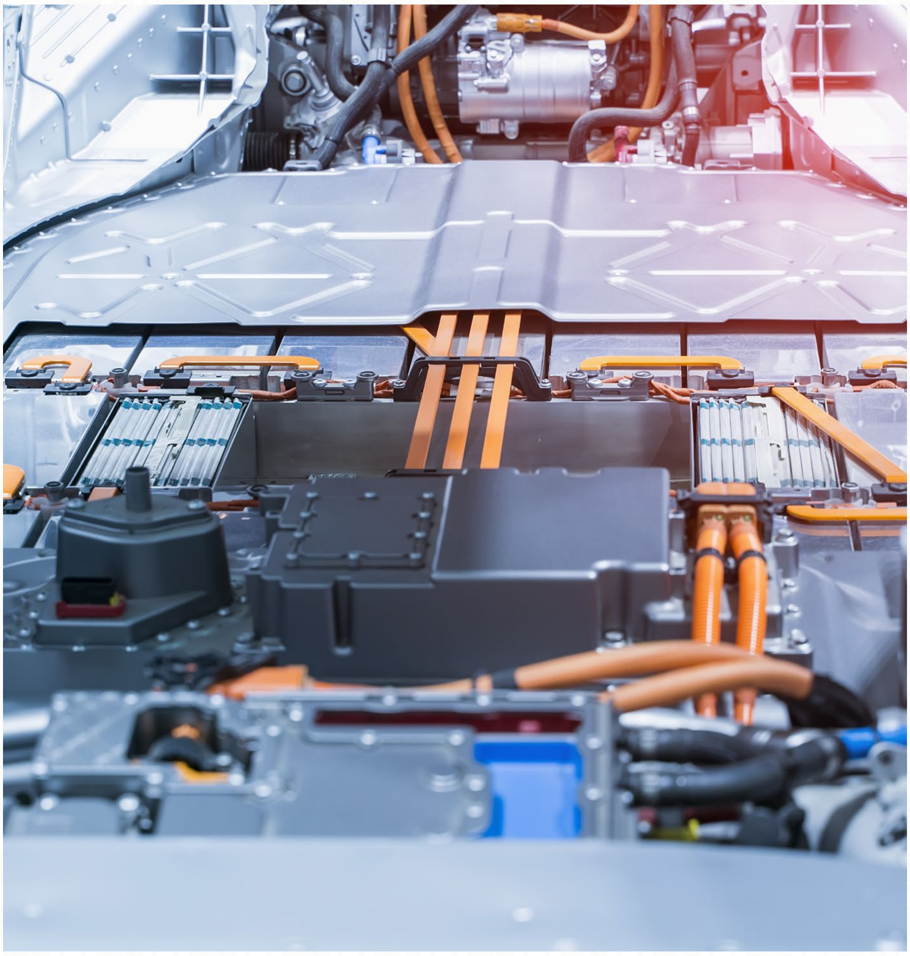

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Current and Future State of the European Li-ion Battery Recycling Market

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Abstract

Lithium-ion batteries (LIBs) are expected to play an important role in clean energy transition in the EU and internationally. At the same time, the production and consumption trends of LIBs, technological innovations, associated sustainability issues and regulatory changes are rapidly transforming the battery recycling industry. This report evaluates the LIBs recycling industry within the EU context and provides an analysis of the current and future state of the market, from the perspectives of industry forces, market forces, key trends and macroeconomic forces. The report presents key considerations for strategic development for LIB recyclers in the EU market.

Table of contents

Summary

Batteries are expected to play an important role in the transition to more clean energy in the EU and globally as a way to displace fossil-based mobility solutions, store energy from the grid and utilise more sustainable electricity produced from renewable sources. At the same time, more stringent environmental requirements on battery production and waste treatment facilities will place greater demand on improved recovery rates in the future.

This report is prepared for the *End-of-life Li-ion battery management integration and technology evaluation* (ELiMINATE) project, which aims to evaluate different battery recycling processes and deliver an implementation framework to advise on the best way forward in terms of establishing local end-of-life lithium-ion battery treatment facilities. This report evaluates the LIBs recycling industry within the EU context and provides an analysis of the current and future state of the market.

The European LIB recycling market is changing rapidly. The capacity of LIB pre-processing within Europe is expected to increase alongside the improved recycling potential of LIB production waste and a shift in European policies towards securing the supply of critical raw materials in Europe. The material processing within Europe is also expected to grow, with greater involvement of battery manufacturers and recyclers from China and South Korea.

It is expected that a large majority of the batteries placed on the global market will be used in light or heavy EVs and Europe is expected to catch up with China's position as the largest producer and consumer of LIBs in the coming years – a change driven by policy and regulatory changes encouraging the electrification of transport. This shift of focus to EVs is expected to transform the LIB manufacturing industry with a dominance of nickel-based cathode chemistries (nickel-manganese-cobalt (NMC) and nickel-cadmium-aluminium (NCA)) and more local production and sourcing of raw materials.

Meanwhile, responsible material sourcing and the issue of conflict mineral mining will continue to be an important issue in the LIB market, though it will continue to be immensely difficult to control due to the current logistical structure as well as low capacity and transparency along the supply chain (especially upstream).

The replacement of the EU Battery Regulation on the EU Battery Directive is expected to significantly impact the way LIBs are produced, used and recycled in Europe, with specific targets on LIB reuse, recycling and material recovery. It will also force supply chain actors to be more transparent regarding ensuring recyclability of LIBs, increasing recovery rates of cobalt, lithium and nickel and proposed levels of recycled contents in new production.

The findings of this report form key considerations for LIB recyclers and the business strategy for LIB recycling. In particular, as battery materials are raw materials traded on the commodity market, there is limited opportunity for LIB recyclers to compete with a product or price differentiation strategies. The main focus for business strategization is therefore on cost leadership, and technological, operational and efficiency improvements that contribute to providing best value for money. Altogether the findings of this report will feed into a business case screening of developed and novel hydrometallurgical technologies for LIB recycling in the EU context in the subsequent stages of the ELiMINATE project.

1 Introduction

Batteries are expected to play an important role in the transition to more clean energy in the EU and globally as a way to displace fossil-based mobility solutions, store energy from the grid and utilise more sustainable electricity produced from renewable sources. At the same time, batteries are also playing an important role in consumer products where cordless alternatives are the main drivers in the market.

Increased environmental requirements on treatment facilities and demand for improved recovery rates on metals are to be expected in the future and hydrometallurgy technologies have previously been assessed to have the greatest potential to meet these future market expectations.

This report is prepared for the *End-of-life Li-ion battery management integration and technology evaluation* (ELiMINATE) project. The objective of ELiMINATE is to evaluate different alternative hydrometallurgical processes relying on a combination of alternative leaching reagents, alternative pre-treatment steps combined with hydrometallurgy, and/or novel solution purification technologies.

The project will deliver an implementation framework to advise on the best way forward in terms of establishing local end-of-life lithium-ion battery treatment facilities. It is anticipated that the outcome of the project will allow improved handling and management of EoL LIBs, reducing the environmental impact associated with the transport and disposal of EoL LIBs, as well as allowing for the local valorisation of LIBs.

The evaluation of the technologies is being done through: 1) market analyses and business case development to understand appropriate value chain integration strategies for different technologies; 2) life cycle assessment to compare the environmental impact of different technologies and to identify requirements for further technical development/improvement; and 3) material flow analyses and reverse logistics optimisation to improve resource efficiency of the lithium-ion battery recycling industry. This report feeds into the first part on market analysis.

This report is limited to evaluate LIBs recycling industry within the EU context. Although the project is limited to explore hydrometallurgy, this report also explores different recycling methods to generate a cohesive picture of the EU LIB recycling market and form a basis for positioning.

With the business model canvas in mind as the later outcome of the project (after selection of novel technologies), this report is a description of the market environment, identification of what influences it and how. It is based on an adaptation of the Business Model Strategizer was used for this analysis. It analyses the business model's environment from the perspectives of the industry, market, trends and macroeconomic forces. The findings of this analysis will feed into developing new circular business models for selected technologies for LIB resource recovery.

Following this introduction, Section 2 provides an overview of LIBs systems including production, use and recycling. Section 3 provides the methodology used to analyse the current and future state of the LIB recycling market in Europe, and the findings are presented in Section 4. Section 5 provides a summary of key insights and the whole report is concluded in Section 6.

2 Lithium-ion batteries

The invention of the rechargeable lithium-ion battery was considered a breakthrough for the society and awarded the Nobel prize in 2019 (to the researchers Akira Yoshino, John B. Goodenough and M. Stanley Whittigham). Lithium-ion batteries (LIBs) are prized for its high energy density and low self-discharge. As a potential source of carbon-free energy (depending of course on the energy source for recharge), it has also become significant in contributing to decarbonization in society. Variations in chemistries give different technical properties, making them suitable for different application areas. Applications range from energy storage systems and industrial applications to everyday objects such as smartphones, laptops or electric vehicles.

The most rapidly growing markets for LIBs are within the automotive sector followed by the previous leader portable devices. Another market expected to grow in the next 5 years is energy storage systems (ESS)(Melin, 2018), where LIBs can be used in solutions to stabilise the electric grid or provide backup power to buildings. The increased demand for LIBs from the automotive industry has resulted in technical breakthroughs and reduced production costs. This has led to new application areas developing over the more recent years, such as electric kick bikes, hover boards, and autonomous robots (Melin, 2018).

2.1 LIB Battery: How it works and production

Lithium-ion batteries all operate after the same principle: in use (discharge), lithium ions move from the anode to the cathode and release electrons which produces electricity. During recharge, the ions move in the opposite direction.

A LIB consists of several connected individual cells mounted together inside a casing, forming a *battery pack*. Lithium-ion battery cells are produced in three shapes: cylindrical, pouch, and prismatic.

Each battery cell contains electrodes (one anode and one cathode), separated by a porous material, and a liquid electrolyte – recent alternatives to liquid electrolytes are solid ceramic electrolytes such as lithium metal oxides (Dragonfly Energy, 2021). A Battery Management System (BMS) manages the charge and discharge, adds safety and defines the specific packs capabilities. Larger battery packs normally also include a cooling system.

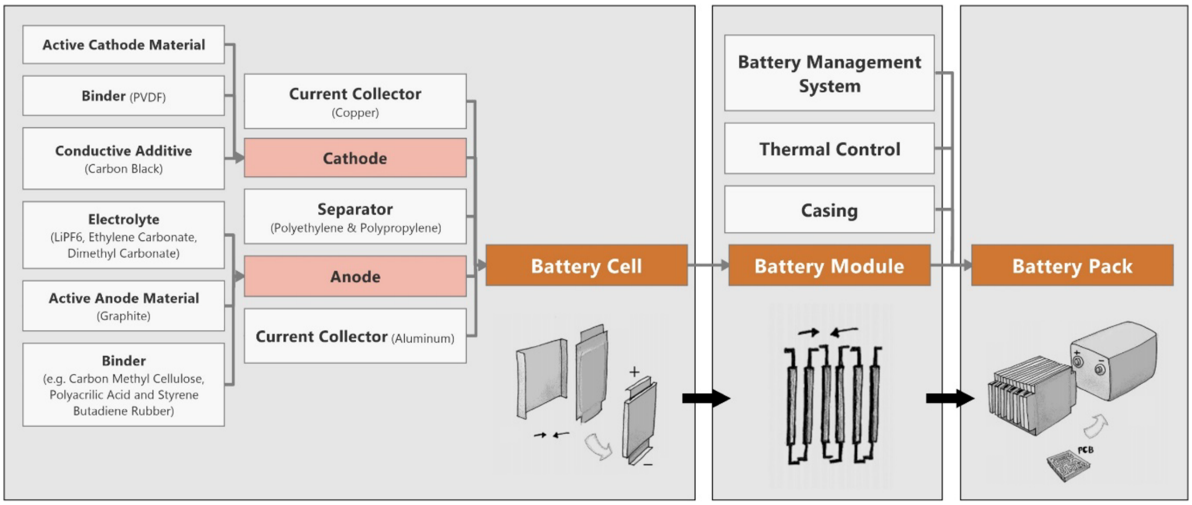

Figure 2-1: A diagram of the different components of a battery pack, a battery module, and a battery cell. (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021)

2.1.1 LIB Production

The production of LIB cells starts with mining and refining of metals into the desired cathode material and anode material. The cathode material is applied on an aluminium foil, and the anode material on a copper foil, together with a binder.

Figure 2-2 shows the materials involved in various LIB cell production processes and illustrates the difference between cathode and anode materials. With one exception (lithium-titanium-oxide (LTO) chemistry) the anode material is graphite which can also be synthetically produced. Cathode materials involves critical metals such as lithium, nickel, cobalt, and manganese. These four metals are considered key materials in key production stages, given their significance in the primary material supply and recycling markets as well as within battery technology development.

