European Commission

JRC TECHNICAL REPORT

Information gap analysis for decision makers to move EU towards a Circular Economy for the lithium-ion battery value chain

Franco Di Persio

Jaco Huisman

Silvia Bobba

Patricia Alves Dias

Gian Andrea Blengini

Darina Blagoeva

2020

Joint Research Centre

EUR 30315 EN

Contact information
Name: Franco Di Persio
Email: francodipersio@sestosenso.es

EU Science Hub
https://ec.europa.eu/jrc

JRC121140

EUR 30315 EN

PDF ISBN 978-92-76-20885-3 ISSN 1831-9424 doi:10.2760/069052

Luxembourg: Publications Office of the European Union, 2020

How to cite this report: Di Persio, F., Huisman, J., Bobba, S., Alves Dias, P., Blengini, G.A. and Blagoeva, D., *Information gap analysis for decision makers to move EU towards a Cirucla Economy for the lithium-ion battery value chain*, EUR 30315 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20885-3, doi:10.2760/069052, JRC121140.

Content

Abstract

This report aims at identifying and discussing how circular economy strategies may support the development of a sustainable battery value chain in Europe and what challenges, including data and information gaps, could hinder it. The aim is to keep product and materials value in the production loop as long as possible and avoid the use of mined Primary Raw Materials in the manufacturing phase. In order to achieve this, this report aims to assess the contribution of reuse, repurposing, remanufacturing, material substitution and recycling of Li-ion batteries to move the EU towards a Circular Economy for the Li-ion battery value chain. Myriad of raw and processed materials are used in the production of the Li-ion battery and this report will focus on the four most emblematic of them: Co, Li, Ni and natural graphite. The timeframe of the analysis starts from the past, goes through the present and looks at the future of the Li-ion battery value-chain. Preliminary conclusion of the analysis is that using the recycling of Li-ion batteries as Secondary Raw Material source and efforts to substitute specific materials are necessary and very important steps that will certainly mitigate supply issues of the incipient European Li-ion manufacturing industry. However, the availability of recycled Secondary Raw Materials is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery put on the market and on how much of it is collected. Several obstacles are of political and regulatory nature, and a strong effort is required to european policy makers for removing them. The EU recycling industry should keep pursuing technological innovation to develop sustainable, scalable and flexible recycling processes able to deal with the incoming growing volumes of Li-ion battery waste and its expected uncertain chemical mix. For Electric Vehicle batteries, before recycling, the options for remanufacturing for reuse and repurposing in a second use applications are also interesting circular economy approaches capable of keeping materials and products value in the loop. However, the efficiency related to environmental, economic and safety aspects of reuse and repurposing practices is not yet properly assessed. It is of paramount importance to be able to estimate the stocks and flows of materials embedded in Li-ion batteries and quantify the present and future availability of secondary raw materials in different scenarios. A robust Material Flow Analysis model is necessary. In this report we propose a simplified Material Flow Analysis model that allows us to perform a qualitative analysis of stocks and flows of cobalt embedded in traction Li-ion batteries.

Keywords

Lithium-ion, battery value chain, Circular Economy, Battery Alliance, European Green Deal, sustainable battery, critical raw materials, resilience, battery waste, WEEE, collection, recycling, Primary and Secondary Raw Material, remanufacturing, EV battery second life, material flow analysis

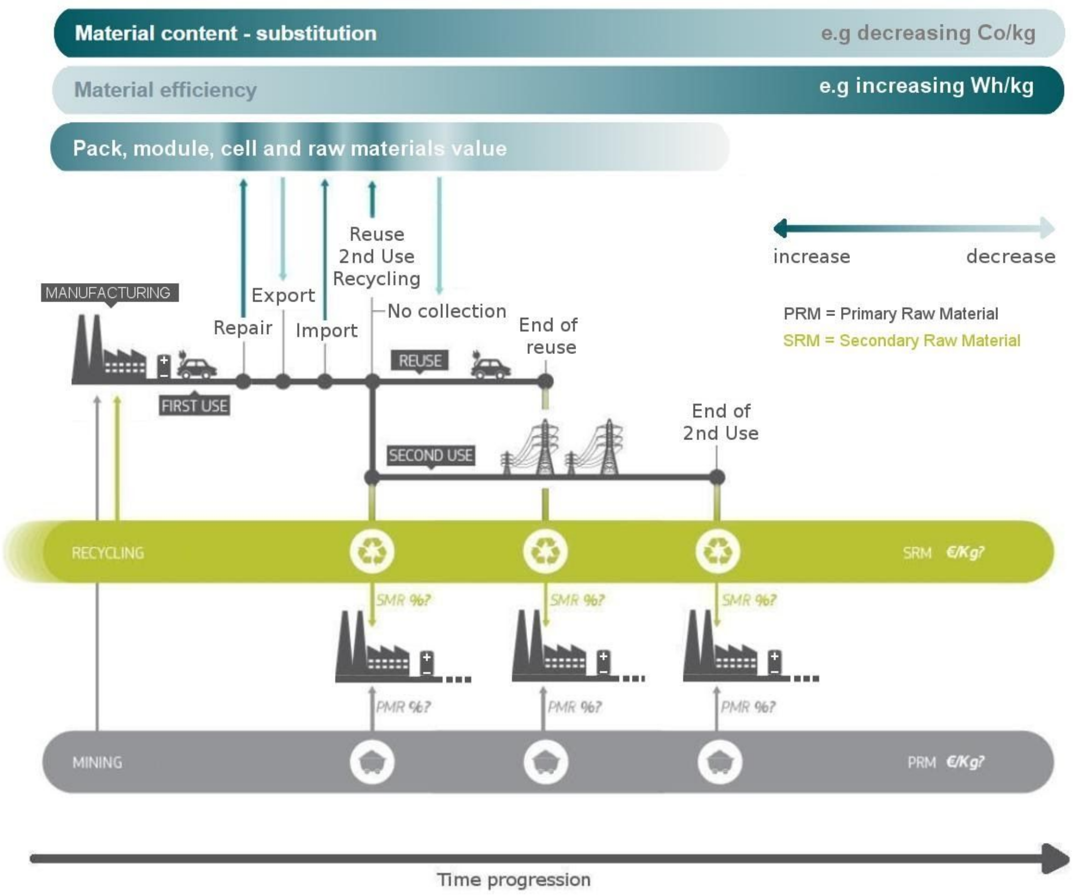
Executive summary

The traditional linear economy approach is still today mostly representing the usual business in the Li-ion battery value chain. Mining and chemical industries provide most of the myriad of raw and processed materials used in the production of the various Li-ion cell components including the anode, cathode, electrolyte and separator. These components are then assembled in individual cells which are then put together in modules and packs and commercialized for different applications. But what is the fate of those battery packs, modules and cells at their End of Life? What percentage of the important and strategic materials and compounds contained in those batteries are recycled? What are the losses? Is it suitable to process and use the recycled raw material back again in the Li-ion cell manufacturing industry? How will the future flow of those materials look like? Is the 'second-life' of electric vehicle batteries a suitable option?

With this report we would like to contribute to reshape the today predominantly linear Li-ion value chain, to close the loop and strongly link the recycling sector back again to the li-ion cell manufacturing sector following a circular economy approach. The aim is to keep product and materials value in the production loop as long as possible and avoid the use of mined Primary Raw Materials in the manufacturing phase. This report intends to identify and discuss how circular economy strategies may support the development of a sustainable battery value chain in Europe and what challenges, including data and information gaps, could hinder it. In order to achieve this, this report aims to assess the contribution of reuse, repurposing, remanufacturing, material substitution and recycling of Li-ion batteries to move the EU towards a Circular Economy for the Li-ion battery value chain.

The lithium-ion battery technology is expected to have a significant market growth in the incoming years. Two main applications are expected to experience the lithium-ion technology growth, the mobility sector with mainly electric vehicles and the electrical stationary storage. In our analysis the mobility scenario is often employed to describe the problems. This report will focus on the four most emblematic materials used in the Li-ion battery production: Co, Li, Ni and natural graphite.

Inevitably, the timeframe of the analysis starts from the past, goes through the present and looks at the future of the Li-ion battery value-chain



To perform the analysis and allow the evaluation of the flow and availability over time of relevant Li-ion batteries raw materials, the report highlights in **Chapter 1** relevant aspects that required a close look such as e.g. the variety and fast evolution of Li-ion technology, the complexity of Li-ion battery classification and the set of still not harmonized terms and definitions.

