veolia, EDI	Dieuze, FR	FR	5	H	
TES	Rotterdam, ND	ND	14	H	In the port of Rotterdam
Glencore, Nikkelver AS	Kristiansand, NO	NO	7	P&H	
Hydrovolt	Fredrikstad, NO	NO	12	H	
RoyalBees	Legnica, PO	PO	3,6	U	
SungEel HiTech, posco	Bukowice, PO	PO	20	H	
Librec (Batrec)	SWI	SWI	8	P	
Altilium Metals	Teesside, UK	UK	10	H	Capacity will increase to 50k tons
Ecobat	Darlaston, UK	UK	10	U	Indicated capacity will be reached by end of 2023. By 2024 it's expected to double
Stena Recycling	Hamlstad, SWE	SWE	10	P	

In table 23 are reported the facilities currently planned to be built in Europe, with estimated date of completion and/or start of works whenever available.

Currently, there are 33 facilities that have declared capacity at completion summing up to an expected volume of 770 kilotons/year. In addition to these, there are 9 facilities that have been announced but their operational capacity is not known yet.

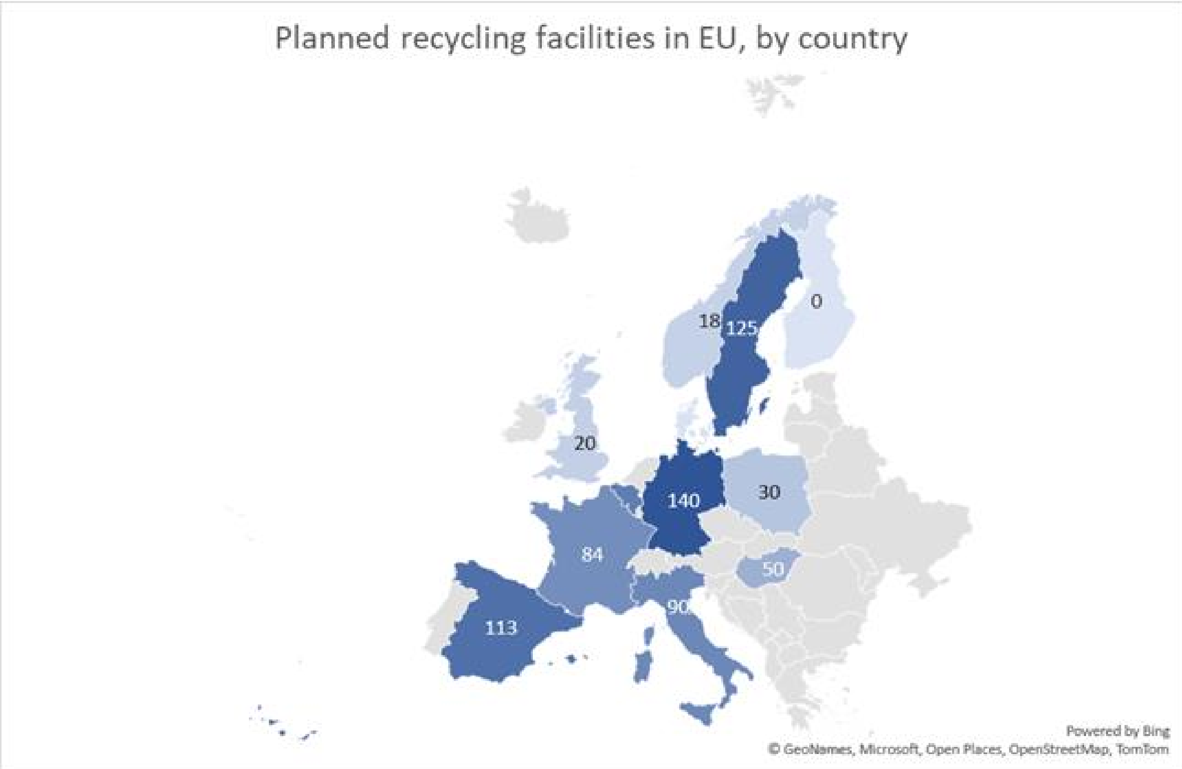
Analyzing trend for the recycling method to be adopted, it is clear how Hydrometallurgy is the preferred one counting 12 facilities. Following there's Pyrometallurgy accounting for 6 facilities and then the combination of both (2 facilities). Like before, there were 13 facilities where was not possible to understand the methodology used.