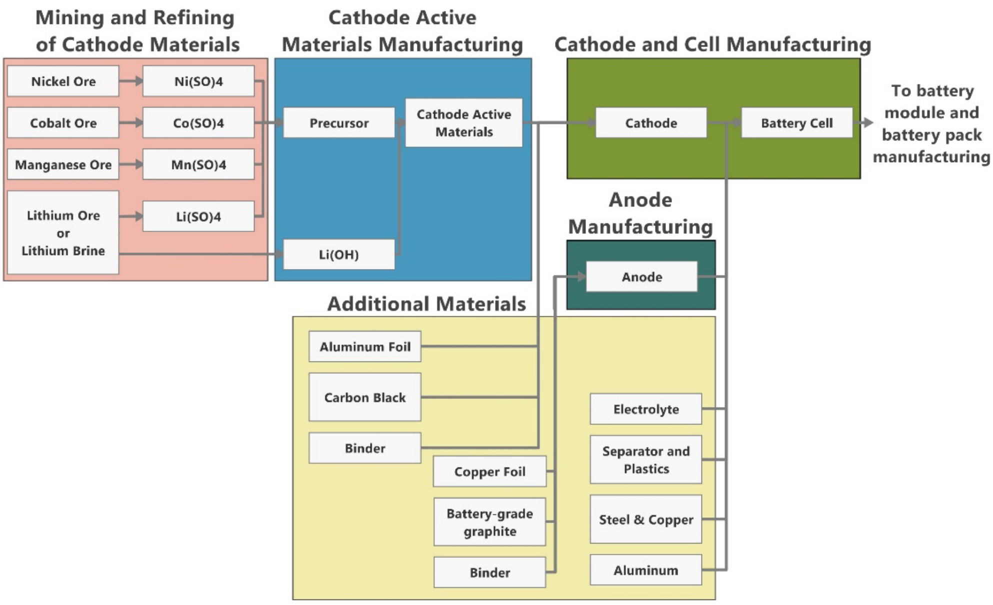

Figure 2-2: Lithium-ion cell production. The boxes represent the parts or materials. The arrows between the boxes often involve process steps. The figure shows the production steps with metals from natural resources. (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021)

2.2 LIB Use

Lithium-ion batteries are produced with various chemistries suitable for different applications. Different applications require different properties and each LIB chemistry has pros and cons. Portable devices for instance are less sensitive to higher cost and ageing than LIBs in electric vehicles, making LCO a viable alternative for portable devices but not for electric vehicles. Table 2-1 lists six LIB chemistries and their common applications. Technical properties of importance are specific energy capacity, life span, specific power, safety, cost and performance – see Table 2-2 for a relative comparison of common LIB chemistries.

Table 2-1: Chemistries for different applications of lithium-ion batteries[1]

Chemistry	Cathode	Anode	Applications
LCO	$LiCoO_2$	Graphite	Mobile phones, laptops, tablets, cameras
LFP	$LiFePO_4$	Graphite	Electric cars (with lower demand of range) energy storage systems (ESS), power tools, utility vehicles, HEV buses, replacement of lead-acid batteries
LMO	$LiMn_2O_4$	Graphite	Older (and recently: new and relatively cheap) models of electric cars, power tools, medical devices, e-bikes, e-scooters
NCA	$LiNiCoAlO_2$	Graphite	Electric cars (Tesla), laptops, medical devices, e-scooters
NMC	$LiNiMnCoO_2$	Graphite	BEVs. power tools, energy storage systems (ESS), medical devices, e-bikes, industrial
LTO	LiNiMnCoO or $LiMn_2O_4$	$Li_4Ti_5O_{12}$	Electric buses (good for opportunity charging), e-bikes

The automotive industry has substantially grown the market for LIBs with the increased demand for plug-in hybrid vehicles (PHEVs) and fully electrical vehicles. Early fully electrical vehicles used lithium-iron-phosphate (LFP), and this is still the case in China and for electric cars with lower demand of range, but leading actors on the European and US markets have progressed to use a combination of nickel-manganese-cobalt (NMC) and lithium-manganese-oxide (LMO) type batteries or NCA (Tesla) (Melin, 2018).

China prohibited the use of NMC in vehicles for safety reasons until 2017 and during this time, the safer LFP has been a standard on the Chinese market. However, since the approval of NMC in vehicles has been granted by the government again in 2017, and alongside general technological advancement, an increase in vehicles using NMC batteries is to be expected on the Chinese market.

LFP is a cheaper alternative than both NCA and NMC, and LFP is suitably used in electric buses (which are charged often), as well as in e-bikes and electric cars with lower demand of range. In

[1] https://batteryuniversity.com/article/bu-205-types-of-lithium-ion
Q2 2021

2020 a new "blade" design of LFP batteries was launched, using only 50% of the volume compared to traditional LFP batteries and thus improving the suitability for applications where battery size is a key design consideration.

Table 2-2: Comparison between technical properties of battery chemistries[7]

Chemistry and commercialization year	**Specific energy capacity [Wh/kg],** from low (red) to high (green)	**Life span,** from low (red) to high (green)	**Specific power,** from low (red) to high (green)	**Safety,** from low (red) to high (green)	**Cost,** from high (red) to low (green)	**Performance,** from low (red) to high (green)
LCO, 1991	*150-200*					
LFP, 1996	*90-120*					
LMO, 1996	*100-150*					
NCA, 1999	*200-260*					
NMC, 2008	*150-220*					
LTO, 2008	*50-80*					

The figure below presents the batteries placed on the market in Europe by both chemistry and application.

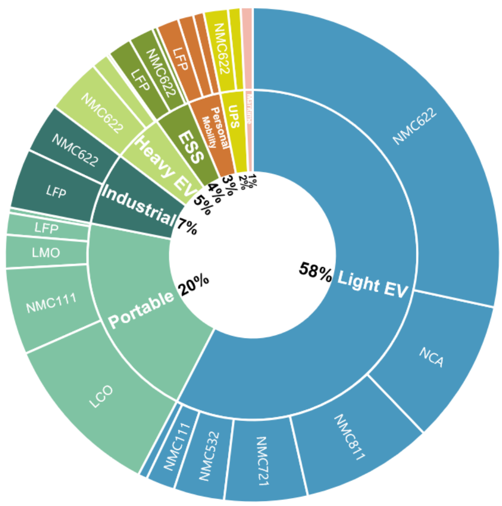

Figure 2-3: Current placed on market of different chemistries in Europe (EEA and Switzerland) measured in GWh[2] (Portable: Computers, laptops, smartphones, power tools; Personal mobility: E-scooters and other

[2] Circular Energy Storage (2020) https://www.circularenergystorage-online.com/copy-of-placed-on-market-3 (paid subscription) Q3 2021

smaller mobility devices; Light EV: Cars; Heavy EV: buses and trucks; Industrial: For industrial applications such as forklifts; ESS: Energy Storage Systems (Stationary); UPS: Uninterruptible power Supply; Maritime: ships) (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021)[3]

2.3 LIB Recycling

This section presents the diverse methods of LIB recycling followed by a brief description of common key treatment steps involved in the material recovery process: pyrometallurgical treatment, hydrometallurgical treatment, and mechanical treatment.

2.3.1 The LIB Recycling process

Technologies and methods used to separate substances in LIB recycling are diverse and can be categorised as either: *pyrometallurgy, hydrometallurgy* or *mechanical treatment.* Each of the treatment processes have their pros and cons and the use of the different processes in sequence enables recovery of more material. Full recycling processes thus vary greatly but can be divided into the two categories illustrated in Figure 2-3 : 1. Pyrometallurgy with subsequent hydrometallurgy, and 2. Hydrometallurgy with mechanical pre-treatment (Brückner et al., 2020). Common variations of the process are also illustrated in Figure 2-3 where thermal treatment is added to e.g. control the energy content reduction and reduce organic content before the mechanical treatment.

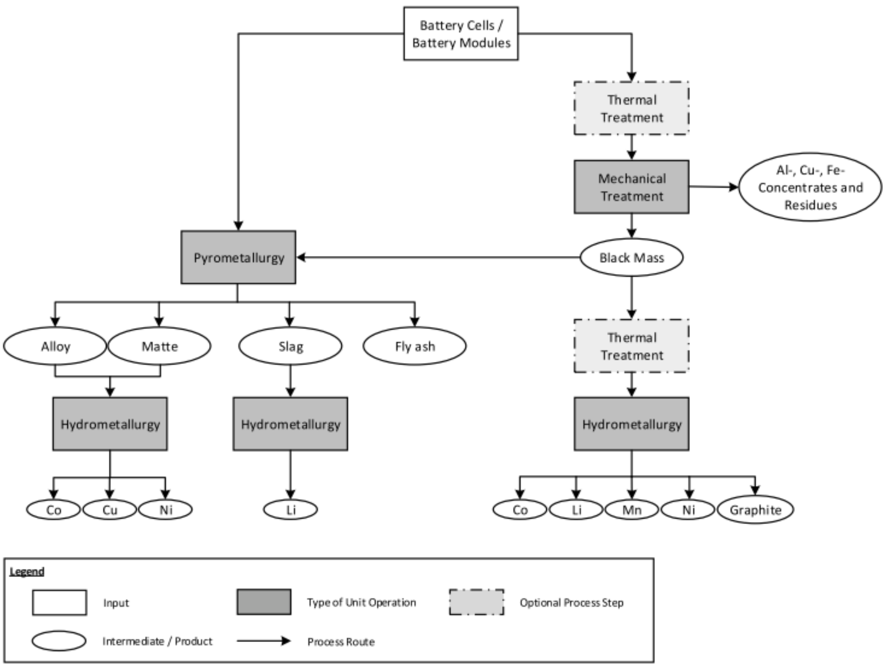

Figure 2-4: Process steps of the two categories of LIB recycling, by Brückner et al. 2020. Copyright 2020 by Brückner et al.

The recycling of LIBs typically starts with mechanical treatment, including disassembly, sorting, crushing, milling and sieving using various methods. This mechanical pre-treatment separates plastic and iron containers from the cathodic materials and ensures a higher degree of material

[3] Report not yet published at the time of writing this report.

recovery from the following pyro- or hydrometallurgical processes (Assefi et al., 2020). Both pyrometallurgical recycling and hydrometallurgical recycling each have benefits and consequences. Key differences between the two are listed in Table 2-3, such as hydrometallurgy's bigger need for disassembly, as well as a need for big sized plants relative to the output, translating to higher costs compared to pyrometallurgy. Pyrometallurgy however requires more energy input and the recovery of material is less efficient.

Table 2-3: Comparison between the two common recycling techniques used today and their aspects (Dahllöf et al., 2019). [11]

	Pyrometallurgical recycling with subsequent hydrometallurgy	Hydrometallurgical recycling
Costs	Relatively cheap	Relatively expensive
Recovery efficiency	Low	High
Flexibility	Flexible to different chemistries	Not flexible, but to some extent within the same chemistry
Disassembly need	Minimal	High
Energy use	High	Low

2.3.2 Pyrometallurgical recycling with subsequent hydrometallurgy

Pyrometallurgical requires less disassembly of the batteries as metals are extracted my smelting. The alloys and slag are then further processed using hydrometallurgy.

The pyrometallurgy process involves heating in different temperatures, as show in Figure 2-4. The LIB material is initially heat treated at a lower temperature to remove unwanted organic materials, followed by a higher temperature treatment to form alloy and slag. and the addition of reducing agents and slag modifiers at higher temperatures to separate the metals into alloys and slag (Assefi et al., 2020).

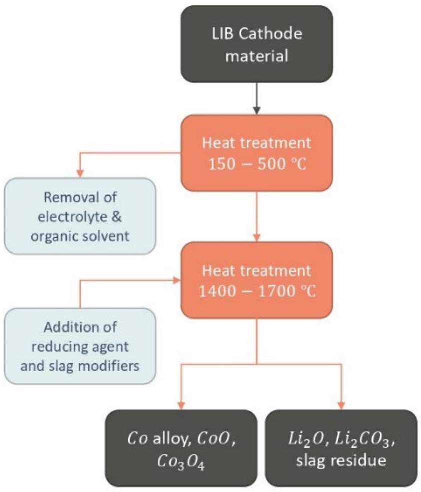

Figure 2-5. Pyrometallurgy process principle on a general level. Authors' modified picture, inspired by Assefi et al. (2020).

2.3.3 Hydrometallurgical recycling

Hydrometallurgy processes use acids to dissolve the batteries and metals are extracted through chemical reactions. Hydrometallurgy processes can produce high quality products and are often used at the end of a chain of processes as refining steps (Brückner et al., 2020).

Hydrometallurgical processes involve three major steps shown in Figure 2-5: 1. Leaching, 2. Purification, and 3. Metal recovery.

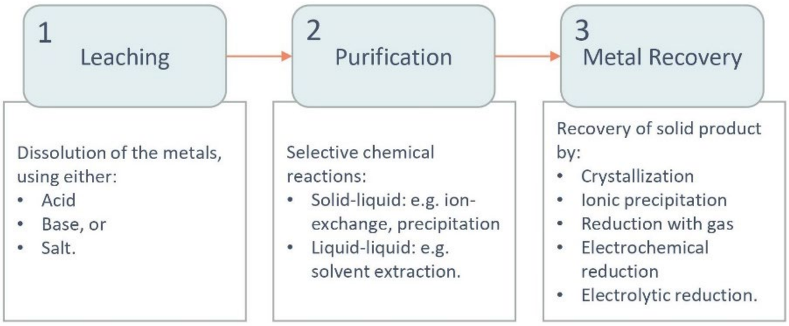

Figure 2-6: The three major steps of hydrometallurgy processes, including basic descriptions of variations. Authors' own figure.

2.3.4 Mechanical recycling

In the future, completely mechanical recycling is wished for in order to retrieve battery quality material rather than retrieving starting material in pure form. Today, mechanical dismantling of parts is done before hydrometallurgical recycling and to some extent before pyrometallurgical recycling. This usually requires a substantial amount of manual labour but there are solutions being developed for partly automated disassembly, such as the AI-powered visual system being developed at the University of Agder in collaboration with industry partners in battery recycling and material production and supply (Christiansen, 2020).

3 Methodology (analysis framework)

The findings presented in this report result from the use of adaptations of various methodology frameworks. The project's *core methodology* builds on the two frameworks Porter's Five Forces and Business Strategy Analyser. The results from the two methods were summarised and translated into actions for recyclers with guidance from the PESTLE framework categorisation of macro-environmental factors. The three frameworks are elaborated below, followed by an explanation of the adapted core methodology.