In **Chapter 2** the analysis focuses on the access to raw materials for Li-ion batteries at present. The resilience approach to criticality of raw materials is discussed in a circular economy context highlighting the relevance of recycling for the access to raw material SRM (Secondary Raw Materials) as an alternative to the mined raw materials PRM (Primary Raw Materials) and the effect of substitution in the Li-ion technology. An overview of the actual global Li-ion raw materials value chain is provided focusing on Lithium, Cobalt, Nickel and Natural graphite especially considering the EU situation.

In **Chapter 3** the report is looking at the potential availability of SRM. Also it looks at the issues that hinder the production and the access to SRM. The availability of SRM is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery that has been Put on the Market (POM) so far and on how much of it has been collected. The main difficulties encountered in this attempt are described considering the uncertainties of the available data. On top of it, the limits of the existing li-ion battery recycling processes and the EV battery second-use flow options are adding more uncertainty at the SRM value chain.

In **Chapter 4** future scenarios are considered looking e.g. at the possible market trends, Li-ion technology evolution, role of EV second use option. The MFA (Material Flow Analysis) model is presented as one of the possible tools for evaluating the availability of SRM in different timeframes. An overview of the main boundary conditions and uncertainties affecting the reliability of the model results is provided.

The sustainability agenda marches relentlessly on. In December 2019, President von der Leyen of the new European Commission presented the European Green Deal to set out how to make Europe the first climate-neutral continent. The European Green Deal covers all sectors of the economy including mobility, energy and industry and provides a roadmap with actions to boost the efficient use of resources by moving to a sustainable circular economy. Back in October 2017 the European Commission promoted the establishment of the European Battery Alliance (EBA) to build a competitive and sustainable European battery cell manufacturing industry. The European Commission called the European stakeholder for actions to build a competitive european battery industry. Quoting the European Commission Vice-President Maroš Šefčovič at the launch of the Friends of the EU Battery Alliance in the European Parliament: "*… We need to establish a whole value chain in Europe. A value chain focused on green batteries, from security of supply to production processes recyclability and second use, to gain competitiveness and economies of scale…*".

In this report we tried to highlight bottlenecks and gaps that are actually preventing turning this vision into reality, including strategies to overcome these bottlenecks.

Preliminary conclusion of the analysis is that using the recycling of Li-ion batteries as Secondary Raw Material source and efforts to substitute specific materials (e.g. lower Co content, Si enriched anode, change of one chemistry with another) are probably not enough to bring the European material supply for the Li-ion manufacturing industry to reach a high level of resilience, but they are necessary and very important steps that will certainly mitigate supply issues.

The availability of recycled Secondary Raw Materials is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery put on the market and on how much of it is collected. Unfortunately there are several uncertainties that are hindering sound estimates for present and future volumes becoming available for recycling. Several obstacles are of political and regulatory nature, and a strong effort is required to european policy makers for removing them. When the Li-ion waste comes to recycling, the performance of the recycling industry becomes determinant. The recycling industry should keep pursuing technological innovation to develop sustainable and flexible recycling processes. For EV batteries, besides recycling, the remanufacturing for reuse in less demanding traction applications or repurposing in a second use for e.g. ESS applications is another circular economy approach capable of keeping the material and product value in the loop. However, The efficiency related to environmental, economic and safety aspects of reuse and repurposing practices is not yet properly assessed.

It is of paramount importance to be able to quantify the present and future availability of Secondary Raw Materials. A robust Material Flow Analysis model is necessary. In this report we proposed a simplified MFA model that allows us to estimate the stocks and flows of materials embedded in LIBs.

1 Introduction

1.1 Background and context

Electrification of road transport is essential for the EU to achieve its targets of CO2 emissions reductions in 2030 and beyond. Clean mobility is one of the priorities of the European Commission as addressed in the Third mobility package "EUROPE ON THE MOVE" launched in May 2018 (1). This initiative identifies batteries development and production as a strategic imperative for Europe in the context of the clean energy transition and it sets 10 key priority actions in its Annex 2 for a Strategic Action Plan on Batteries. In October 2017 the European Commission with its Vice-President Maroš Šefčovič (2) promoted the establishment of the European Battery Alliance (EBA) (3) to build a competitive and sustainable European battery cell manufacturing industry. Under the umbrella of the EBA the European industry, investment banking and the R&I European actors joined and engaged in the implementation of the 10 priority actions set in the Strategic Action Plan on Batteries. In December 2019, President von der Leyen of the new European Commission presented the European Green Deal to set out how to make Europe the first climate-neutral continent. The European Green Deal covers all sectors of the economy including mobility, energy and industry and provides a roadmap with actions to boost the efficient use of resources by moving to a sustainable circular economy.

Lithium-ion batteries (LIBs) are crucial for the successful deployment of electric mobility in the EU and adequate, continuous and sustainable access to raw materials is one of the aspects addressed in the Strategic Action Plan on Batteries. Also, the experts of the SET-Plan Temporary Working Group on Action 7, now contributing to the battery-related R&I initiative BatteRIes Europe (4), in the context of their work identifying the battery R&I priorities for Europe to become competitive, had highlighted the access to refined raw materials in the Li-ion battery cell manufacturing industry as a clear bottleneck (5).

To address the lithium-ion raw materials issues a cross-border and integrated European approach covering the whole value chain of the batteries ecosystem is necessary. The lithium-ion battery technology is expected to have a significant market growth in the incoming years. Two main applications are expected to experience the lithium-ion technology growth, the mobility sector (e.g. EVs (Electric Vehicles)) and the electrical stationary storage (ESS). The global growth scenarios up to 2040 for those two applications shows in terms of GWh a tenfold figure for EVs compared to the stationary storage (6). That is why in our analysis the mobility scenario is often employed to describe the problems. For instance, the up-stream part of the EV Battery value chain (as represented in Figure 1) is where the raw and processed materials are procured and it is where the criticality for the EU battery industry begins.

Figure 1. Linear EV battery value chain diagram (109)

The EU is strongly dependent on imports of raw materials required in LIBs, most of them with highly geographically concentrated and insecure supply, predominantly imported from very few countries. In addition, LIBs is a highly intensive materials technology – raw materials for anode and cathode account between 25 and 30 % of the battery cell production cost (7). Therefore, raw materials costs may impact greatly on the battery manufacturing industry profits and ultimately the speed of uptake of e-mobility. Consequently, Europe's ambition to develop a competitive lithium-ion cell manufacturing industry can only materialize if Europe can secure access to responsibly sourced battery raw materials at reasonable price.

However, when raw material is sourced from outside EU countries, ensuring a sustainable production and a low price may be challenging. The raw materials necessary for manufacturing Li-ion batteries are mainly originating from mining activities, so called Primary Raw Materials (PRM). Deposits are distributed unequally on the planet and considerable financial and technological investment is required to extract them. The international raw materials trade tends to be characterized by long-term contracts and short-term speculation. Intercompany contracts and shareholding structures are crucially influencing the market with upstream and downstream integration between the raw material processing and the raw material extraction industry (e.g. shareholdings by mining companies in processing companies, and other way around). On top of this reality, antagonistic geopolitical strategies (e.g. subsidies, trade tariffs), oligopolistic structures and concentration of resources in unstable regions determine a complex geography along which lines hot spots are erupting, resulting in conflicts with increasing costs and high environmental collateral damages (8).

Those raw materials that have a high supply-risk and economic importance for the EU are flagged as "critical raw materials" (CRMs). The European Commission publishes a list of CRMs which is reviewed and updated every three years as explained in the EC Communication (9).

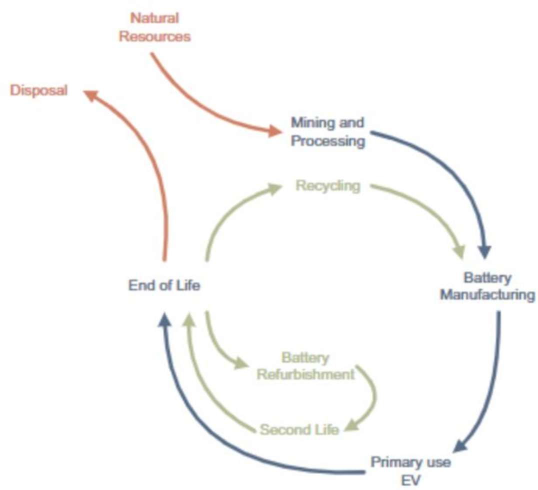
The Lithium-ion cell manufacturing industry uses a wide range of materials and some of them are considered Critical Raw Materials (CRM) (e.g., cobalt, natural graphite and silicon (metal)) or at risk to become CRM (e.g. lithium) (10). One important aspect of the criticality study is the assessment of the resilience of a material supply value chain. The EU resilience of Lithium, Cobalt and Graphite supply value chain has been evaluated along several technologies, including Lithium-ion batteries for electro-mobility (11). The recycling and substitution of those materials play an important role in improving their supply value chain resilience.