Looking at the geographical distribution (see fig. 25), Germany's leadership is not in discussion as thing stands, being at the top also for facilities planned to be built in the next few years. Nordic countries will play a crucial role in the future, driven by the huge Northvolt facility to be built in Sweden, but also Norway, Denmark and Finland will contribute to create a strong industry.

Spain is currently lagging behind having no facilities established at the moment and therefore is investing to catch up. Econil, Novolitio and Librec have announced their new plants and are going to manage 113 kilotons/year of EOL batteries. VK has also already manifested the intention to develop a recycling facility but is not clear yet where and its capacity.

Aurubis has announced a huge investment in Belgium, with the objective to deliver a 100 kilotons/year facility in Olen, the second biggest facility announced after Northvolt's one in Sweden. No others are planned to be built in the Benelux area as things stand.

Figure 25: Planned Recycling facilities in EU, by country



Italy is among the worst positioned countries, having no recycling facilities in its territory and issues in starting works to ensure the construction of future plants. Glencore has announced its intention to reconvert the existing Portovesme plant into the first plant to recycle LIBs in Italy, but is facing bureaucratic issues. [100] Italvolt announced would have built the biggest gigafactory in Europe, but after having announced its initial project in Scarmagno would be relocated in Termini Imerese, recently this option was also discarded leaving more than one doubt regarding the company's intentions. [101]

Keeping Italvolt's issues aside, it's clear how Italy is having difficulties in attracting companies to its territory, with no sign of a change in direction.

Table 22: Planned Recycling European Facilities

Company	Location	Country	Volume (kilotons/year)	Facility Type	Notes
Aurubis	Olen, BE	BE	100	H	Est. Q2 2024
Aurubis	Hamburg, DE	DE	U	U	
BASF	Schwarzheide, DE	DE	15	U	Est. 2024
Lueg	Meppen, DE	DE	20	U	Est. Q3 2024
Mercedes	Kuppenheim, DE	DE	2,5	H	Est. Q3 2023 start of works
Northvolt	Heide, DE	DE	U	U	
Stena Recycling	Wangerland, DE	DE	2,5	P	Existing plant to be scaled up Q3 2023
Stena Recycling	DE	DE	U	P	
SungEel HiTech, Samsung	DE	DE	20	H	Est. Start of work Q1 2024
Cylib	Aachen, DN	DN	U	U	Start-up: Additive-free Battery Recycling; Demo plant commissioned
Fortum	Harjavalta, FI	FI	U	U	
Battri	FR	FR	U	U	Advanced battery diagnostics; Recycling; Battery transportation
Ecobat	Bazoches, FR	FR	20	U	
SNAM	Saint Quentin, FR	FR	10	H	
Suez, Eramet	Dunkirk, FR	FR	50	H	Est. Start of works 2025. Target start-up 2027
Veolia, Renault, Solway	Amneville, FR	FR	4	H	Experimental phase: pre-industrial demo plan. No updates since announcement in 2021
SungEel HiTech	Multiple, HU	HU	50	H	Company fined by Hungarian authorities for serious hazards to workers and environment
Arabat	Foggia, IT	IT	U	H	Company is a start-up who announced intention to build a plant in the future in Puglia
Glencore	TBD, IT	IT	50	P&H	Existing plant to be converted. Currently project is blocked for bureaucracy
Italvolt	TBD, IT	IT	TBD	U	Location yet TBD
Li-Cycle	NO	NO	10	H	Est. Q1 2024, partnership with ECO STOR
Northvolt	Frederikstad, NO	NO	8	U	
Econili (CarbonX)	Alicente, SP	SP	45	U	Construction start Q2 2023
Novolitio (Endesa)	Cubillos del Sil, SP	SP	8		Construction start Q2 2023
Librec (Batrec)	PO, DE, IT, SP	EU	200	P	Est. 2024 - 2026

SungEel HiTech	Navarre, SP	SP	10	H	Est. 2025
Northvolt	SWE	SWE	125	U	
Fenix	Whitehall, UK	UK	10	H	
Glencore, Britishvolt	Northfleet, UK	UK	10	P&H	Est. Q2 2023. As of 10/23 does not result operative yet
Veolia	Minworth, UK	UK	U	H	Est. Q3 2024

To have a full picture, a brief description of the American situation will also be given.

In table 24 are reported the facilities currently running in North America that are active in the recycling process. NAATBAT database is more complete involving also companies that do not directly recycle but also are in charge of sorting, dismantling and all other kind of activities, but are not of interest for the thesis work.