3.1 Porter's Five Forces

Porter's Five Forces is a framework for understanding the competitive forces in an industry. The underlying drivers for profitability are the same across different industries and the framework can be used to assess competition, strategic positions, and to identify industry trends (Harvard Business School, n.d.). The framework identifies the following five forces: 1) *Bargaining power of buyers, 2) Bargaining power of suppliers,* 3) *Threat of new entrants,* 4) *Threat of substitute products or services,* 5) *Rivalry among existing competitors.*

This project is focused on the three forces highlighted in Figure 3-1 and involving the following stakeholders: buyers, suppliers, and competitors. These three forces form parts of this project's core methodology further explained and illustrated in Section 3.4. *Substitute products/services* (in this case referring to virgin material providers) and *new entrants* were excluded due to time and resource constraints and in order to place greater detailed focus on the recycling industry itself.

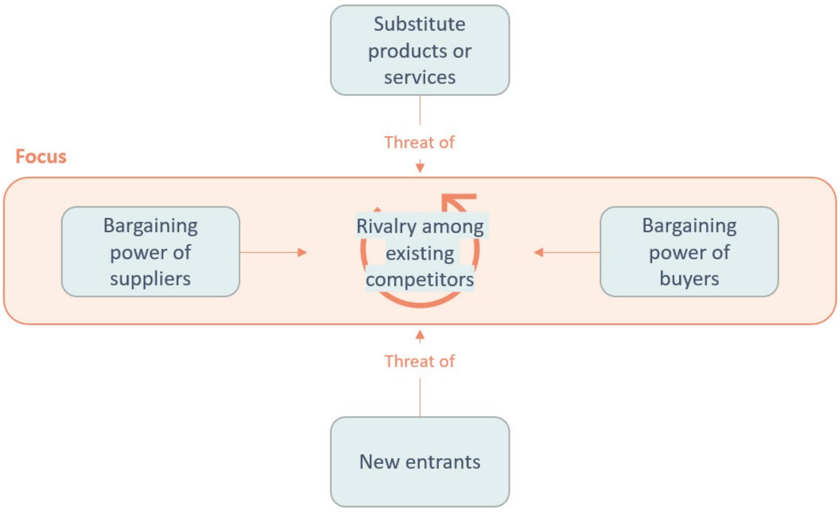

Figure 3-1: The performed analysis focused on the highlighted three parts of the Porter's Five Forces framework: bargaining power of suppliers, bargaining power of buyers, and rivalry among existing competitors. Authors' own figure.

3.2 Business Strategy Analyser

The Business Model Design Space method builds on questioning existing business models through the mapping of the surrounding environment. This is done by answering a number of pre-decided questions for each of the four areas: 1) market forces, 2) key trends, 3) industry forces, and 4) macroeconomic forces. In the original method the questions are answered regarding an existing business model. However, in the project adaptation the questions were used as a guide while researching the market environment.

3.3 PESTLE

The PESTLE analysis framework, illustrated in Figure 3-2, is used to identify the external forces facing an organisation on macro level and complements the analysis of an organisation's internal strengths and weaknesses. The framework builds on exploring the following six categories of macro-environmental factors: political, economic, social, technological, environmental (or ethical), and legal. The PESTLE framework was used as a guide to present the project findings in terms of key aspects that relate to or impact the recycling industry, as well as to identify key considerations for how recyclers should address these aspects.

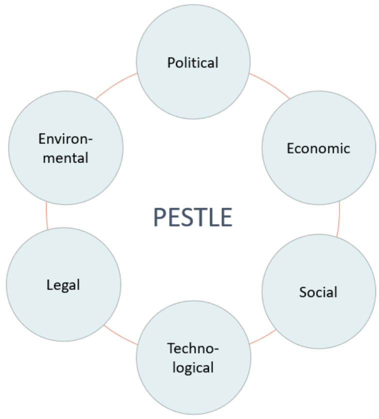

Figure 3-2:The six macro-environmental factors of the PESTLE framework.

3.4 Core Methodology

The previously described methodologies were adapted to suit the project scope and the specific context of the LIB value chain and resulted in a core methodology illustrated in Figure 3-3. The major stages of the LIB value chain are shown in grey boxes and the arrows represent the general flows of material from primary sources (mines) and from secondary sources (recycling), altogether taking place in a context defined by identifiable key trends and macroeconomic forces.

Within the scope of the project the considered main competitors are actors within recycling, suppliers are in the business of collecting or refining waste or end-of-life products, and buyers are the producers of batteries.

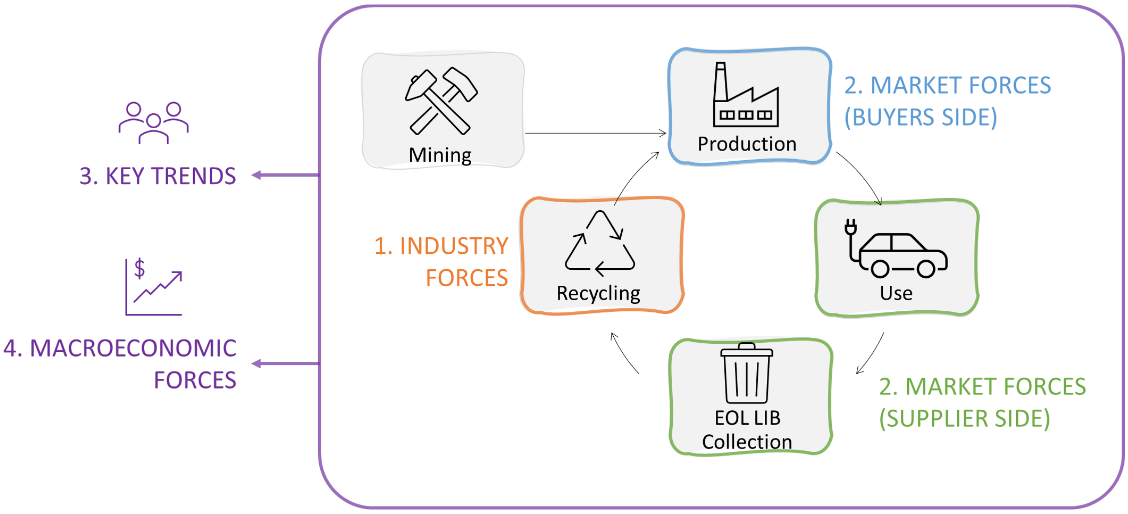

Figure 3-3: Illustration of this project's core methodology building on a combination of traditional frameworks.

4 Current and future state of the market

4.1 Industry – the EU Recycling Market

In this section, findings on the current and future state of LIB recycling in Europe is presented from the industry perspective – i.e. the LIB recyclers as competitors on the market, the historical and forecasted battery volumes available for recycling and analysis.

4.1.1 EU LIB recyclers: Competitors on the market

Based mainly on data from Circular Energy Storage (CES Online, 2021) with an extensive listing of global and European LIB recyclers, the total capacity of LIB recycling in Europe is around 45,900 tonnes per year. Most operational recycling plants are located in the Nordics, Central Europe and some in Eastern Europe. The country with the most plants and recycling capacity is in Germany (7 plants with a total of 20,700 tonnes), followed by France (3 plants with a total of 12,000 tonnes followed by Belgium (the Umicore plant with 7,000 tonnes). In terms of the biggest plants actually operating hydrometallurgical recycling, Umicore (pyrometallurgical with subsequent hydrometallurgical plant) in Belgium and Veolia in France have the biggest plants with capacity of 7,000 tonnes and 6,000 tonnes respectively.

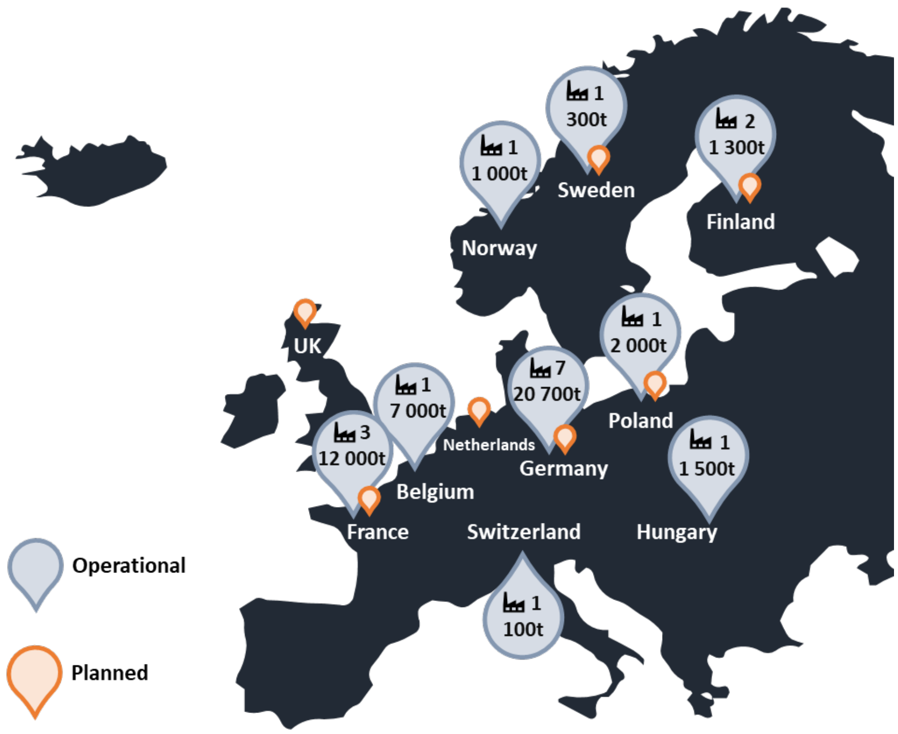

Figure 4-1 Number of operating recycling facilities and capacity (in tonnes) in Europe

The following table provides a list of all operational LIB recyclers, the recycling processes used and total capacities. In facilities that only conduct hydrometallurgical recycling, they represent the latter step of material recovery (of higher value metals such as cobalt and nickel), where the pretreatment (including sorting/disassembly and production of black mass for material recovery) is done elsewhere. Planned future plants are also included but no data on capacity is yet available, though there has been a tendency for European recyclers to focus only on one of the multiple recycling steps in their operations.

Table 4. List of European LIB recyclers

<table>
<tr><th rowspan="2">Recycler name</th><th rowspan="2">Country</th><th rowspan="2">Capacity (tonnes)</th><th colspan="4">Recycling process</th></tr>
<tr><th>Sorting/ Disassembly</th><th>Pyrometallurgical</th><th>Mechanical</th><th>Hydrometallurgical</th></tr>
<tr><td>Umicore</td><td>Belgium</td><td>7000</td><td></td><td>X</td><td></td><td>X</td></tr>
<tr><td>Umicore</td><td>Germany</td><td>7000</td><td>x</td><td></td><td></td><td></td></tr>
<tr><td>Euro Dieuze (Veolia)</td><td>France</td><td>6000</td><td>x</td><td></td><td></td><td>x</td></tr>
<tr><td>SNAM</td><td>France</td><td>5000</td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Accurec</td><td>Germany</td><td>5000</td><td>x</td><td>x</td><td>x</td><td></td></tr>
<tr><td>Duesenfeld</td><td>N/A</td><td>3000</td><td></td><td></td><td>x</td><td></td></tr>
<tr><td>Redux</td><td>Germany</td><td>2500</td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Royal Bee</td><td>Poland</td><td>2000</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Sungeel</td><td>Hungary</td><td>1500</td><td></td><td></td><td>x</td><td></td></tr>
<tr><td>Volkswagen</td><td>Germany</td><td>1200</td><td></td><td></td><td>x</td><td>x</td></tr>
<tr><td>Akkuser</td><td>Finland</td><td>1000</td><td></td><td></td><td>x</td><td></td></tr>
<tr><td>TES-AMM</td><td>France</td><td>1000</td><td></td><td></td><td>x</td><td></td></tr>
<tr><td>Erlos</td><td>Germany</td><td>1000</td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Nickelhütte</td><td>Germany</td><td>1000</td><td></td><td>x</td><td></td><td>x</td></tr>
<tr><td>Glencore Nikkelverk</td><td>Norway</td><td>1000</td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Fortum</td><td>N/A</td><td>300</td><td></td><td></td><td>x</td><td>x</td></tr>
<tr><td>Revolt</td><td>Sweden</td><td>300</td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Kyburz Group</td><td>Switzerland</td><td>100</td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Eramet</td><td>France</td><td>0</td><td colspan="4" rowspan="10">Planned facilities (not yet in operation)</td></tr>
<tr><td>Finnish Minerals Group</td><td>Germany</td><td>0</td></tr>
<tr><td>BASF</td><td>N/A</td><td>0</td></tr>
<tr><td>Primobius</td><td>N/A</td><td>0</td></tr>
<tr><td>Norsk Hydro</td><td>N/A</td><td>0</td></tr>
<tr><td>Ecopro</td><td>Poland</td><td>0</td></tr>
<tr><td>Elemental Holding</td><td>Poland</td><td>0</td></tr>
<tr><td>Johnson Matthey</td><td>United Kingdom</td><td>0</td></tr>
<tr><td>Fenix Recycling</td><td>United Kingdom</td><td>0</td></tr>
<tr><td>RS Bruce Metals</td><td>United Kingdom</td><td>0</td></tr>
</table>

4.1.2 Battery volumes available for recycling

"Available for recycling" refers to batteries collected by companies that either 1) fully process them to recover materials, 2) pre-process them in preparation for recycling, or 3) have the permit to export them as e-waste. In Europe, collected waste batteries are not necessarily treated or recycled in Europe. Rather, they are typically exported to other markets for reuse, or pre-processed in Europe for export and trade on the international e-waste market for recycling, usually South Korea and Southeast Asia, with China as the final destination. Therefore there is actually a gap (or leakage) of waste battery flows between what is collected and "available for recycling" and what is actually recycled.