In the down-stream part of the EV Battery value chain (Figure 1), the recycling may connect back to the up-stream raw material part offering an opportunity to close the loop, and engage the EU battery industry in the circular economy. Although raw materials sourced from the EU will be not able to meet the total projected future demand of LIBs (12), the expansion/creation of a domestic European source of raw materials may indeed boost the EU battery cell manufacturing industry. A circular economy approach applied to the Li-ion battery value chain securing access to Secondary Raw Material (SRM) through recycling may give additional strategic leverage to the future EU cell manufacturing industry over international competitors. Moreover, other emerging circular economy strategies such as re-use and remanufacturing, which have the aim to increase lifetime duration of batteries may slightly relax the tensions on raw materials supply although keeping valuable resources in batteries may delay their availability. In the shorter term, the main concern for the EU industry is timely availability of raw materials since mining and refining investments generally take long lead times.

1.2 Objective and scope

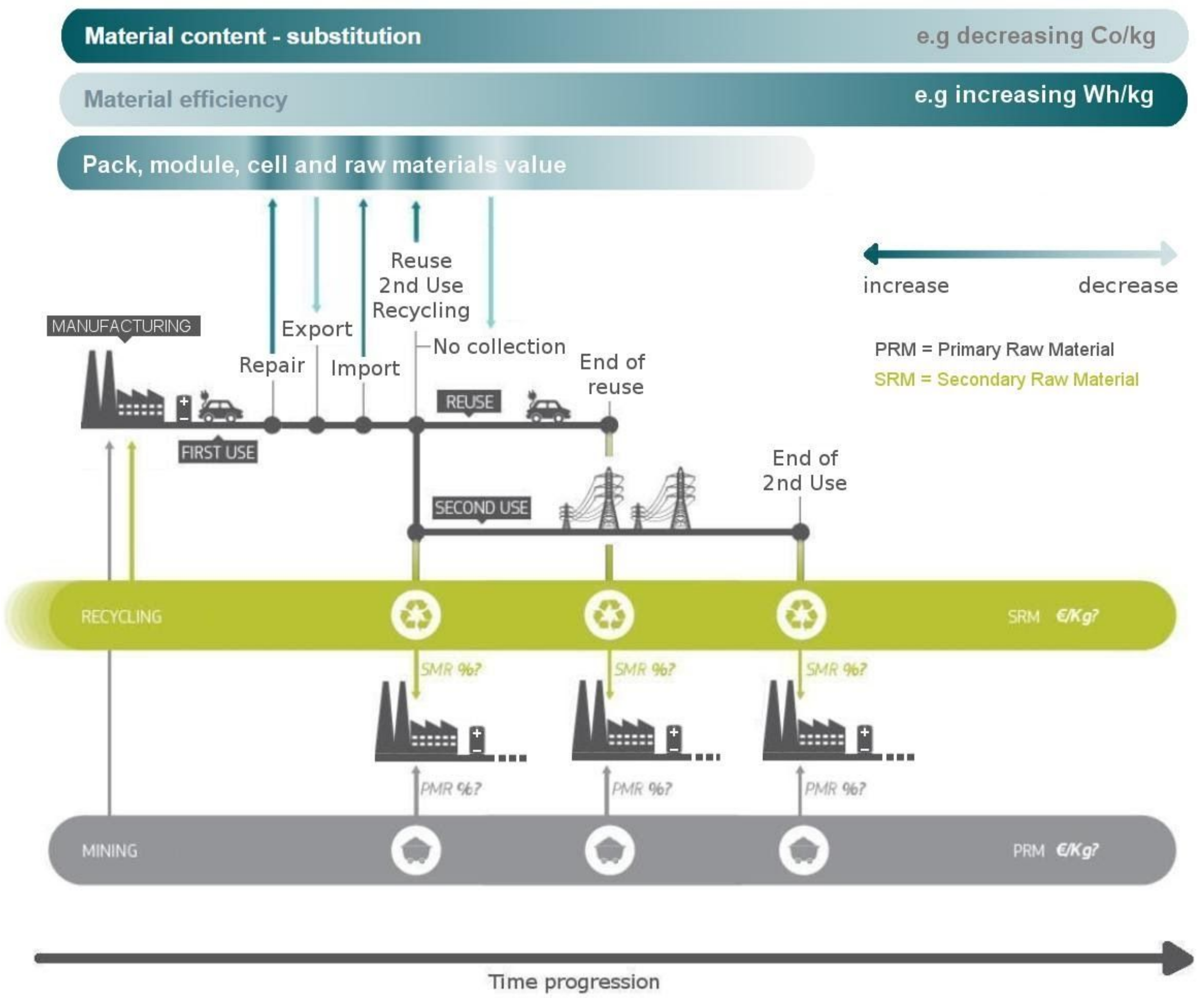
This report aims at identifying and discussing how circular economy strategies may support the development of a sustainable battery value chain in Europe and what challenges, including data and information gaps, could hinder it. The focus of the report is on one hand **to highlight what information is already available** and on the other hand **to identify what knowledge is missing,** in particular related to future material availability. In order to achieve this, this report aims to assess the contribution of the 'inner loops' of the reuse, repurposing, remanufacturing and recycling to the circular economy as represented in the diagram in Figure 2 (13). However, although this diagram may better represent the circularity of the battery value chain compared with the simpler diagram of Figure 1, still the representation does not allow to grasp the time dimension and values comparison, which are of crucial significance in our analysis.

Figure 2. Two dimensional EV battery circular value chain diagram (13)



The Figure 3 below provides a multidimensional illustration in terms of time, material price and material value retention of the EV battery circular economy.

Figure 3. EV battery material price, material efficiency and value evolution in a circular economy context. Source: JRC, (2020)



This diagram represents several connections points in the timeline progression of the material flow. In those points the interactions of the material flows will depend on several variables which are evolving in time. Especially interesting for our analysis are the following variables:

- The expected improving material efficiency of the Li-ion battery technology expressed as increasing performance in terms of Wh per kg and decreasing concentration of key raw material per Wh (e.g. decreasing Co content)
- The retention of pack, module, cell and raw materials value in a circular economy context
- The primary raw material (PRM) price
- The secondary raw material (SRM) price

One important point is battery manufacturing. For the Li-ion battery manufacturing industry the cost of materials is predominant. According to (6) around 60% to 75 % of the EV battery pack cost is due to the materials and around 70% of it is the cost of materials for anode and cathode electrodes. For the anode and cathodes active materials the refined battery grade raw materials could come from mined PRM as well as recycled SRM. The share of SRM that the battery cell manufacturing industry will adopt will strongly depend on how competitive its price is compared with the price of PRM. PRM price may be also extremely volatile and on the other hand SRM coming from recycling of waste batteries could become competitive considering the expected growing volume of Li-ion batteries in the EU. Necessarily, the price of SRM will strongly depend on the cost of Li-ion battery recycling processes and its logistics. For instance, the volume of collected waste battery, the concentration of valuable raw material in the waste battery mass, as well as the role of innovation to improve efficiency and flexibility of the industrial recycling process to obtain a battery grade level material from a battery waste. Besides those market driven factors, the regulatory and enforcement framework is adding an environmental price for the measures adopted to avoid the negative environmental impact associated with the battery waste landfill. Overall, the balance between the price of SRMs compared to PRMs will be the main economic driver for increasing resource efficiency.