Table 23: North America Established Recycling Facilities

Company	Location	Volume (ktons/year)	Facility Type	Chemistry
Li-Cycle	Kingston, ON, CA	5	H	N.S.
Glencore	Greater Sudbury,ON,Canada	20	U	All LIB
Retriev (Toxco)	Trail, BC, CA	4,5	H	N.S.
Li-Cycle	Gilbert, AZ, US	30	H	N.S.
Li-Cycle	Tuscaloosa, AL, US	10	H	N.S.
Inmetco	Elwood, PA, US	6	P	N.S.
Redwood Materials	Carson City,NV, US	40	U	N.S.
Agmet LLC	Oakwood,OH, US	50	U	NMC
Ascend Elements	Covington,GA,US	30	H	NMC
Clean Earth Inc.	West Melbourne,FL,US	15	U	All LIB
Clean Earth Inc.	Allentown,PA,US	15	U	All LIB
RecycLiCo Battery Materials Inc.	Richmond,BC,Canada	U	U	N.S.

In table 25 are reported the biggest planned facilities to be built in the US in the next few years, with the date of estimated completion when available.

Figure 26: North America Planned Recycling Facilities

Company	Location	Volume (ktons/year)	Facility Type	Chemistry	Notes
ABT	TRIC, NV, US	20	U	NMC, LCO, NCA, LMO	Est. U
Li-Cycle	Rochester, NY, US	35	H	N.S.	Est. Q3 2023
Redwood Materials	Charleston, SC, US	U	U	N.S.	Est. U
Ascend Elements	Hopkinsville, KY, US	24	H	NMC	Est. Q1 2025
Cirba Solutions	Multiple	300	H	N.S.	Many more facilities announced (Biggest in Pennsylvania, South Carolina)
ACE Green Recycling	TE, US	20	U	All LIB	Est. Q4 2023

4.2.1. FACILITIES CAPACITY AND EOL BATTERIES VOLUMES: IS IT ENOUGH?

The volume of LIBs available for recycling today is modest and largely dominated by batteries in waste electronic products. The fast-paced increase of EV sales and demand for energy storage will certainly alter this situation by the end of the decade.

An influx of spent batteries is coming, since as previously stated the average duration of batteries is of 8-10 years as things stand. If remanufacturing and repurposing become a structural part of the EOL management the life could increase of 5-6 years.
As of now, though, it's possible to determine the influx of batteries coming to EOL and therefore that will need to be managed in the next few years just looking at electric car sales.

According to Harper et al. when all the electric cars sold in 2019 reach the end of their lifetime, this would result in 500 000 tons of unprocessed battery pack waste [87]. According to IEA, Sales of electric cars reached 2,1 million globally in 2019 and exceeded 10 millions in 2022. Therefore, taking these number we can assume that 1 battery sold generates around 230 kg of waste.

Taking the new registrations of electric cars from European Environment Agency (see tab. 24) [102], it's possible to determine how many of the sales happened in EU. This is useful to determine the amount of waste batteries European countries have produced from 2017 to 2022, and will therefore be collected (assuming all batteries are collected).

Table 24: EV registrations in EU (EEA, 2022)

Year	2017	2018	2019	2020	2021	2022
Battery electric cars (BEV)	83.491	132.377	242.966	536.186	878.092	1.126.682
Plug-in electric cars (PHEV)	88.334	106.502	137.632	525.311	862.569	873.042
Total Electric	171.825	238.879	380.598	1.061.497	1.740.661	1.999.724
Tons of waste (recycling supply)	40.911	56.876	90.619	252.737	414.443	476.125

Therefore, assuming a 10 year life duration for batteries, tons of waste can be seen the internal recycling supply for facilities in Europe. To determine whether European facilities will bear the incoming influx of EOL batteries, in table 25 are reported the total capacity of currently established facilities, the announced capacity improvements that will be completed during 2023 or 2024 on aforementioned facilities, and the planned facilities to be completed in the medium term (3-5 years). It has to be noted that projects with huge uncertainty, or unknown state of the works have been left out from the planned facilities (accounting for 104 000 tons). In particular, the facilities left out are Dunkirk (start of work target 2027), Amneville (not enough data on this facility), Italian planned facilities currently blocked by bureaucracy.