In general, the biggest market segments are 1) portable batteries, 2) personal mobility and 3) light and heavy electric vehicles. Portable batteries make up 75% of global volumes for batteries available for recycling and in Europe, as mentioned a large fraction of the flows end up on global e-waste markets. Flows for personal mobility typically include batteries used in electric scooters, motorcycles, bicycles and kick-bikes. Currently the most significant flows are in China and other specific regions, however e-bike volumes in Europe are becoming an increasingly important market. Personal mobility batteries also tend to have shorter lifetimes and are thus cycled more frequently, outliving the vehicle it powers rather than the other way around (as seen with light and heavy EVs).

Light electric vehicles primarily refer to passenger cars and vans while heavy electric vehicles included buses and trucks. In Europe the biggest expected market for batteries reaching recycling is light EVs followed by heavy EVs. However, in both cases volumes are not expected to be significant until almost 2030 given that EV batteries tend to have longer use in their host applications, and also the reuse value in second-life applications (typically as energy storage solutions). These factors lead to a delay in the waste batteries reaching EoL and becoming available for recycling.

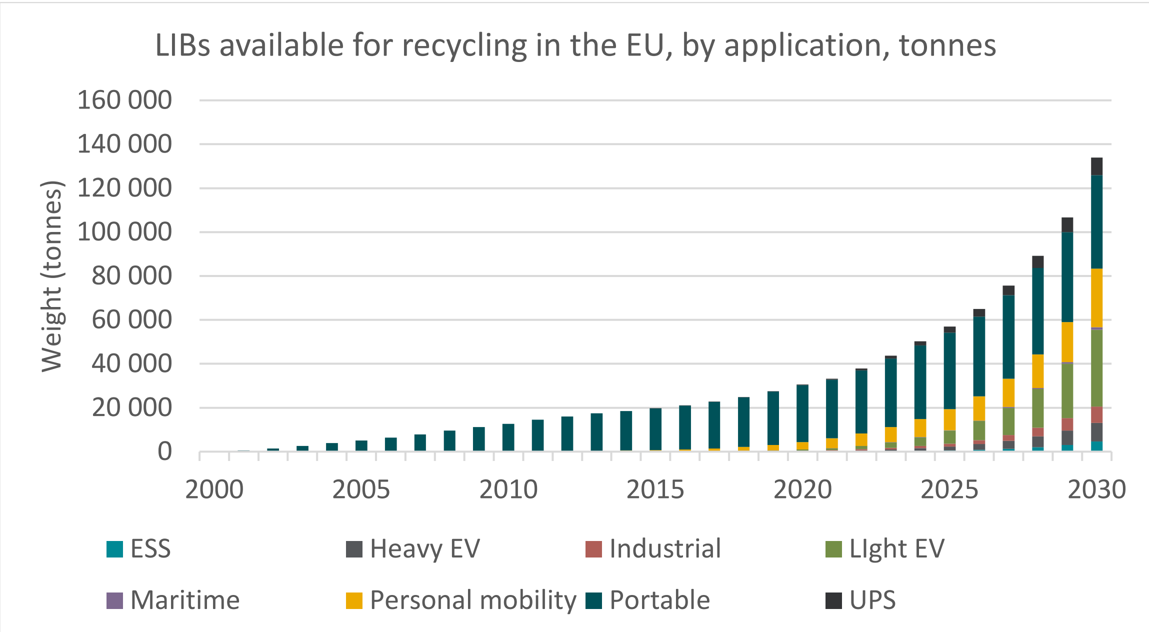

Figure 4-2 LIBs available for recycling in EU, by application, tonnes (CES Online, 2020a)

In terms of batteries available for recycling by chemistry, the most notable trends are in LCO and NMC chemistries. LCO volumes reaching recycling has been steadily growing but are expected to peak and then decrease before 2025, likely to be explained by the trend in low-cobalt design strategies for batteries especially in the EV sector, driven by growing social and environmental sustainability risks in mining critical materials such as cobalt, and the associated combination of regulatory change, consumer awareness/demand for conflict-free products and changes supply chain requirements in material sourcing. This trend is now being replaced by high nickel chemistries given the higher specific energy (Wh/kg), although safety management and slightly shorter lifespans are an ongoing technological consideration.

The significant growth of NMC chemistries is associated with the expansion of the EV, energy storage and battery-based power tools markets where NMC chemistries are typically used.

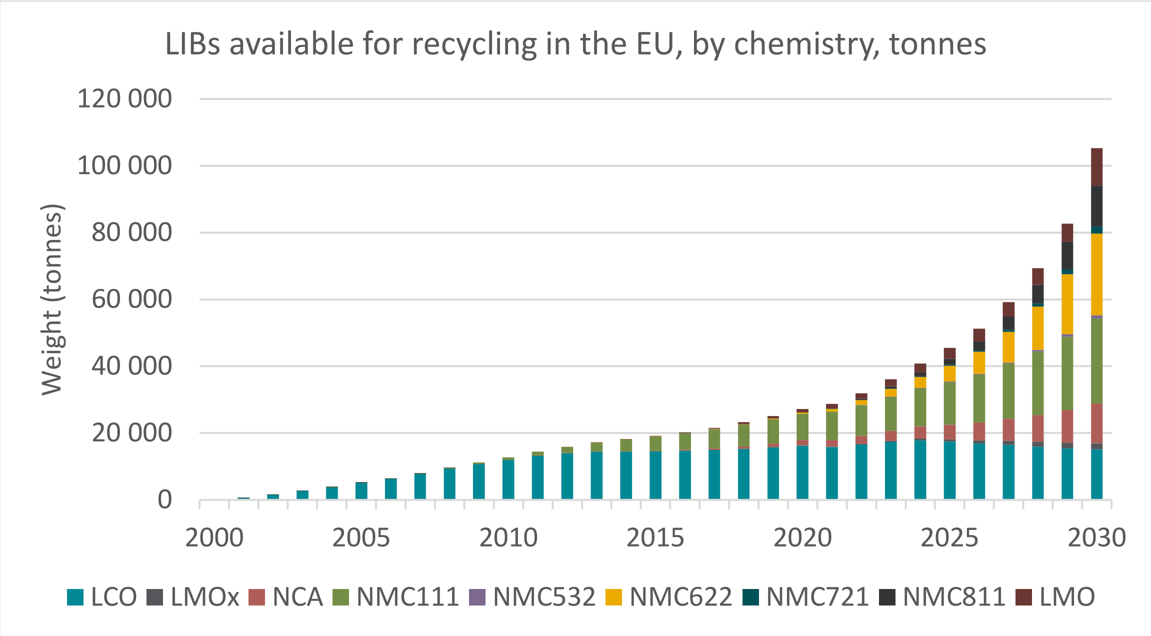

Figure 4-3 LIBs available for recycling in EU, by chemistry, tonnes (CES Online, 2020a)

4.1.2.1 Position of EU in LIB recycling compared to global

Today, most of the global recycling capacity is concentrated in China, followed by South Korea and Japan. This is made possible by the high and dense populations in these countries resulting in large domestic markets. China is also the largest manufacturer of electronic devices and a leader in refurbishment and remanufacturing of LIBs. Furthermore, China has the largest recycling and smelting/refining infrastructure of both virgin and recycled materials (especially in the case of cobalt) (CES Online, 2020a; Jacques, 2021).

Despite being the leader in batteries placed on the market per capita, the EU is behind on LIB recycling. At the same time, Europe has faced limited volumes of waste batteries to market. As such, the European recycling infrastructure has not been able to collect sufficient volumes for hydrometallurgical recycling and thus has been limited to pyrometallurgical recycling for non-precious metals, and the products of pre-treatment and black mass (containing precious metals) have typically been sent abroad to hydrometallurgical recyclers in the US, Canada and China for the recovery of precious metals. This has resulted in the leakage of precious metals supply in Europe, though it is starting to change as increasing European actors are investing, developing and operating material recovery facilities in Europe (CES Online, 2020a; Jacques, 2021).

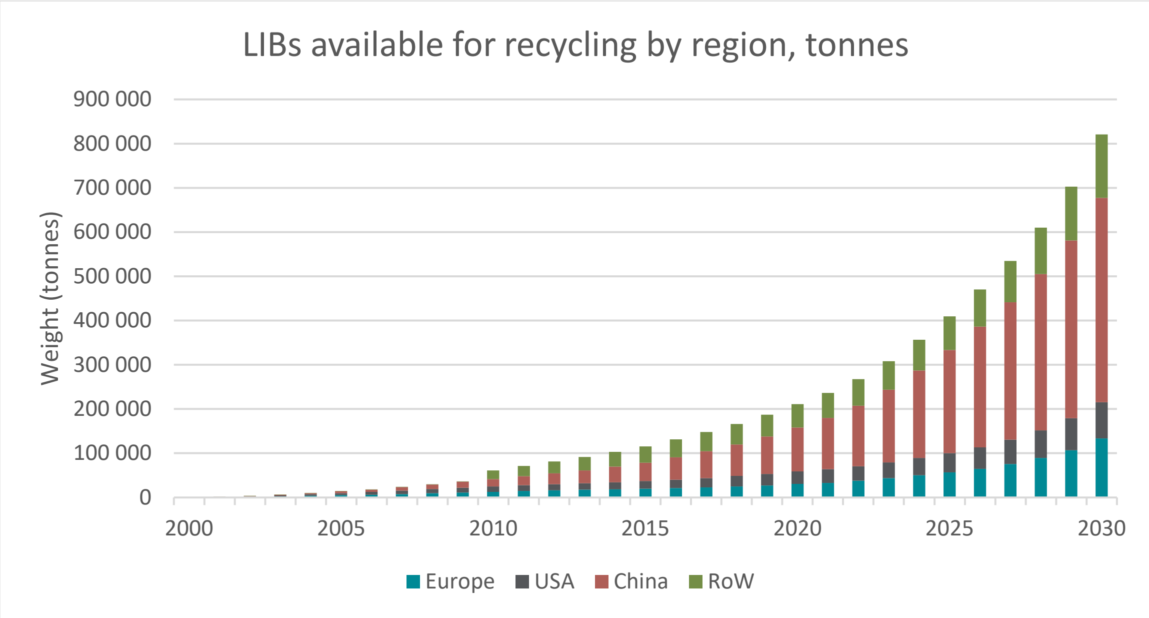

Figure 4-4 LIBs available for recycling in global market in tonnes (CES Online, 2020a)

In response to this, EU policy and strategy has recognized the need to secure the supply of raw materials and decrease the dependence on imports. As such hydrometallurgical recycling infrastructure is being planned and built, and battery policy is being changed to facilitate better LIB collection, labelling and setting targets for precious metals recovery, with the aim to boost volumes to sustain economies of scale and a profitable market in Europe. This growth of the European market is also expected to attract Chinese investors to build and/or invest in recycling facilities in Europe especially targeting production waste (CES Online, 2020a; Jacques, 2021).

The diagram below shows the estimated recycling capacity in 2030 compared to 2019. Much more emphasis will be placed on hydrometallurgical recycling than pre-processing to keep precious metal supply within European borders.

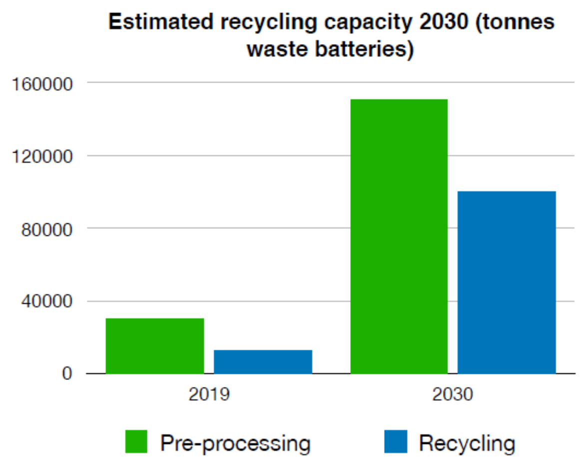

Figure 4-5 Estimated recycling capacity in Europe 2019 vs 2030 (CES, 2019)

4.1.3 Analysis

The recycling of all batteries in Europe has for a long time mainly been driven by the EU Battery Directive, which involves compliance schemes for a collection target of at least 45% of the average volume of portable batteries placed on the market in the last three years. This includes all battery types including nickel cadmium, alkaline and lithium-ion, however in practice the collection of LIBs is actually much lower. This is because LIBs are typically built into devices with high reuse value, and are thus typically trade and exported outside Europe. As a result, LIB recycling is of only marginal benefit to EU recyclers especially in comparison with single-use chemistries that enter the waste stream much faster and in a much more aggregated way.

Nonetheless, the increase in LIB volumes available for recycling can be attributed to the industrial side from electric vehicles, e-bikes and energy storage applications. It has mainly been the large recyclers with the economies of scale and capacity that have access to the consolidated streams of LIBs, but overall the handling, sorting and disassembly of LIBs in EU is inefficient. This is expected to improve with larger volumes as more LIBs reach EoL.

Over the last 10 years, focus on the LIB products and recycling has increased significantly in Europe, especially with the recycling potential of LIB production waste and European policy shifting towards securing the supply of critical raw materials in Europe. The capacity of LIB pre-processing is expected to increase significantly while material processing capacity (for recovery of precious and critical metals) is also expected to grow alongside, but at lower rates and likely with the involvement and control of Asian battery manufacturers from China and South Korea. This may affect the EU's long-term goals related to securing material supply within EU borders.

In summary, these trends point to significant competition in the market which will drive the need for efficient processes and value-added solutions downstream of the LIB value chain (CES Online, 2021).