In a circular economy strategy focus must be not only on price, but also on values. The aim is to keep product and materials value in the loop as long as possible and avoid the use of PRM in the manufacturing phase. As an underlying strategy this means designing 'products that last' (14). For instance there are points in the diagrams of figure 3 that may result in increasing and decreasing of the LIBs material values. For instance, the repairing of EV battery packs and imports of EVs are increasing the LIBs material, pack and cells values, while exports of EVs is decreasing the LIBs material, pack and cells values. A more crucial point in the diagram of Figure 3 is the EV battery end of first life. At that point the batteries must be first collected to avoid a fatal loss of material value and a reliable and accountable collection scheme for all LIBs should be implanted. Then there are three available options and all of them are capable of keeping the material and product value in the loop. They are: recycling, remanufacturing for reuse in EVs and repurposing in a second use for e.g. ESS applications. There are several measures that can be adopted to promote those options. This can be done for instance by designing the EV battery for a second life by improving modularity, upgradeability, reparability and dismantling possibilities. However, those options may carry side-effects. For instance, if EV batteries go through a second life, the key raw materials contained in those batteries will be retained in applications and not available for more years to come. This will lower the volume of available batteries for the recycling industry, possibly limiting their revenues, impeding the immediate use of key and valuable raw materials (e.g. Co). This may possibly affect the price of SRM, and for the cell manufacturing industry to limit the access to a domestic source of raw material to produce more resource efficient batteries.

To transform the Li-ion battery value chain according to a Circular Economy paradigm key information gaps and barriers affecting the flow of raw materials along this diagram timeline must be located and analysed. This report will introduce a simplified raw Material Flow Analysis (MFA) model that can help to estimate the amount of SRMs that may participate to satisfy the future demand of LIBs and supporting the sustainability assessment of the circular economy approach

1.3 Approach

Analysing the potential contributions of circular economy approaches for the development of a sustainable battery value chain in Europe requires a well-defined research framework and reflection on what key information is available versus not available. Inevitably, the timeframe of the analysis must start from the past, go through the present and look at the future of the Li-ion battery value-chain as represented in Figure 3. The following aspects relevant for the evaluation of the flow and availability over time of raw material will be looked at:

1.3.1 Battery classifications

For the purpose of describing the mass flows of both Li-ion battery products, components, cells and materials, the various chemistries and applications should be distinguished in a detailed and flexible manner. For research purposes, several classification approaches for batteries exist, depending on cell chemistry, hazardousness, re-chargeability, and area of application. However, there is no well-structured classification available to describe raw material content. In this context, the H2020 ProSUM project proposed a well-structured classification taking into account several aspects related to batteries (e.g. chemistries, applications, etc.) (15). Based on expert knowledge on battery systems and the resources they contain, as well as an analysis of existing battery classifications, the ProSUM battery classification of electrochemical cells was developed. The battery types cover the six current main electrochemical systems based on lithium, zinc, nickel-cadmium, nickel-metal hydride, lead-acid and others. The six battery types were further divided into 16 sub-groups, defined as BATT keys. These keys are compatible with classifications by chargeability type, the Battery Directive descriptions, battery recycling flows and other trade codes such as the EU List of wastes, ProdCom, the Combined Nomenclature (CN), as well as the United Nations Committee of Experts on the Transport of Dangerous Goods (16). The classification is further updated under the scope of the H2020 ORAMA project towards 52 BATT keys (17), including new chemistries appearing on the horizon for commercial applications, like LFP for e-buses and heavy duty vehicles.

The distinction between single-use (primary) and rechargeable (secondary) batteries is important, as most of the CRMs are contained in rechargeable batteries. The same is true for the chemistries. There are differences in the ways that Member States collect and publish data on batteries placed on the market and on end-of-life batteries collected, and the level of detail of the reporting varies significantly (18). For research purposes, information on the different chemical types of batteries gives a good indication of the embedded CRMs. This information is also valuable to recyclers. Improving the harmonisation of reporting and market analysis by changing the level of detail in the data reporting will support future assessment of the CRM flows in the European urban mine.

The ‘flexible’ battery classification from the ProSUM project (19) is similar to the framework developed for the WEEE Directive (20). It allows constructing groups of batteries with comparable chemistries, absolute weights, application types and lifespans in meaningful clusters with comparable properties (21). The latest and slightly updated classification is included in the Annex 1. Here below a simplified version of it (Table 1):

Table 1. Battery classification main chemistries to applications (left) and Names, acronyms and applications of main battery chemistries (right)

Chemistry	Applications	Chemistry	Applications
LCO	Portable PC	LFP	Others portable
	Cell phones		e-bikes
	Camera/games		Industrial excl. mobility
	e-bikes		SLI
	Industrial excl. mobility		e-bus
	Tablets		e-truck
LMO	Cameras/games	Li-Primary	Primary
	Others portable	LMO	Primary
	e-bikes	LCF	Primary
	PHEV	LSO	Primary
	BEV	LTC	Primary
	Industrial excl. mobility	LFS	Primary
NMC	Portable PC	NiCd	Cordless tools
	Tablets		Others Portable
	Cell phones		Industrial excl. mobility
	Cameras/games	NiMH	Portable PC
	Cordless tools		Cordless tools
	Others Portable		Others portable
	e-bikes		HEV
	HEV		Industrial excl. mobility
	PHEV	PbA	Others portable
	BEV		SLI
	SLI		e-bikes
	Industrial excl. mobility		Industrial excl. mobility
NCA	BEV	Zn	Primary
	Industrial excl. mobility	Other	Industrial excl. mobility

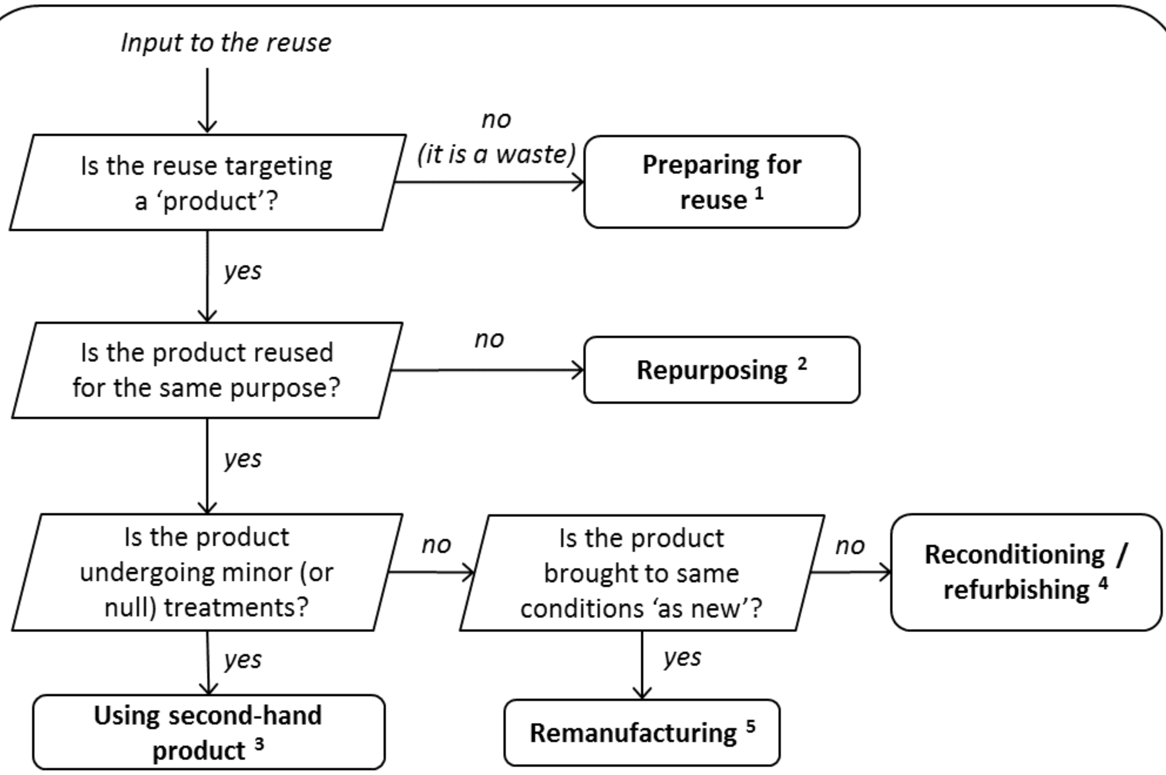
Full name	Abbr.	Chemistry
Rechargeable batteries		
Lithium Cobalt Oxide	LCO	$LiCoO_2$
Lithium Iron Phosphate	LFP	$LiFePO_4$
Lithium Manganese Oxide	LMO	$LiMn_2O_4$
Lithium Nickel Cobalt Aluminum Oxide	NCA	$LiNiCoAlO_2$
Lithium Nickel Manganese Cobalt Oxide	NMC	$LiNiMnCoO_2$
Lithium Titanate	LTO	$Li_4Ti_5O_{12}$
Nickel Cadmium	NiCd	NiCd
Nickel Metal Hydride	NiMH	NiMH
Lead Acid	PbA	$PbSO_4$
Primary batteries		
Lithium Thionyl chloride	LCF	$Li(CF)_x$
Lithium Sulfur Dioxide	LSO	$LiS0_2$
Lithium Thionyl Chloride	LTC	$LiSOCl_2$
Lithium Iron Disulfide	LFS	$LiFeS_2$
Lithium Manganese Oxide	LMO	$LiMn_2O_4$

The main advantage of the classification is that it allows flexible grouping and sorting of the underlying battery data. As an example, the main applications can also easily be grouped e.g. per chemistry instead of vice versa. See (22) for more details.