Total capacity in the medium term sums up to 1.111.450 tons, and is therefore enough to cover the expected waste batteries coming to EOL in the medium term (3-5 years). This would true also considering the assumption that all batteries will be collected, that is very far from the real situation considering that as previously stated around 5% of batteries are currently collected, but the collection rate is expected to increase in a considerable way.

Even considering an expected life of 8 years for all batteries involved, the capacity would be enough to cover the internal quantity of waste produced.

All these assumptions are valid taking into account the planned facilities announced will get to final completion stage, not considering possible cancellation or delay of projects.

As discussed earlier, the impact of 2nd life needs to be also considered, since it extends the battery life, taking away the input of the battery recycling process, creating a material efficiency problem. Looking at the projections discussed, this might be problematic for the EU from a strategic standpoint and needs to be considered carefully.

Even if capacity might be dealt with, an important issue to address is that companies should make easily adaptable and scalable to different chemistries.

Table 25: Established and Planned European Recycling facilities

Type of facility	Tons	Notes
Established	395.450	
Established TBC short-term	50.000	Facilities of Teesside, Darlaston
Planned medium term	666.000	
Total Capacity medium term	**1.111.450**	

DIRECTIONS OF FUTURE RESEARCH

In the previous chapter during the discussion of all aspects related to EOL battery supply chain management several aspects were individuated as gaps in the literature or current processes.

For clarity, here are reported in a comprehensive section, from the most urgent to the least urgent issues.

1. Holistic approach on battery design
   Batteries need to be designed having a holistic approach. Traditionally, battery development and EOL have been considered separately leading to low performances in the battery lifecycle. Recycling processes are therefore much more complex and variable, leading to higher costs and scalability issues.
2. Disassembly process
   Strictly related to the previous point, batteries need to be designed in a way to facilitate disassembling for EOL management both for costs and safety.
   In addition, this process is still manual and automatization is needed mainly for the safety of operators.
3. SOH diagnosis
   There's still a lack of literature and investments on cells deterioration identification in module and a standardized method needs to be identified yet.
4. Recycling process optimization
   Currently, no recycling process looks profitable in a consistent way. Pyrometallurgy is the most reliable, but does not recover all elements and cobalt that is the main value source is being progressively reduced for ESG reasons. Hydrometallurgical process needs a cost reduction to be effective and Direct recycling is still in laboratory stage.
5. Battery passport and data availability
   This would be fundamental for ensuring sustainability of all the value chain, having an instrument where to monitor different actors involved in the sector. Main issue is interoperability of data and different interests at stake
6. Other technology improvements
   New battery technologies like sodium, ASSB and flow batteries. In addition to this, battery sensing and self-healing could prove very important.

CONCLUSIONS

The accelerating demand for Lithium-Ion Batteries (LIBs) poses significant challenges across manufacturing, supply chain logistics, and end-of-life management. This surge in demand surpasses current raw material production rates, leading to infrastructure strains.

Addressing the End-Of-Life phase could extend raw material availability, crucial for meeting future battery demands. Yet, existing recycling infrastructures and technologies lack resilience. The diverse array of battery types further complicates collection, sorting, recycling, and remanufacturing processes, posing significant hurdles.

Overcoming these challenges demands collaborative efforts spanning different technical aspects of manufacturing, chemical engineering, material science, and sustainability management. This interdisciplinary approach inspired a comprehensive review of LIBs End-of-Life management, highlighting technology and market intricacies, battery degradation and dismantling issues, and both forward and reverse supply chain. All these aspects were discussed always taking into account the geopolitical situation, discussing different regulations when necessary. It emerges the importance of recycling in the supply chain, particularly useful to reduce raw materials market volatility impact on the supply chain.

Huge steps ahead have been done in the last years, with second life and recycling processes gaining more and more importance both on academical and industrial level. A holistic approach is still missing, though, considering the end-of-life waste management since the battery design phase. A closed Loop Supply Chain standard model is proposed, being a fundamental within this transition from ICEs to EVs for economic, environmental and strategical reasons.

Europe was analyzed with particular focus, with positive results emerging from a recycling facility perspective, having companies preparing timely for the upcoming influx of spent battery. More doubts circulate around Remanufacturing and Repurposing processes, being yet undeveloped sectors and that should be more considered from OEMs.

While this exploratory study surveys current research advancements acknowledging information from expert in the field, identifies main bottlenecks in the industry and future directions, does not cover all the works and topics in the field. However, the author is hopeful his work will help and encourage other researchers interested in the topic.

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