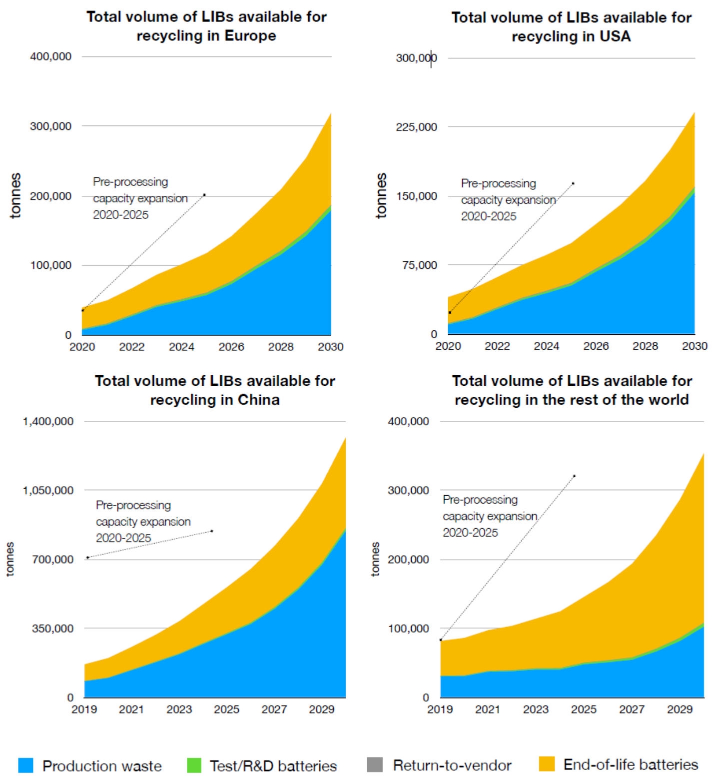

Figure 4-6 Capacity vs predicted volume in Europe compared with other regions (CES, 2021)

4.2 Market (Supplier and Buyer of Recyclers)

In this section, the market situation in terms of suppliers of materials for LIB recyclers and buyers of recycled LIB materials is represented. On the supplier side, this is broken down into volumes and projections on batteries present in new products (applications), batteries for reuse and batteries for end-of-life collection.

4.2.1 Supplier side

4.2.1.1 Primary LIBs

The LIBs market is seeing explosive growth. The number of LIBs placed on the global market in 2020 was over eight times larger than that of 2010. It is estimated that by 2030, the total amount of GWh will be nine times larger than that of 2020, meaning a compound growth rate of 25% (CES Online, 2021).

When LIBs were first introduced in the 1990s and early 2000s, the global market was dominated by single cells and small packs used in different portable electronics products. The batteries were replaceable and users were able to remove and replace them. Since the 2010s LIBs have been used in even more applications such as backup devices and electric vehicles, and except for power tools they are now built into the device without the possibility for a normal user to remove/replace them. Many portable devices today contain such built-in LIB (Ibid.).

Until 2019, the most common application for LIB batteries in Europe was portable electronics. Since then, light EVs as well as heavy and commercial EVs have started to dominate the market. Stationary energy storage, personal mobility, uninterrupted power supply (UPS), industrial and maritime applications are also becoming significant (Ibid.).

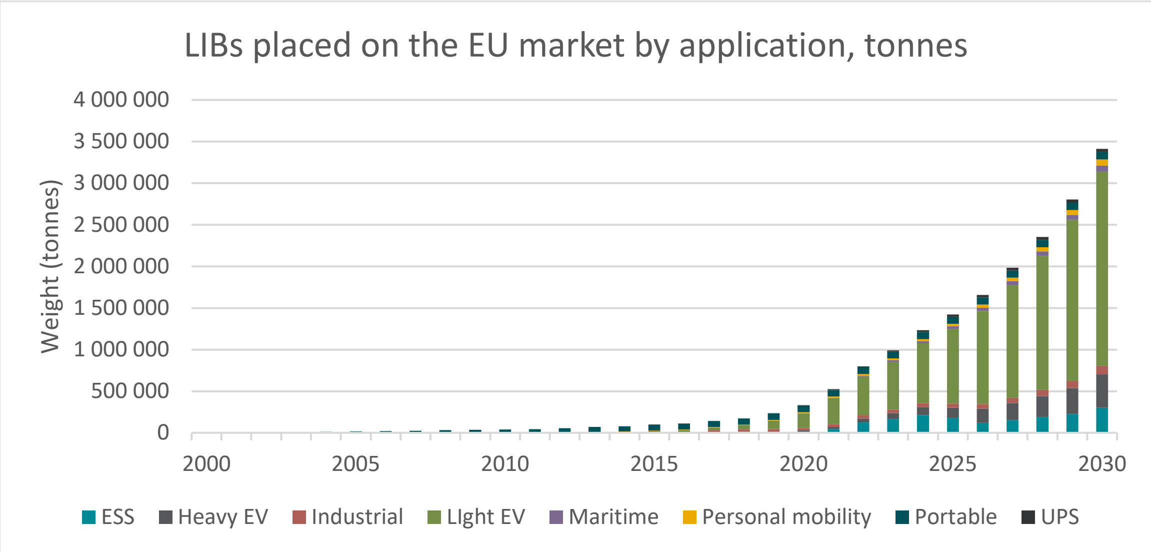

Figure 4-7 LIBs placed on the EU market by application, tonnes (CES Online, 2021)

The increasing focus on EVs in Europe will transform the industry with the dominance of nickel-based cathode chemistries (namely NMC and NCA) coupled with more local production and increased local sourcing of raw materials.

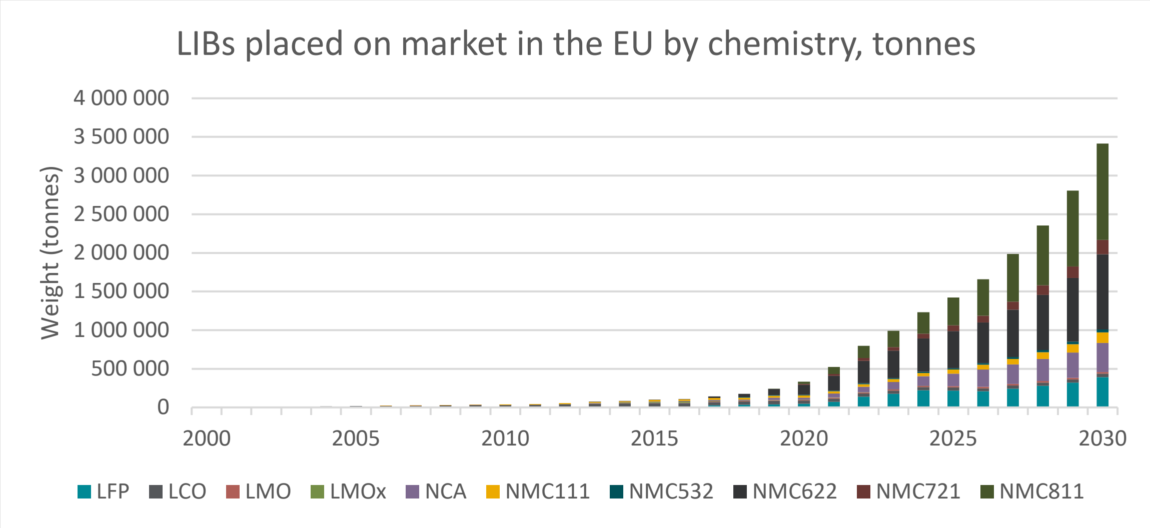

Figure 4-8 LIBs placed on the EU market by chemistry, tonnes (CES Online, 2021)

Nonetheless, it is namely the electrification of transport (currently light EV sectors) that is driving the LIBs industry. In 2030 it is expected that over 80% of all LIBs placed on global market will be used in light or heavy EVs, which means that the automotive sector will take over from the mobile and IT sectors in terms of driving the future growth of the LIB market. The expansion of economies of scale in the LIB industry will also enable the use of LIBs in other markets and the most notable markets are stationary energy storage, backup systems for telecom base stations and data centers, industrial applications (e.g. forklifts and robots), and leading ultimately to the maritime sector (ships and small boats) (Ibid.).

China is the largest producer and consumer of LIBs with over 70% of production and almost 50% of all batteries placed on the market. But Europe is expected to catch up in the coming years, with similar growth as in China mainly driven by policy and regulatory changes to increase the electrification of transport (Ibid.). The estimated annual market value of LIBs in Europe is EUR 250 billion from 2025 and onwards (European Battery Alliance, 2021).

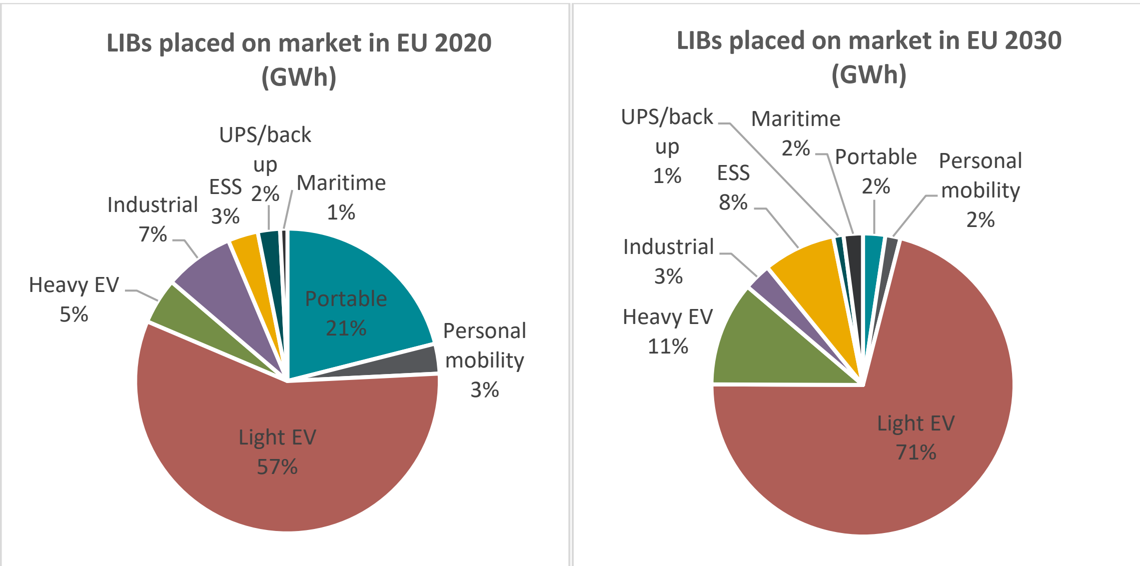

Figure 4-9 Current vs. 2030 in LIBs placed on market of different applications (CES Online, 2021)

4.2.1.2 Reuse

LIB reuse has been in operation for the past 10 years and while it has mainly been characterized by low transparency and arbitrage-driven trade (i.e. the simultaneous purchase and sale of the same product in different markets to profit from small differences in the listed price), the market is becoming industrialized and professional (CES Online, 2021).

The LIB reuse market is driven by economic benefit given that reuse is always more profitable than recycling. For example, the price for recycling an LCO battery (common in portable devices) in Europe is USD 7-8/kg for recycling but for reuse it is valued at USD 20/kg (Ibid.).

The market is dominated by portable devices (for direct reuse or sold as battery banks), but this was surpassed in 2021 by EVs (for industrial energy storage). New markets for reuse are also emerging, such as boat electrification, DIY powerwalls, range extension of EVs and EV conversion of combustion engine vehicles (CES, 2019).

Most of the LIBs are not collected by waste collectors but rather by refurbishers and e-waste companies. The global reuse market is dominated by China both for supply and demand, but this is increasing in Europe (Ibid.).

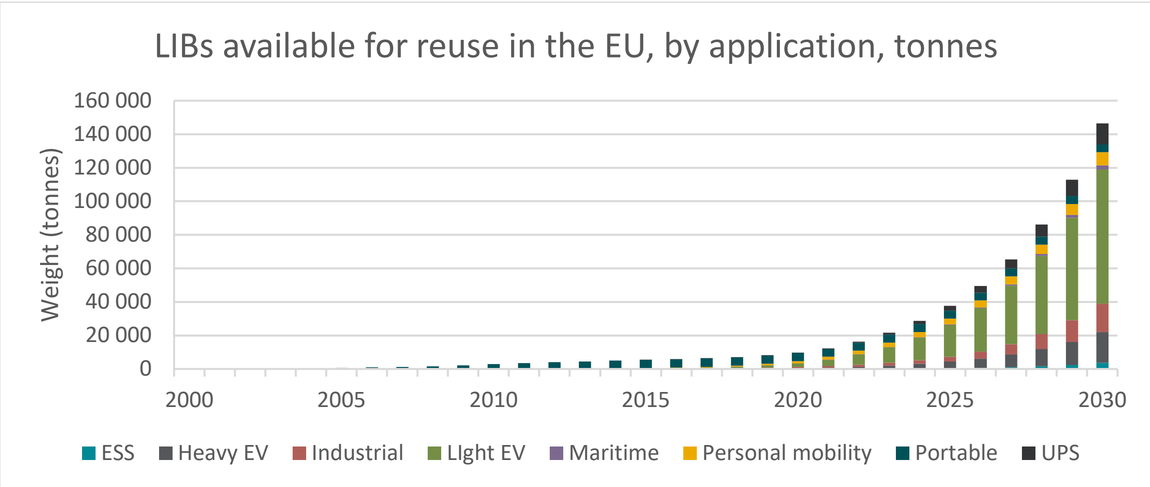

Figure 4-10 LIBs available for reuse in the EU, by application (CES Online, 2020b)