1.3.2 Terms and definitions

In particular for ‘reuse’, there are various terms and definitions used in academic literature, technical reports and in legislation. Different types for reuse, repurposing, refurbishing, remanufacturing, etc are often confused or used synonymously. The text box in Figure 4 taken from (23), explains the definitions used in this report:

Figure 4. Definition of relevant terms for operations alternative to recycling used in this report (23)



Definitions:

[1] **Preparing for reuse** "means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be reused […]" (EU, 2008).

[2] **Repurposing** means to "utilize a product or its components in a role that it was not originally designed to perform" (as the definition of "repurpose" by BSI (2009)).

[3] **Second-hand product** "shall mean tangible movable property that is suitable for further use as it is or after repair […]" (as the definition of "second-hand good" by European Council (2006)).

[4] **Reconditioning (or refurbishing)** means to "return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components" (as the definition of "recondition" by BSI (2009)).

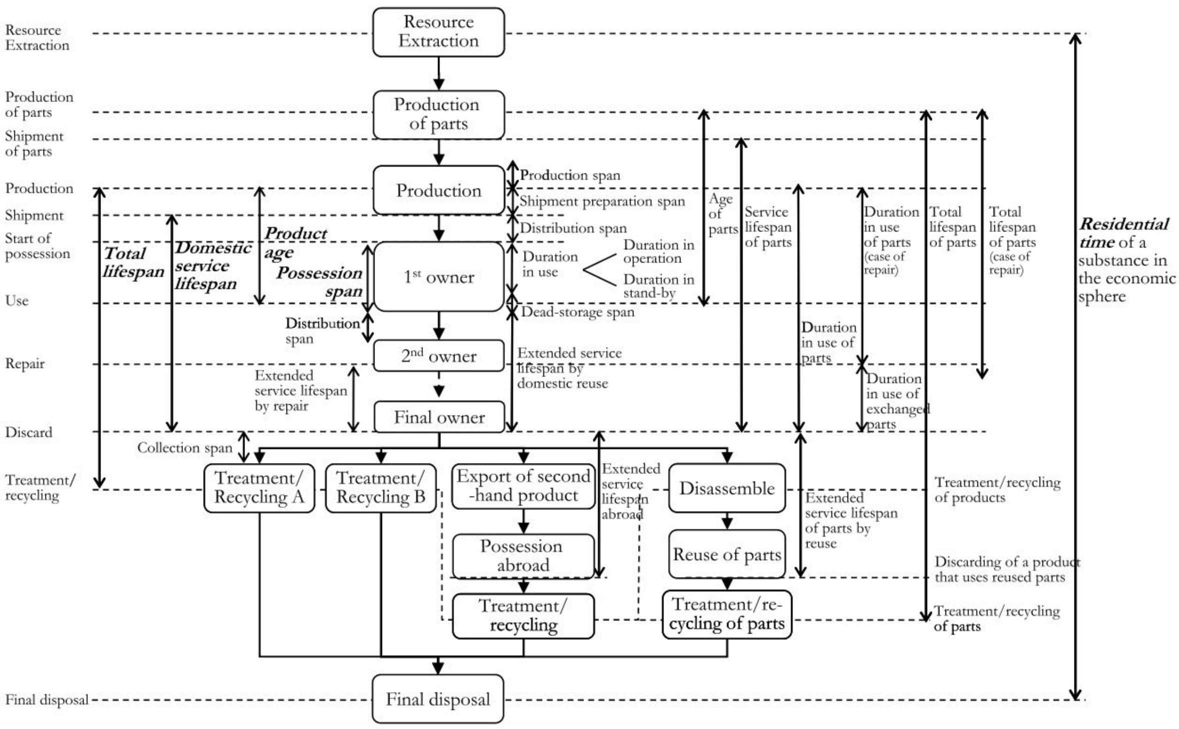
[5] **Remanufacturing** means to "return a used product [or component] to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product" (modified from the definition of "remanufacture" by BSI (2009), with the addition of the term within brackets).

1.3.3 Lifespan of products

In order to determine stocks of products in use or hibernated at households, businesses and public space, the lifespan, or better said, the residence time distribution needs to be understood. The residence time is the total time batteries remain in (subsequent first, second or third) use before being discarded as waste or shipped outside the EU territory which is used as the system border. Here, some initial information exists, but again retrieving and updating parameters for stock and flow modelling will require filling data gaps especially in understanding the potential of reuse and remanufacturing.

To have an overview of the difference between the different "life" terminology see Figure 5 below (24)

Figure 5. Definition of relevant terms for life used in this report (24)



1.3.4 Reuse and remanufacturing

A sustainability strategy to reduce the impacts of production per unit of time is to extend the lifespan of batteries in other applications. However, this may significantly delay the availability of materials to the recycling and cell manufacturing industry for the primary intended application, for instance when EV batteries are repurposed in Energy Storage Systems (ESS) with a significant additional life. Here, again limited information is available on the level this may occur. Few EV batteries have reached their first end of life making the economic feasibility of reuse and remanufacturing uncertain Technical challenges also exist especially linked with the absence of a standardised methodology for the State of Health (SoH) assessment of used Li-ion batteries.

1.3.5 Li-ion technology evolution, chemical composition and access to raw materials

The Li-ion technology has been on the market since several decades, but it is not yet a mature technology. Battery chemistries and design have evolved considerably, covering an increasing number of applications, thanks to intense R&I activities accompanied by huge industrial efforts to improve performance and reducing costs. More changes are expected in the coming years. For instance there is a clear trend in reducing the amount of the most expensive materials (e.g. Cobalt). These developments require a proper understanding and data availability to acquire representative time dependent data for battery compositions. This information will be essential for any analysis of potential raw material content stocked in batteries.

1.3.6 Past time series of products placed on market (POM)

Future secondary raw materials will come to a large extent from past market sales. Hence, (re-)constructing of the historic time series of battery sales is needed for periods where the majority of Li-batteries where found in very different applications compared to nowadays. Here, the report will provide an overview of what information is already available and what is still missing for these past sales. Additionally, most historic time series are based on product (containing a battery pack) units sold. This requires a conversion via compositions and average weights of the battery pack. Some of this work is executed in the ProSUM project (21) resulting in full time series for all battery types (also covering lead, zinc and nickel primary and rechargeable batteries) via the Urban Mine Platform (19) and other additional information is available to provide a more complete picture.

1.3.7 Collection rates and trade flows

The evaluation of stocks and waste generation in terms of volume and quantities of batteries, should include disposal in municipal solid waste, export of waste, export of batteries often embedded in used electronics and vehicles as well as all sorts of reuse and remanufacturing scenarios. However, in the majority of cases, proper mass balance data is not available. For reporting of battery waste collection performance only aggregated data is available for portable, automotive and industrial batteries on a Member State level, without details for the exact mix of chemistries and applications within these datasets. The ProSUM developed Urban Mine Platform, which provides the latest battery collection data as time series for the years 2010- 2015 for all member states and at the same time illustrates substantial data gaps in its datasets.

1.3.8 The unclear future Li-ion battery value chain

The assessment of the SRM potential passes through an estimation of the future flow of Li-ion batteries. However, the battery market is very dynamic, which is increasing uncertainty when analysing forecasts and projections on sales and penetration of Li-ion technology. The chosen tool for the assessment of SRM is the material flow analysis (MFA) methodology. This report will focus on the information that is missing or that needs to be improved to make the MFA model capable to produce reliable results.

1.4 Structure of this report

Chapter 2. In Chapter 2 the analysis will focus on the access to raw materials for Li-ion batteries at present. The resilience approach to criticality of raw materials is discussed in a circular economy context highlighting the relevance of recycling for the access to raw material (SRM) as an alternative to the PRM and the effect of substitution. An overview of the actual global Li-ion raw materials value chain is provided focusing on Lithium, Cobalt, Nickel and Natural graphite especially considering the EU situation.