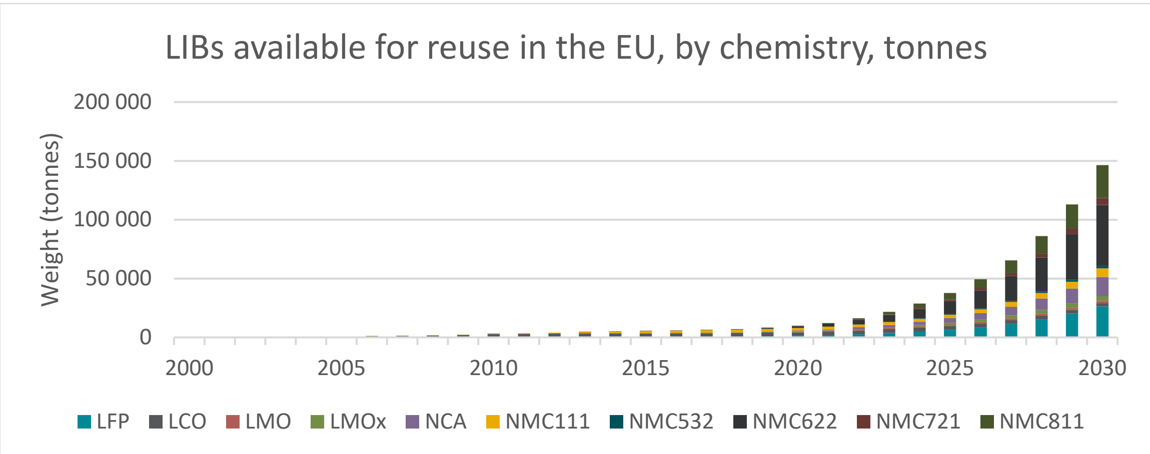

Figure 4-11 LIBs available for reuse in the EU, tonnes (CES Online, 2020b)

4.2.1.3 EoL Collection

In Europe, there is legislation to govern the ownership and responsibilities for batteries at its end-of-life (EoL). The Extender Producer Responsibility (EPR) for batteries means that the company placing the batteries on the market is responsible for their collection when they are scrapped by the consumer. Usually OEMs join resources to finance collection and treatment through Producer Responsibility Organizations (PROs) who take over the EPR obligations for producers (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

There is currently no legal requirement for the owner of a battery to send it for recycling when it is no longer used by the consumer. Coupled with the historically low economies of scale for recycling in Europe, many end-of-life batteries for consumer electronics may stay in with the original owner for many years instead of getting recycled. For EV batteries, like LFP batteries, batteries may be disassembled from buses and left in storage indefinitely until a purpose for them is found (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

EV batteries are supposed to be removed during the pretreatment process to comply with the ELV Directive (Directive on end-of-life vehicles), and the percent of batteries for which it takes place should be high as it directly correlates with the stock available for the recycling industry. Obtaining batteries for recycling relies on getting the batteries from the EOL EVs, but the value of LIBs creates an incentive for illegal dismantling (Ibid.).

The EU is already losing track of a large part of the vehicle stocks, shown to be about 38% vehicles in a 2014 study (Oeko-Institut, 2017). Some additional reasons for the high number in the study include lack of tracking of vehicles between country borders in the EU, and lack of collection points (Bergh, 2020). Tracking will be important to ensure that as much of the LIBs are returning to recycle, to ensure circularity.

Globally, LIBs are reaching EoL at a slower pace than before mainly because of better technology and a gentler use of the cells. EVs are driven less than internal combustion vehicles causing less wear on the battery. This is sometimes due to the limited capacity of the battery, and also because the secondhand value of cars can be retained long beyond 10 years (even with high car mileage), meaning that the vehicle and battery reaching EoL is later than before (CES Online, 2020a).

While batteries in new EVs placed on market are being dominated by nickel-based chemistries (NMC and NCA), the batteries from these applications will not reach EoL until 2030. Until then, the chemistries in EVs and portable devices placed on market so far will constitute current EoL volumes, mainly LFP and LCO (Ibid.).

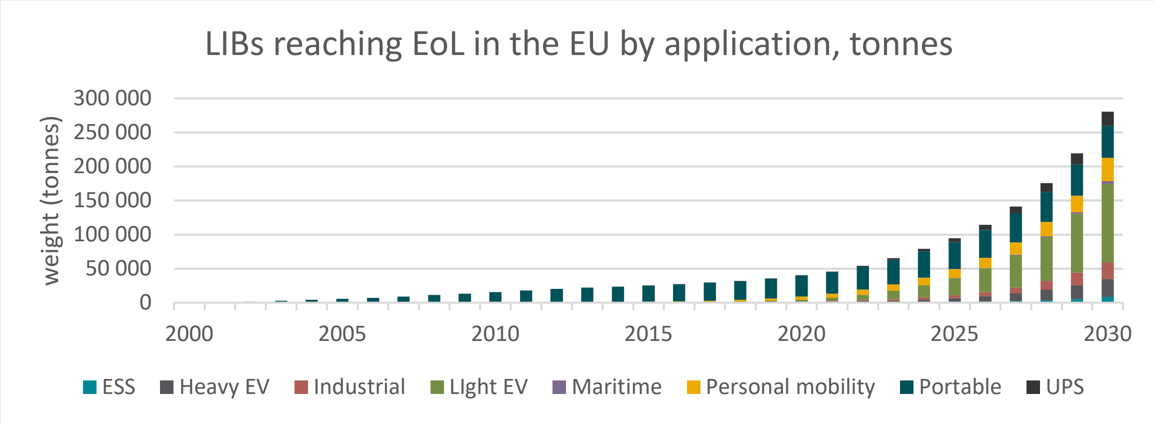

Figure 4-12 LIBs reaching EoL in the EU by application (CES Online, 2020c)

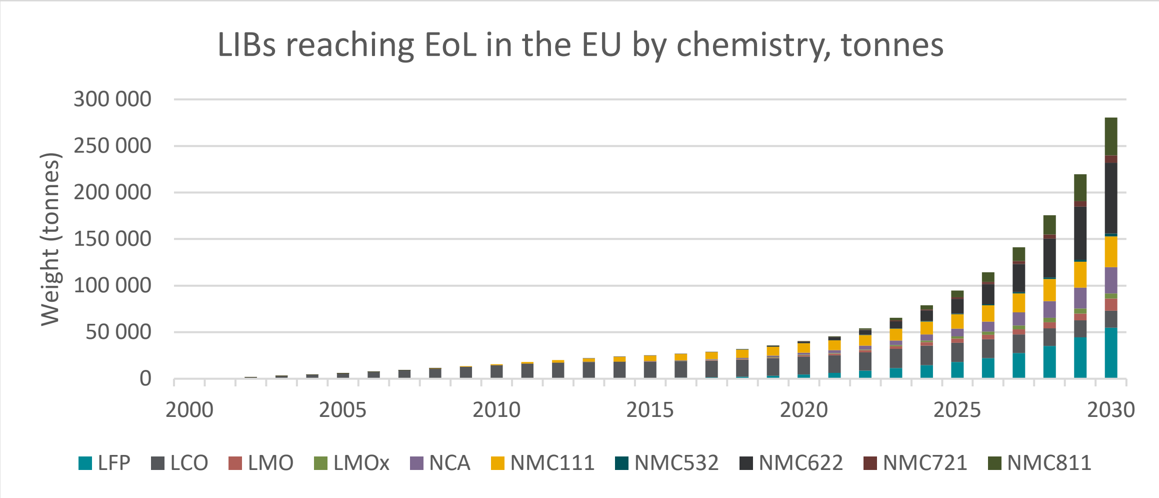

Figure 4-13 LIBs reaching EoL in the EU by chemistry (CES Online, 2020c)

However, EoL batteries will move geographically, mainly in the applications its encased in and typically from more developed markets and countries to less developed markets and countries. This has been the case for portable electronics but increasingly also for EVs. Portable devices have mainly ended up in China where they are refurbished, remanufactured and then ultimately redistributed to global markets. The largest buyers of EVs today are former Soviet countries such as Russia, Ukraine and the Baltic States, Georgia and Belarus, purchasing from Europe, US and Japan. Africa is also a buyer country but the share of EVs remains low (Ibid.).

4.2.2 Buyer side

The output streams of recycled batteries are used by smelters and refiners who combine the recycled material with virgin material to produce secondary materials that are then purchased by component and part manufacturers of different value chains. This can include the battery cell producers but also manufacturers of other products that use the same materials, such as magnets, chemicals and other alloys (for cobalt); alloys for plating of transport vehicles (for lithium), various coatings and alloy elements for consumer goods (for nickel); and clear glass and stainless steel (for manganese).

At this stage however, there is limited data on tracking the flow and volumes of recycled Co, Li, Ni and Mn in the production of new products. This is expected to be alleviated by the upcoming EU Battery Regulation (see Section 4.3.3.2 EU Battery Regulation).

4.3 Key social, environmental, technological and regulatory trends

In this section, the societal trends and environmental considerations related to various stages of the LIB lifecycle is presented, as this could create impact on the recycling stage further downstream. Then, technological trends are discussed in relation to battery design and recycling. Finally, regulatory trends are presented in terms of the key European policies, regulations and directives that affect LIB management and recycling, as well as key relevant initiatives.

4.3.1 Societal trends and environmental impacts

The LIB industry has, for a long time, been driven by the electronics and portable devices sector. Only in the past five years has the industry been overtaken by the electric vehicle market. In Europe, the societal shift towards transport electrification has mainly been driven by policies and political strategies to reduce carbon footprint targeting both in both private car ownership and in public transport.

However, the fulfilment of such high demand of LIBs comes at a high cost from the environmental and sustainability perspectives. LIBs are composed of various basic and precious metals, the most important of which include the cathode materials cobalt, lithium, nickel and manganese. The extraction of these metals in mining cause significant negative sustainability impacts, in particular cobalt and lithium which are on the EU Critical Raw Materials List.

The top global producers of cobalt is the Democratic Republic of Congo (DRC) (63% of global supply), of lithium they are Australia (54%) and Chile (25%), of nickel it is Indonesia and of manganese they are South Africa (30%), Australia (15%) and Gabon (15%) (Reichl, 2021).

As with most raw material extraction and industrial production processes, negative environmental and social impacts can occur all along the value chain. For example, all stages of mineral mining, extraction, smelting/refining, manufacturing and transport can produce air and water pollution. Negative social impacts can also be found in countries with inadequate regulations and norms to protect workers' rights and safety, and where child labour is present (Wu, 2020). Of all key battery materials however, cobalt is the one with the most severe artisanal mining issues.

Artisanal mining in developing countries is particularly problematic given the complex interlinkage of socioeconomic issues and the historical dependence of it as a source of livelihood for local peoples. The issues typically associated with artisanal mining are (Wu, 2020):

- Human health issues: where artisanal miners typically work under hazardous conditions without basic protective equipment and are susceptible to chronic illness and disease,
- Child labour: for example, about 40,000 children are estimated to work in artisanal mines in the DRC, some as young as seven years old. The working hours can be long, some reaching 12 hours per day,

- Abuse and exploitation: where artisanal miners can be taken advantage of by armed groups involved in military conflict, war and violence, and
- Severe environmental pollution: occurring as a result of toxic chemicals being leached in the mining process and released into water bodies and into the air, as well as deforestation to clear lands for mines, ultimately impacting local wildlife and biodiversity.

The responsible sourcing challenge is compounded by local trading markets, in which ore from numerous artisanal mines are collected together and sold, making it immensely difficult to trace sources of unsustainable metals (Ibid).

4.3.2 Technology trends

Europe faces challenge with raw material supply security but material recovery infrastructure has been lagging

The EU produces just 1% of all battery raw materials to cover the needs of the mobility and energy storage sectors, but access to 7-18 times more lithium and 2-5 times more cobalt by 2030 are needed (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021). At the same time, only 8-9% processed materials and components are domestically sourced from within the EU, while 84% of processed materials and components are imported from Asia (Ibid). Investments in local material recovery, including infrastructure building, are being made, but the demand still exceeds the planned supply.

One of the biggest barriers to building regional material recovery facilities in Europe is insufficient volumes for hydrometallurgical recycling of black mass. The current EU Battery Directive also does not place specific limitations on the recycled content of lithium-ion batteries, meaning that recyclers would usually recycle the easiest-to-recycle or most valuable materials. The proposal for the new EU Battery Regulation will likely require recyclers to introduce different methods of recycling in order to adjust the percentage of metals which are recovered (Ibid).

The increasing trend for reducing cobalt content in batteries to reduce supply chain sustainability risks also means that the value for LIB recyclers is reduced. LFP recycling is therefore very low or non-existent in Europe at the moment. This obstacle may be mitigated by the proposed battery regulation with its proposed recovery rates of cobalt, lithium and nickel as well as the proposed recycled contents in the production of new batteries. The proposed regulation will also force the companies in the battery supply chain to be more transparent regarding ensuring recyclability (enabling disassembly) (Ibid).

Systemic challenges hindering recycling: from design to collection

One of the biggest barriers to LIB recycling is disassembly, especially considering the trend of integrating/building in the battery into its device by glues and adhesives. This makes it very cumbersome and exhaustive for recyclers to disassemble. The lack of standardization in providing and organizing information on battery content and chemistry for recyclers also poses a challenge.

In Europe, recyclers collect a gate fee from collectors to process and recycle batteries, whereas in China recyclers pay a fee to buy the batteries for recycling. As such, in Europe there is no incentive for collectors to send the batteries to recyclers. OEMs and producers also do not have an economic incentive to design batteries for recycling since the current Battery Directive does not contain specific requirements for them to do so. As such, the focus for most OEMs at the moment is simply on producing devices and EVs at lowest cost and best sales value from the battery perspective.

Nickel-based chemistries dominate the market but LFP estimated to make a comeback

The cathode chemistries placed on the market have largely remained the same from 2010 to 2019 in terms of composition, but the detailed formulas (relative content) have and continue to change. Nickel-based chemistries (NMC and NCA) dominate EV battery market with the trend largely focusing on decreasing cobalt content. A shift has been seen from NMC532 and NMC622 (i.e. 5 and 6 parts Ni, 3 and 2 parts Mn and 2 and 2 parts Co) to NMC811 (i.e. 8 parts Ni, 1 part Mn and 1 part Co) introduced in new EV designs in China in 2019 and 2020 (CES Online, 2021). Even more variants are expected such as a new NCMA chemistry launched by General Motors and LG Chem containing both Mn and Al in the cathode, and NMC712 by BASF and other cathode makers.

As EV battery density technology advanced over time, LFP has increasingly been replaced by NMC and NCA, but in 2020 a revival is expected with innovations in the pack structure. CATL launched a cell-to-pack design which enables higher energy density by eliminating modules in the pack. The Tesla Model 3 is now using this in place of NMC chemistries and it has been the top-selling model in China. Such developments are also being seen by other Chinese, European and American EV manufacturers (Ibid.).

The future recycling market will have increasing focus on battery production waste as input

Production scrap from battery manufacturing is increasingly seen by LIB recycling actors as an increasingly interesting market to capture input volumes, though no official data can be found to estimate the amounts (CES Online, 2021; Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021). Some recyclers in Europe already include production scrap but these are very few, and a number of planned operations in Europe are already including production scrap as part of planned capacities, with the expected investment and control from Asian investors in the future.

4.3.3 Regulatory trends

In this section, the key European policies related to LIB management and recycling are presented. This includes the EU Battery Directive, the upcoming EU Battery Regulation, WEEE Directive, EU List of Waste, EU Waste Shipment Regulation and Basel Convention, Ecodesign Directive, and the RoHS and REACH regulations related to hazardous chemicals management. Key industry/multistakeholder initiatives directly focusing on LIBs are also presented – these are the European Battery Alliance and the Global Battery Alliance.

4.3.3.1 EU Battery Directive

The first battery directive was published in March 1991, which was the Council Directive 91/157/EEC of 18 March 1991 on batteries and accumulators containing certain dangerous substances. This was replaced in 2006 by the Battery Directive 2006/66/EC. The Battery Directive applies to all batteries placed on the market within the European Union. It categorises batteries as portable (e.g. for power tools, laptops, smartphones and computers), industrial or automotive. The directive establishes objectives and targets (e.g. on collection and recycling); it specifies measures (such as phasing out mercury or establishing national schemes for collection) and enables actions (e.g. reporting or labelling) to achieve them. It also sets maximum quantities for certain chemicals and metals, sets waste battery collection rates and sets administrative rules for labelling, marking, documentation and review (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

As it stands, the Battery Directive sets minimum recycling efficiency requirements for lead-acid batteries, nickel-cadmium batteries and "other waste batteries and accumulators". This means that lithium-ion batteries are not included as a standalone category despite the increasing significance and use of LIBs in society in the past 20 years. As such, the collection and availability of official LIB data is inadequate and insufficient at the EU level. It is hoped that this will change with the EU Battery Regulation.

4.3.3.2 EU Battery Regulation

An evaluation of the 2006 Battery Directive was completed in 2019 to contribute to a revision of the Directive, given the increased use of batteries in society as a result of the diversification of communication technologies and growing demand for renewable energy. The European Batteries Alliance (EBA), which aims to ensure a whole value chain for the manufacturing of advanced cells and batteries in the EU, is also a key part of the policy development context which called for the revision of the Battery Directive. Collection of waste batteries, efficiency of material recovery and the lack of a mechanism to incorporate new technologies and battery uses were identified as the biggest limitations for the EU to keep up with technological change (European Commission, n.d.-a).

In December 2020, the EC released a proposal for a new Battery Regulation consisting of three objectives: 1) strengthening the functioning of the internal market (including products, processes, waste batteries and recyclates), by ensuring a level playing field through a common set of rules; 2) promoting a circular economy; and 3) reducing environmental and social impacts throughout all stages of the battery life cycle (European Union, 2020). The proposed Regulation seeks to address three main problem groups (European Commission, n.d.-a):

1. Lack of framework conditions providing incentives to invest in production capacity for sustainable batteries, due mainly to the inefficient functioning of the EU single market and lack of sufficiently level playing field (from diverging regulatory frameworks across EU member states).
2. Sub-optimal functioning of recycling markets and insufficiently closed material loops, due mainly to a lack of clear and harmonised rules from the current Batteries Directive, which form barriers to recycling profitability as well as disincentivise further investment in new technologies and capacity increase for battery recycling.
3. Social and environmental risks associated with batteries that are not currently covered by EU environmental law, which are 1) lack of transparency in raw material sourcing, 2) hazardous substances and 3) untapped potential for offsetting environmental impacts in battery life cycles.

The proposed Battery Regulation mainly consists of 13 broad policy measures, each consisting of alternative sub-measures at varying levels of ambition. The EC further identifies the alternative sub-measure of preference balancing between effectiveness (to reach the potential ambition of the proposal) and efficiency (cost-effectiveness). Below is a summary of the broad measures and the EU's identified sub-measures of preference (related to lithium-ion batteries only):

Measure	**Preferred sub-measure(s)**
1. Classification and definition	New category for EV batteries. Weight limit of 5 kg to differentiate portable from industrial batteries OR New calculation methodology for collection rates of portable batteries based on batteries available for collection*

2. Second-life of industrial batteries	At the end of the first life, used batteries are considered waste (except for reuse). Repurposing is considered a waste treatment operation. Repurposed (second life) batteries are considered as new products which have to comply with the product requirements when they are placed on the market
3. Collection rate for portable batteries[4]	65% collection target in 2025, 70% collection target in 2030
4. Collection rate for automotive and industrial batteries	New reporting system for automotive, EV and industrial batteries. Collection target for batteries powering light transport vehicles.*
5. Recycling efficiency and material recovery	Recycling efficiency: 65% by 2025, 70% by 2030 Material recovery rates for Co, Ni, Li, Cu: resp. 90%, 90%, 35% and 90% in 2025; 95%, 95%, 70% and 95% in 2030
6. Carbon footprint for industrial and EV batteries	Mandatory carbon footprint declaration. Carbon footprint performance classes and maximum carbon thresholds for batteries as a condition for placement on the market
7. Performance and durability of rechargeable industrial and EV batteries	Information requirements on performance and durability. Minimum performance and durability requirements for industrial batteries as a condition for placement on the market
8. Non-rechargeable portable batteries	Technical parameters for performance and durability of portable primary batteries.* Phase out of portable primary batteries of general use.*
9. Recycled content in industrial, EV and automotive batteries	Mandatory declaration of levels of recycled content, in 2025. Mandatory levels of recycled content, in 2030 and 2035.
10. Extended producer responsibility	Clear specifications for extended producer responsibility obligations for industrial batteries. Minimum standards for PROs.
11. Design requirements for portable batteries	Strengthened obligation on removability. New obligation on replaceability.
12. Provision of information	Provision of basic information (as labels, technical documentation or online). Provision of more specific information to end-users and economic operators (with selective access).

[4] "Portable batteries" include batteries for portable devices (e.g. for power tools, laptops, smartphones and computers)

	Setting up an electronic information exchange system for batteries and a passport scheme (for industrial and electric vehicle batteries only).
13. Supply-chain due diligence for raw materials in industrial and EV batteries	Mandatory supply chain due diligence.

*Preferred sub-measure option pending a revision clause.

At the time of writing this report, the proposed Battery Regulation is under examination in the European Council and Parliament, with discussions involving various EU policy bodies (European Parliament, 2021). The process is likely to continue into 2022 with a decision in 2023 (EUROBAT, 2021).

4.3.3.2.1 Potential concerns for EU battery recyclers

A study conducted in 2021 identified and analysed potential shortcomings of the proposed EU Battery Regulation on European li-ion battery recyclers. These shortcomings are summarized below (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021):

On the minimum recycling and secondary material content targets: Most of the recyclers interviewed in the study indicated that the targets are good as proposed. However, some expressed concerns that the material recovery rates may be unrealistic to obtain by 2030 due to the delay in time between the batteries enters the market and reach their end-of-life and the time needed for technologies and innovation to become established.

On the impact of minimum recycling targets on marginal costs: The minimum recycling targets bring considerations for marginal costs for recyclers for each additional unit of material recovered. For example, a recycler may reach the 90% recycling target for cobalt, but the treatment cost may exponentially increase for each marginal increase in the recycling rate. This brings considerations on which metals recyclers will increase marginal effort to recycle because targeting one metal may come at the loss of another (e.g. nickel vs. cobalt).

On the impact of minimum recycling targets on market structure: One concern from small recyclers and pre-processors is that refineries that cannot reach the recovery targets may be pushed off the market and replaced by large scale recyclers, which can result in logistical and transport changes impacting small pre-processors, needing to increase cost resulting in reduced competitiveness. Furthermore, the regulation affects car manufacturers because the requirements and targets of batteries will be on the car manufacturer and not the battery manufacturer[5].

On the impact of collection rules: Currently, the proposed regulation states that the collection point has the right either to transfer the batteries to Producer Responsibility Organisations (PROs) (as currently done) or to other authorised waste recyclers (a new addition). This can be problematic because alkaline batteries have a negative value and Co-containing li-ion batteries have a positive value. So, PROs could end up receiving and processing all the alkaline batteries, but cobalt batteries would be sold by collection points to recyclers so that PROs cannot get them back.

[5] Stena Metall Interview with Christer Forsgren conducted by Alexandra Wu and Erik Emilsson. Q1 2021.

4.3.3.3 WEEE Directive

The Waste Electrical and Electronic Equipment (WEEE) Directive[6] implements the principle of "extended producer responsibility", where producers of EEE (Electrical and Electronic Equipment) are expected to take responsibility for the environmental impact of their products at the end-of-life. The WEEE Directive aims to reduce the environmental effects by setting targets for the separate collection, reuse, recovery, recycling, and environmentally sound disposal of WEEE. Batteries are included in the scope of the WEEE Directive, however the categorization and definitions of waste streams did not distinguish lithium-ion batteries as its own stream, and as such the tracking and data collection of li-ion battery waste has been inadequate.

4.3.3.4 EU List of Waste

The EU List of Waste[7] provides a common reference for classifying waste produced in the EU. It complements the EU Waste Framework Directive and is also relevant in the Regulation on Waste Shipment. The last update to the EU List of Waste was in 2014 and did not include a classification for lithium-ion batteries. A number of European battery recycling actors have stressed the importance of aligning the EU List of Waste so that appropriate waste codes can be assigned to lithium-ion batteries as well as the appropriate waste streams produced as a result of the battery recycling process, such as black mass.

In addition, certain waste streams like black mass are not classified. In that case, it can leave room for interpretation and cause problems, such as the black mass dumping and illegal shipment of black mass - where black market actors exploited loopholes. In this sense, official recyclers cannot compete with black market actors, who exploit the loopholes. The knowledge of supervising authorities must also be clear, and they must have access to the right information on the hazardous properties of the waste streams.

4.3.3.5 EU Waste Shipment Regulation and Basel Convention

Lithium-ion battery waste is considered as hazardous waste because of the risks for combustion and self-ignition caused by thermal runaway during transport, and the emission of hazardous gases. The EU Waste Shipment Regulation[8] includes rules for transporting waste across borders and implements the Basel Convention[9]. Under the Regulation, shipments of hazardous waste and waste destined for disposal are prohibited to non-OECD countries outside the EU. Shipments to OECD countries are generally subject to a *prior notification and consent* procedure which requires prior written consent of all relevant authorities on the dispatch, transit and destination of the waste (European Commission, n.d.-c).

However, given the difficulty of shipping end-of-life batteries internationally for recycling, many waste batteries are destroyed without the recovery of valuable materials or electronic scrap is shipped with labels such as "under repair" to circumvent the Basel Convention, without the batteries actually being repaired and reused, OR recycled properly outside the EU. The result is a leakage of valuable battery waste outside the EU and associated negative human and

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[6] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast)

[7] Commission Decision of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (notified under document number C(2000) 1147) (Text with EEA relevance) (2000/532/EC)

[8] Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste

[9] Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, entered into force in 1992

environmental health impacts (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

As such, there is increasing demand from the li-ion battery recycling industry to update and align the EU Waste Shipment Regulation to support the transition to a circular economy in the EU, restrict export of EU waste to third countries and strengthen its enforcement (Fortum, n.d.; Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

4.3.3.6 EU Ecodesign Directive

The EU Ecodesign Directive[10] establishes a framework for setting eco-design requirements on energy-related products and consistent EU-wide rules for improving the environmental performance of products. It is relevant to battery recycling because it will affect the design and production of batteries in the future which will impact the recycling process, such as dismantling and collection, and even expected timeline to reach end-of-life given focus on e.g. use phase extension.

For li-ion batteries, the most relevant aspects of the Ecodesign Directive are the increasing priority on resource efficiency requirements in relation to the EU Circular Economy Action Plan and EU Green Deal, to promote the role of batteries in green transport, clean energy and to contribute to achieving climate neutrality and transition to a circular economy.

A number of specific product regulations and working documents have been developed under the Ecodesign Directive. Some highlights are given below for battery-containing devices (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021):

- **Servers and data storage products:** batteries in servers and data storage products need to be easily removable to support repair and separation at end-of-life. Manufacturers are required to ensure that joining, fastening or sealing of products do not prevent disassembly during repair/reuse. Instructions on disassembly must include the type of operation, type and number of fastening techniques to be unlocked and tools required. Further, Information needs to be provided on the cobalt content of batteries in relation to concerns on conflict minerals (Commission Regulation (EU) 2019/424).
- **Smartphones and tablets (working documents)**: proposed requirements include designing for repair and reuse, and reliability. There are also recycling requirements on providing accessible information on dismantling to access the batter(ies), dismantling steps and the tools or technologies needed to access batter(ies).