Chapter 3. What is at the moment the availability of SRM? What are the issues that hinder the production and the access to SRM? The availability of SRM is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery that has been put on the market (POM) so far and on how much of it has been collected. The main difficulties encountered in this attempt are described considering the uncertainties of the available data. On top of it, the limits of the existing li-ion battery recycling processes and the EV battery second-use flow options are adding more uncertainty at the SRM value chain.

Chapter 4. In Chapter 4 future scenarios are considered. The MFA (Material Flow Analysis) model is presented as one of the possible tools for evaluating the availability of SRM in different timeframes. An overview of the main boundary conditions and uncertainties affecting the reliability of the model results is provided.

Chapter 5. In Chapter 5 the main conclusions are reported with an eye on policy implications and with indication on the necessary future works.

2 Overview on battery raw materials supply chains, criticality and resilience

The 6 segments of the simple representation of the Li-ion battery value chain of Figure 1 spanns from raw material mining to battery recycling. This traditional linear economy approach is still today mostly representing the usual business in the Li-ion battery value chain. Mining and chemical industries provide the myriad of raw and processed materials used in the production of the various cell components including the anode, cathode, electrolyte and separator. These components are then assembled in individual cells. Some materials are produced and used exclusively in Li-ion cell production while others can be used for other purposes. For the nature of this report, the focus will be in the first (Mining – Refining) and in the last (Recycling) segment of the value chain analysing how far is the closure of the loop.

A wide range of metals and minerals is used in Li-ion battery cells including lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), aluminium (Al), copper (Cu), silicon (Si), tin (Sn), titanium (Ti) and natural graphite (C). These are mainly derived from raw materials mined from the earth's crust, either from the surface or underground. This report will focus on the four most emblematic materials used in the Li-ion battery production: **Co, Li, Ni and natural graphite.** For each of those materials an **overview of their value chain** will be provided highlighting the **most emblematic facts relevant for the aim of this report**. Then a more in depth analysis of Co, Li and natural graphite supply chain will be performed especially focusing on its **criticality and resilience**.

2.1 Lithium-ion battery raw materials value chain and EU context

Key information gaps and issues

1. Resources and reserves data of PRM is always very uncertain due to variations in reporting methodologies, hence, the presented numbers should only be taken as indicative.
2. Trade data is generally not configured to capture individual material content in components and products. As a result, the data for consumption of the materials are often an under-estimate.
3. Cross-border movements of waste containing relevant raw materials from the EU are significant with possible negative balance (Nickel case)
4. Mineral production statistics are not consistent among various sources. Data providers rely on a wide range of sources including government departments, national statistical offices, specialist commodity authorities, company reports, etc (e.g. BGS, https://www.bgs.ac.uk/mineralsuk/statistics/worldStatistics.html)
5. Raw materials prices are volatile and its evolution is very difficult to predict. For some materials (e.g. graphite) transactions are largely based on direct negotiations between the buyer and seller.
6. Market actors for mining and processing activities are very dynamically changing
7. The unclear and not uniform regulatory context for mining in EU may be a limiting factor for attracting mining investments in the EU hindering domestic production
8. PRM EU domestic production is not nearly sufficient to meet the actual and forecasted LIBs EU industry demand.

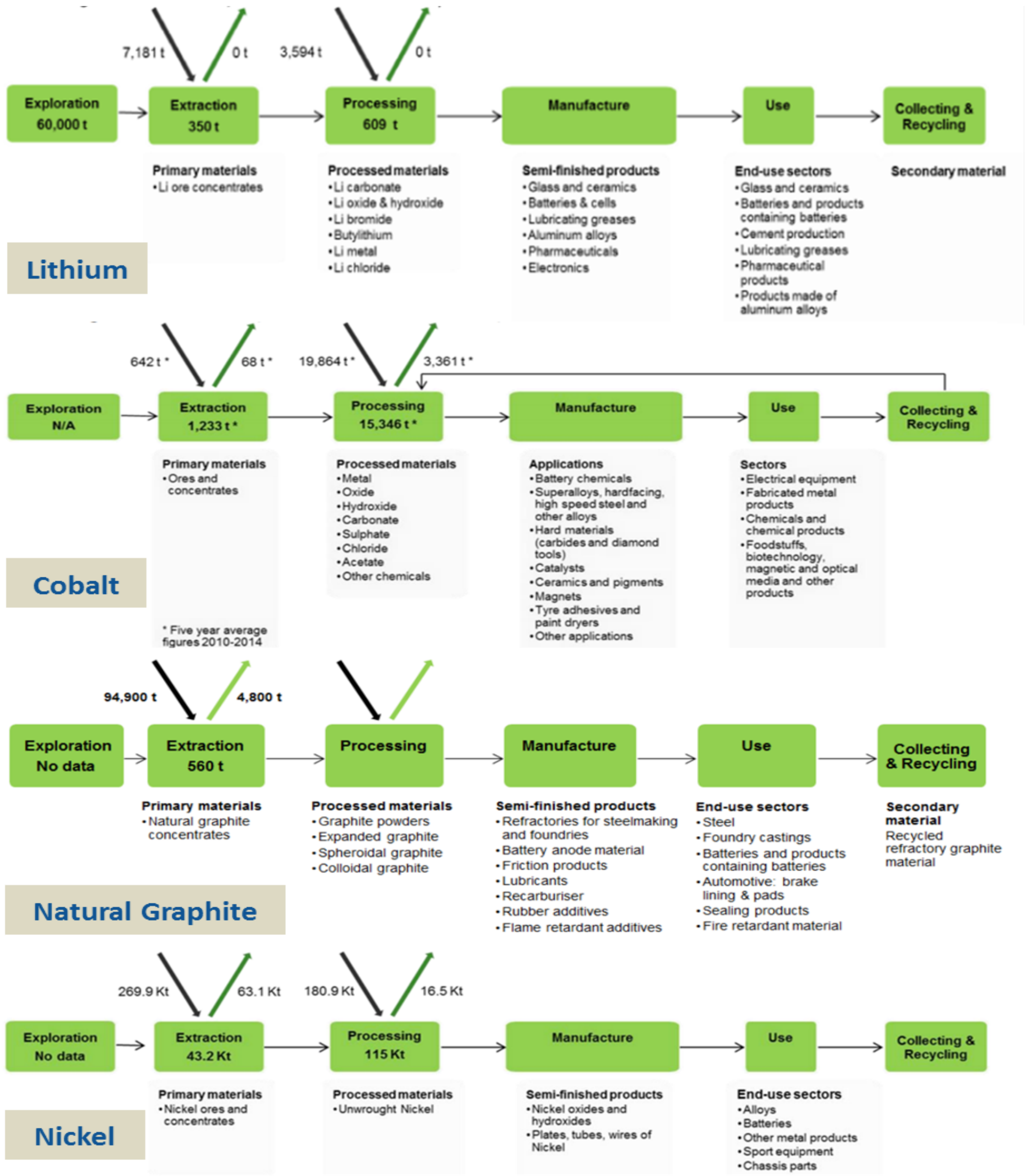
For each of the materials concerned the value chain includes exploration, extraction, processing, manufacture, use, collection and recycling. The following simplified schemes taken from (25) illustrate the steps involved, the types of primary and processed materials, products and end-use sectors. The amount of material which participates in European value chains is also identified, appearing as inputs and outputs in the different types of productive activity (Figure 6).

China and Europe overview - Box 1

China is leading the way in securing raw materials needs for its booming LIB manufacturing industry with top producers firms of cobalt, lithium and nickel (26) all Chinese. In Europe, despite mineral extraction and metal production potentials, the number of exploration projects are significantly lower than identified mineral deposits. Also, domestic production is not sufficient to meet overall demand (27). Europe is highly dependent on imports of raw materials (28) exposing inevitably its economy to potential supply disruption and prices rise and volatility (29).

The EU mining industry has no big players and is rather searching for overseas partnerships with Canadian, South American and Australian companies (30).

Figure 6. Simplified value chains for battery raw materials as presented in (25). Production and trade are five year average figures 2010-2014.