So far, the battery-based product scope of the Ecodesign Directive has mainly been appliances, which means that electric vehicle batteries are not included. However, the European Commission is now exploring the inclusion of electric vehicle batteries in the Ecodesign Directive, as the Ecodesign Preparatory Study for Batteries was completed in 2020 and the consultation process continues (European Commission, n.d.-b).

[10] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products

4.3.3.7 RoHS and REACH

The Restriction of Hazardous Substances (RoHS) Directive[11] sets restrictions on the use of ten substances[12] in electrical and electronic equipment of which batteries are explicitly covered. The Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)[13] requires all companies manufacturing or importing chemical substances into the European Union in quantities of one ton or more per year to register these substances with the European Chemicals Agency (ECHA).

'Substances of Very High Concern' (SVHC) that are listed on the 'Candidate List' and contained in products in concentrations higher than 0.1% weight by weight per article must be reported. These materials may be found in batteries, probably as an electrolyte solvent. The Candidate List of substances of very high concern contains at least two sub-stances known for use in Li-ion batteries (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021):

- 1,2-dimethoxyethane or ethylene glycol dimethyl ether (EGDME, $C4H10O2$) which is an electrolyte solvent that are very persistent and very bio-accumulative (vPvB)
- 1,3-propanesultone or 1,2-oxathiolane, 2,2-dioxide ($C3H6O3S$) which is an electrolyte fluid in lithium-ion batteries which is carcinogenic.

4.3.3.8 Other initiatives

4.3.3.8.1 European Battery Alliance

The European Battery Alliance (EBA) was launched in 2017 by the European Commission, EU countries, industry and the scientific community. It consists of over 700 industry and innovation actors in the batteries industry, from mining to recycling. The objective is to build a strong and competitive European battery industry (EBA, n.d.). Its expected outcomes are to build at least 15 giga-factories in the EU by 2025 and supply battery cells to power 6 million electric cars (360 GWh) by 2025 (Viegand Maagøe A/S and IVL Swedish Environmental Research Institute, 2021).

4.3.3.8.2 Global Battery Alliance

The Global Battery Alliance (GBA) is a recently developed initiative that comprises a partnership of over 70 businesses, governments, academia, IGOs and NGOs. Its flagship program is the GBA Battery Passport, which aims to develop guiding principles covering the circular recovery of battery materials, ensuring transparency and progressive reduction of GHG emissions and the elimination of child and forced labour in the battery material value chain (GBA, n.d.).

4.4 Macroeconomic forces

Cobalt is the most expensive of all battery materials. Its price has been volatile and susceptible to supply constraints and ethical concerns, not least also because it is often mined as a by-product of nickel or copper, with only a small percentage from primary cobalt sources (LME, 2021a). Following cobalt, nickel and lithium can be seen as the next most valuable recoverable materials.

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[11] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast)

[12] The RoHS Directive currently restricts the use of ten substances: lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE), bis(2-ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), dibutyl phthalate (DBP) and diisobutyl phthalate (DIBP).

[13] Regulation (EC) No 765/2008 of the European Parliament and of the Council of 9 July 2008 setting out the requirements for accreditation and market surveillance relating to the marketing of products and repealing Regulation (EEC) No 339/93

The demand for nickel has increased and will continue to increase as NMC battery chemistries become more dominant. It is estimated that the demand for nickel for EVs is projected to grow more than 10 times from 60 000 tonnes in 2018 to 665 000mt by 2025 (LME, 2021b). Circular Energy Storage estimates a demand of 68,254 tonnes of lithium (around 341,270 LCE) from battery production aimed for the European market in 2030 (Melin, 2020).

Instability in the battery raw material market also results in price increases, and the supply problems are attributed to conflict, unstable regions, increased demand and scarcity, and rising energy cost affecting production. As a result, OEMs and producers are looking increasingly to the use of recycled materials to address these issues and secure supply (Hieronymi, 2012). Cobalt has faced uncertainty in price fluctuations and supply security especially considering the disruptions to global supply chains as a result of the Covid-19 pandemic.

The material recycling market competes with the primary material market. In the LIB recycling market, LCO chemistries have been the main driving force given the high value of cobalt. Given the finite amount of primary sources, in the long-term greater efforts will need to be made by mining enterprises to resort to lower grade and more remote deposits, increasing the cost of primary material mining over time. This will increase the competitiveness of material recycling (Söderholm, 2019). Recycled materials in the context of supply chain instability, insecurity and uncertainty are also comparatively advantageous over primary materials given the greater stability they provide. On the other hand, insufficient volumes in the EU and policy gaps have not allowed for the economies of scale and business case needed to scale up material recovery. This should be addressed over time now that capacities and infrastructure are growing across the EU.

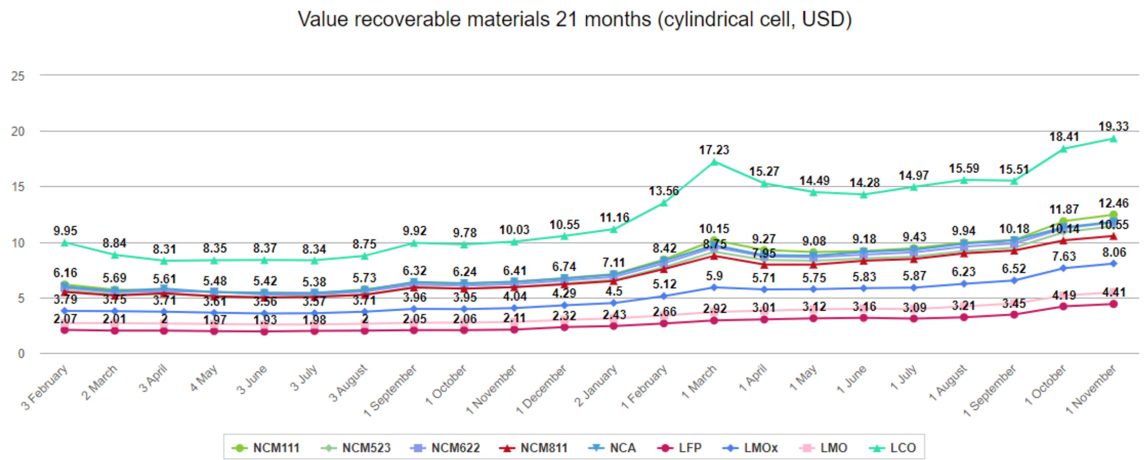

Figure 4-14. Value of recoverable materials by battery chemistry from February 2020 to November 2021 (for cylindrical cells in USD) (CES Online, 2021)

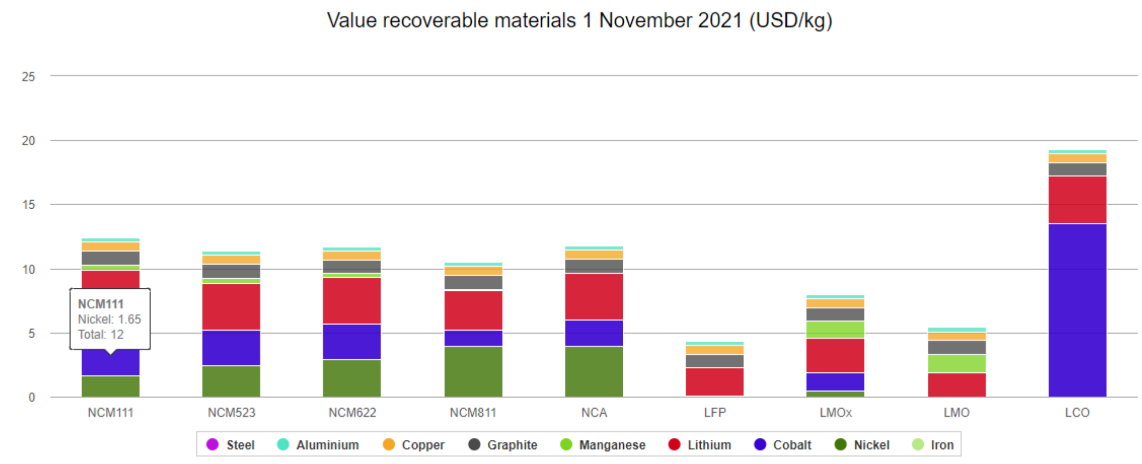

Figure 4-15. Value of recoverable materials by chemistry in November 2021 (in USD/kg) (CES Online, 2021)

5 PESTLE summary

In this section, key aspects of the above findings are laid out into an adapted PESTLE framework with associated impacts to the LIB recycling market, as well as possible response strategies recyclers can take. The purpose of this is to facilitate the development of LIB recycling business models.

Table 5. Highlights of the situation and impacts to the LIB recycling market (author's elaboration based on (CES, 2021))

Perspective (PESTLE)	Key aspects	Impact to the LIB recycling market
Political and Legal	Biggest change will be the new EU Battery Regulation with collection and recycling targets for battery materials. Future initiatives on supply chain transparency (e.g. battery passport) as covered by the new EU Battery Regulation and other industry initiatives.	Producers will be pressured to invest in collection and recycling. The collection and recycling system in EU need to ensure materials do not leave EU borders, otherwise will lose market share to international competitors (mainly in Asia). Recyclers could try to capture fragmented volumes by investing in overseas collection and local servicing/processing.
Economic	Portable batteries make up the majority of volumes of batteries available for recycling, but personal mobility and light and heavy EVs are taking over. However, volumes are not expected to be significant until 2040. The demand for cobalt and nickel will continue to grow.	Recyclers will need to plan according to the delay expected until sufficient volumes reach the EoL and recycling stages. Nonetheless, the demand for LIB materials will ensure a market for recyclers. In the meantime, recyclers may also consider capturing other related market segments such as providing services for reuse (consolidation, curation, refurbishment, repurposing), recycling of production scrap, repair and remanufacturing.
Technological	Low cobalt designs in new batteries to reduce ethical impacts in supply chain. Nickel-based cathode chemistries (NMC and NCA) volumes will become much more significant in the future – both for new LIBs placed on market and eventually EoL volumes available for recycling.	Recyclers can target other battery chemistries beyond cobalt-based chemistries, to capture the value of recycling e.g. nickel. Investment in recycling of production scrap.

	Increased focus on production scrap as input supply to recycling.	
Social and Environmental	As society continues to electrify, especially in transport, the demand for LIBs and LIB materials will continue to grow. Nonetheless, the environmental and social sustainability impacts remain. Initiatives are increasing to address this by producers and value chain actors, by e.g. industry initiatives to increase supply chain transparency backed by EU policies and strategies. Nonetheless, progress on this is expected to be slow.	LIB material recycling provides a competitive advantage against material mining in tackling these social and environmental sustainability issues in virgin material extraction.

6 Conclusion

The European LIB recycling market is changing rapidly. The capacity of LIB pre-processing within Europe is expected to increase alongside the improved recycling potential of LIB production waste and a shift in European policies towards securing the supply of critical raw materials in Europe. The material processing within Europe is also expected to grow, but at lower rates and with involvement and control of battery manufacturers from China and South Korea.

It is expected that a large majority of the batteries placed on the global market will be used in light or heavy EVs and Europe is expected to catch up with China's position as the largest producer and consumer of LIBs in the coming years – a change driven by policy and regulatory changes encouraging the electrification of transport. This shift of focus to EVs is expected to transform the LIB manufacturing industry with a dominance of nickel-based cathode chemistries (NMC and NCA) and more local production and sourcing of raw materials

Meanwhile, responsible material sourcing and the issue of conflict mineral mining will continue to be an important issue in the LIB market, though it will continue to be immensely difficult to control due to the current logistic structure as well as low capacity and transparency along the supply chain (especially upstream).

Related to technological change in battery chemistry, LFP chemistries have increasingly been replaced by NMC and NCA, but may become more common again with recent innovations in the pack structure. The trend of reducing cobalt content in LIBs to manage price and conflict mineral issues will also affect the value of cobalt for recyclers.

On a regulatory level, there are a number of directive applicable to LIB value chain (EU Battery Directive, WEEE Directive, EU Ecodesign Directive, RoHS Directive) and two regulations (REACH and EU Waste Shipment Regulation) as well as the proposed Battery Regulation, preceded by the 2006 Battery Directive, including measures related to specifically LIBs. The replacement of the EU Battery Regulation on the EU Battery Directive is expected to significantly impact the way LIBs are produced, used and recycled in Europe, with specific targets on LIB reuse, recycling and material recovery. It will also force supply chain actors to be more transparent regarding ensuring recyclability of LIBs, increasing recovery rates of cobalt, lithium and nickel and proposed levels of recycled contents in new production. Changes to the Ecodesign Directive are also expected whereas the European Commission is exploring the inclusion of electric vehicle batteries in the battery-based product scope.

The demand for lithium from battery production is expected to grow substantially and the demand for nickel is projected to grow significantly from 2018 to 2025. The competitiveness of material recycling will increase for LCO chemistries given the finite availability and the high value of cobalt. Related to this, instability in the battery raw material market has resulted in OEMs and producers looking to the use of recycled materials. Policy gaps and insufficient volumes in the EU have not yet allowed for economies of scale for recycled materials, but this is an area that is expected to be addressed with growing EU capacities and infrastructure.

The findings of this report form key considerations for LIB recyclers and the business strategy for LIB recycling. In particular, as battery materials are raw materials traded on the commodity market, there is limited opportunity for LIB recyclers to compete with a product or price differentiation strategies. The main focus for business strategization is therefore on cost leadership, and technological, operational and efficiency improvements that contribute to providing best value for money. Altogether the findings of this report will feed into a business case screening of developed and novel hydrometallurgical technologies for LIB recycling in the EU context in the subsequent stages of the ELiMINATE project.

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