2.1.1 Lithium Value Chain

Some facts about Lithium - Box 2
According to the RMIS Raw Material profile (22): Lithium (chemical symbol Li, atomic number 3, alkali metal group) is a silver-white to grey metal. Lithium has excellent electrical conductivity and the highest electrochemical potential of all metals, which in combination with its low mass, makes lithium an ideal material for battery applications with an excellent energy-to-weight performance. Average lithium concentration in Earth's crust is estimated between 17-20 parts per million; at this abundance, lithium ranks about 30th among the elements. Lithium-bearing minerals are generally associated with granitic pegmatite deposits. Additionally, substantial lithium resources occur in brine deposits. These brines are formed in enclosed basins where inflowing surface and underground water with a medium content of dissolved solids from surrounding weathered rocks becomes mineral-rich due to evaporation at high ambient temperatures. Exploitable Li deposits of brines mainly occur in areas where arid climate and high evaporation has resulted in high lithium enrichment (0.04-0.15 % Li average grade); these deposits are usually associated with salt lakes or salt pans. Likewise, economically viable concentrations of lithium are found in geothermal and oilfield brines where lithium extraction has been demonstrated as a by- or co-product of existing operations, although not yet on a commercial scale.

EV market growth is propelling lithium demand and this is expected to remain the key driver for lithium market growth in the years ahead

As the demand for electronic equipment, EV and stationary batteries grows, there is a simultaneous increasing pressure for the supply of lithium. In addition to rechargeable batteries, a number of possible products and applications are recognised including glass and ceramics, lubricating greases, aluminium alloys and pharmaceuticals (Figure 7). Already in 2016 the largest demand for lithium was brought about by LIB battery manufacturing. It was estimated that this sector had a consumption of around 70 000 tonnes of lithium carbonate equivalent (LCE) representing approximately 35% of the lithium market (31,32).

Figure 7. Global lithium demand by market in 2016 (31).

As electric vehicles become more affordable and practical for consumers, the use of lithium in passenger EVs, for example, is expected to increase by almost 50 times between today and 2030 (33). However, pushing towards the electrification of road transport does bring about specific challenges to build up supply chain capacity.

Brines and hard rock mineral sources are the two sources for commercial lithium extraction

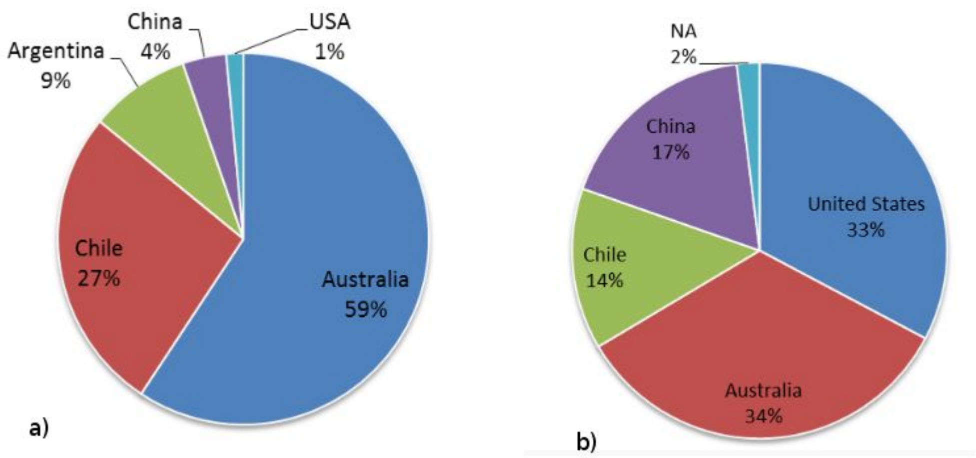
Brines as well as hard rock mineral sources are the main sources for commercial production. Lithium brine deposits have gained more interest in recent years, representing today around 40% of the overall production (34).

In 2017, 3 mines located in Australia and Chile accounted for 50% of the total production (Total production in 2017 was estimated to be 366.701 tonnes LCE) and 5 companies with headquarters in the US, Australia, Chile and China, were responsible for 74% of overall production (Figure 8) (34):

- Albemarle Corp. (US)
- Mineral Resources Ltd. (Australia)
- Sociedad Quimica y Minera (Chile)

- Chengdu Tianqi Industry Grp Co (China)
- Galaxy Resources Ltd. (Australia)

Figure 8. Lithium producing countries (a) and companies´ headquarters (b) in 2017 (34). Lithium producers depicted – regions and companies - are responsible for about 90% of global lithium production



EU production is residual in the global context and has been destined to the ceramic sector

In the EU about 782 tonnes Li_2O were produced in 2017 from Portugal (35). Such production represented approximately 1% of the global lithium market, but its output was entirely used for glass and ceramics where it is used as a flux in furnaces (36). Although establishment of domestic battery grade refining capacity is perceived essential to create new value chain opportunities, developing such activities has remained affected by challenging economics.

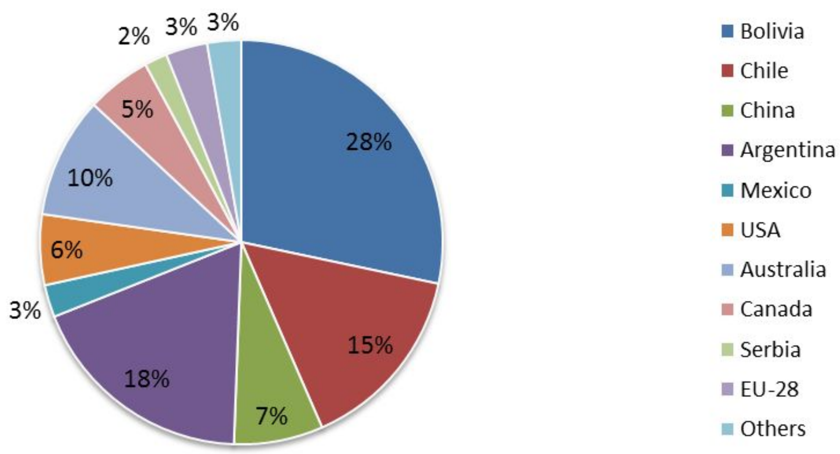
Lithium exploration is taking place in various EU MS

Lithium hard rock mining is especially widespread in Australia, but resources and reserves are also found in the EU, Canada and China (34).

In the EU, Cínovec (Czech Republic), at an advanced stage of development, is the largest lithium deposit in Europe with the potential to produce annually 20 800 tonnes/year of battery grade lithium carbonate on site. Mine start-up is expected in 2022 (34).

In 2017, 9 exploration projects were additionally ongoing in Spain, Germany, Finland, Portugal and Austria. Estimates for the amount of lithium resources and reserves in the EU represent around 3% of the global (137 824 030 tonnes of LCE) (Figure 9).

Figure 9. Lithium resources and reserves at mining and exploration projects by country in 2017 (34).



Demand for processed materials is split between lithium carbonate and hydroxide

Lithium is processed and sold in a number of forms. To be suitable for cell manufacturing lithium products must have a very high purity rate. Battery grade lithium carbonate (Li_2CO_3) is the most used lithium compound, although battery grade lithium hydroxide (LiOH) is being increasingly used, despite its higher price, as it enables achieving greater battery energy density and improved range of electric vehicles (37).

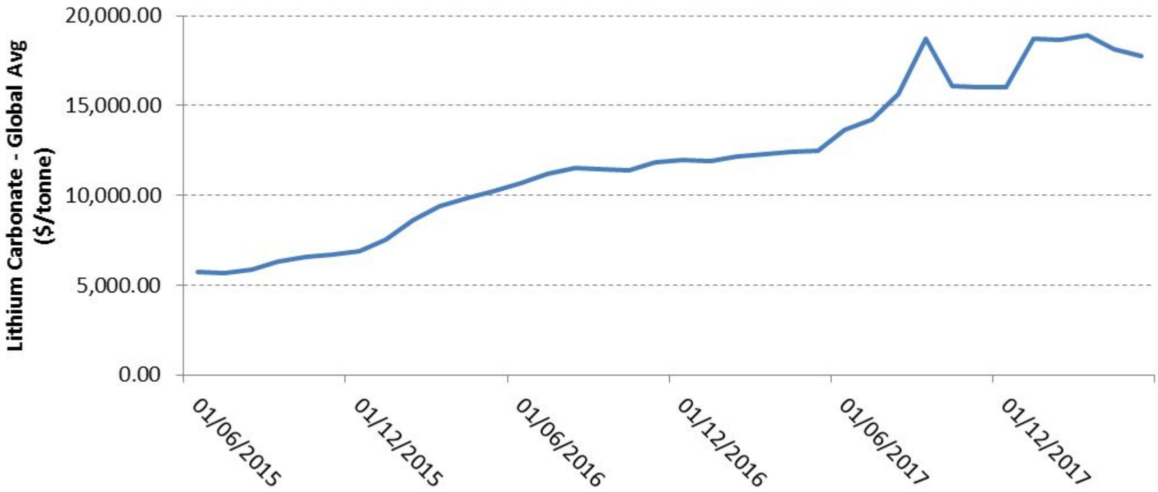
Lithium recycling is a critical aspect of the value chain but still needs to be developed

Currently, less than 1 % of lithium used in consumer products is recycled from various sources (38). However, there are significant economic drivers to support the development of an industry revolving around the recycling of lithium, in particular from EV batteries which may be easier to collect (10).

Between 2015 and 2018 there has been a 3-fold increase in the price of lithium

Between 2015 and 2018 the price of LCE tripled, from around 6000 $/tonne in 2015 to 18000 $/tonne in 2018, as shown in Figure 10. This increase was primarily driven by a growing demand in the manufacture of LIB, and triggered by forecasts anticipating potential lithium shortages in the future. Such a trend will also contribute to further deploy battery recycling.

Figure 10. Evolution of lithium prices between 2015 and 2018 (34).



2.1.2 Cobalt Value Chain

Some facts about Cobalt - Box 3
According to the RMIS Raw Material profile (22): Cobalt (chemical symbol Co, atomic number 27, transition metal group) is a shiny, silver-grey metal. It has two oxidation states (2+ and 3+) and one naturally occurring isotope (59Co). Cobalt melts at 1,495°C, its density is 8.85 gr/cm3 and has fairly low thermal and electrical conductivity. It is a hard (with a hardness of 5.0-5.5 on Moh's scale) and brittle metal, retaining its strength at high temperatures. Since cobalt is ferromagnetic, it can be magnetised and it keeps its magnetic properties at high temperatures up to 1,121°C. It is also able to form alloys with other metals imparting high-temperature strength and increasing wear-resistance to some. Being multivalent, Co enhances catalytic action. Cobalt is not found as a pure metal in nature but in conjunction with other elements (mainly Fe, Ni, Cu and S), and these are usually predominant. Cobalt compounds have an average concentration of 25 parts per million in the Earth's crust. Among common cobalt-bearing minerals are sulphides and arsenides such as cobaltite CoAsS, carrollite Cu(Co,Ni)2S4 and skutterudite (Co,Ni)As3-x. The majority of the world's cobalt production is associated with three types of ore deposits: sediment-hosted Cu-Co sulphides and oxides; magmatic Ni-Cu (-Co-PGE) sulphides; and Ni-Co laterites. Cobalt is mainly produced through recovery as a by-product of copper and nickel mining. Typical economic grades of cobalt ores vary from 0.05 % to 0.4 %. Globally, the United States Geological Survey estimates cobalt terrestrial resources to be approximately 25 million tonnes, the richest of them located in the

copper-cobalt deposits in the area commonly known as the central African Copper belt in the Democratic Republic of Congo and Zambia. Significant additional resources of cobalt, estimated at more than 120 million tonnes with grades in the range of 1 % to 2.5 %, are known to occur on the seafloor within Fe-Mn nodules and Fe-Mn cobalt-rich crusts which lie at water depths of as great as 6,000 meters. Up to now legal, economic, and technological barriers have prevented exploitation of these cobalt resources.

The rechargeable battery market is the largest and fastest growing for cobalt demand

While cobalt is still used in nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) batteries, over 90 % of current consumption in the battery industry is bound to the production of LIB (39). In 2015, rechargeable batteries accounted for 49 % of total cobalt consumption (90330 tonnes), while this usage represented around 28 % of total cobalt demand in 2010 (Figure 11).

The remaining end sectors consist of nickel alloys, including superalloys, which accounted for 18 % of total consumption in 2015, tool materials, catalysts, pigments and decolourisers, magnets, soaps and dryers and a number of other minor end-uses.

Figure 11. Cobalt demand by end-use in 2015 (39).

Because of the increasing penetration of electric vehicles (EVs) the worldwide demand for cobalt could potentially increase threefold within the next decade even assuming the future adoption of low-cobalt chemistries in EV-battery manufacturing (40).

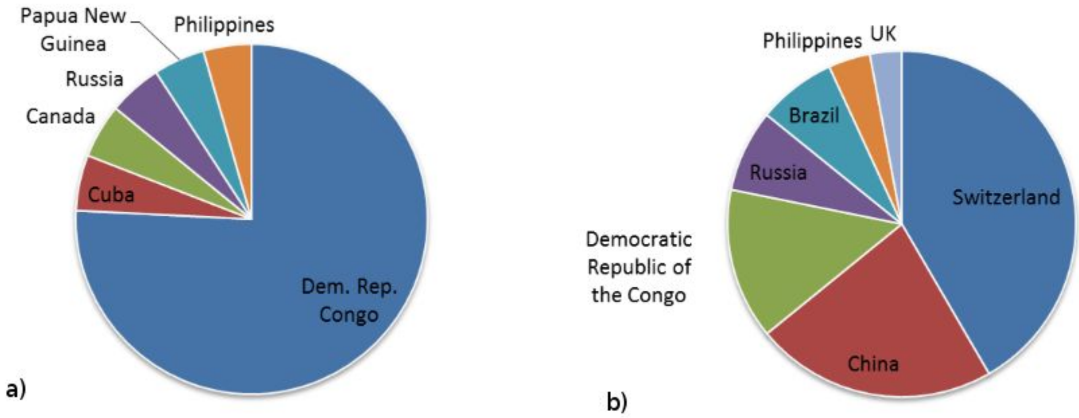
In 2017, 62% of cobalt mine production originated from the DRC

In 2017 cobalt mine production was estimated in 135.500 tonnes, 62% of which originated from the Democratic Republic of Congo (DRC) (35). 2 mines located in the DRC were responsible for around 35% of the total production (34).

5 companies with headquarters in Switzerland, China, DRC, Russia and Brazil were responsible for 50% of the global cobalt production (Figure 12):

- Glencore Plc
- China Molybdenum Co. Ltd.
- Gecamines S.A
- PJSC MMC Norilsk Nickel
- Vale S.A.

Figure 12. Cobalt producing countries (a) (responsible for 61% of global cobalt production) and headquarters of the top-10 companies (b) (65% of global cobalt production), in 2017 (34)



Unethical practices in DRC´s artisanal mining operations have been identified

In 2017 approximately 20 % of DRC's cobalt production comes from artisanal based operations (41), in which an unethical use of child labour has been identified (42). As analysts believe DRC will continue to be a main source of cobalt in the future, car makers and technology companies such as Apple, Microsoft and Tesla are looking to secure future cobalt supply sourcing ethically (40).

EU production of cobalt and refined cobalt is substantial but reliant on imports of ores and concentrates

In 2016, cobalt refinery production amounted to 98 000 tonnes (43). China is the largest producer of refined cobalt, accounting for 46 % of global production. In the EU, cobalt is refined in Finland (13 % of the global total), Belgium (6.5 %) and France (0.1 %) (43).

Production of cobalt ores and concentrates on the other hand was estimated at 2 300 tonnes in 2017 (35), all sourced from Finland (around 1.7 % of global primary cobalt supply). With relatively low levels of indigenous production, the EU is not self-sufficient as regards cobalt, and is highly dependent on imports. According to (25) 52% of EU-28 consumption is supplied by imports which mainly originate from Russia (91%) and the DRC (7%).

Cobalt use in EV batteries will be reduced in the future driven by substitution efforts

The future deployment of optimised battery chemistries will result in the partial replacement of cobalt in batteries triggering a reduction in demand. According to (40) until 2025, cobalt can be reduced by 17 %, and by another 12 % between 2025 and 2030, on account of changes in EV battery chemistries, towards a more widespread use of NMC 622 and NMC 811 cathodes.

While a more or less balanced market for cobalt is expected until 2025, projections show shortages beyond this point in time

Cobalt supply and demand projections until 2030 do not point to a relaxed situation especially after 2025. Beyond this point in time worldwide demand is expected to exceed supply in average scenarios considered for the deployment of EVs (40).

In the EU, cobalt resources have been identified in projects undergoing advanced exploration however many prospective areas have remained under-explored

Cobalt resources have been identified in projects undergoing advanced exploration and a significant number of projects at an early stage can additionally be found in various EU Member States. However while recent exploration has focused on some of the favourable regions, many prospective areas have remained under-explored and a large number of exploration projects appear to be currently inactive (40). The current regulatory context in which the right to mine is not ensured provided other conditions are met has been considered the main factor limiting mining investments in the EU.

Although cobalt has been historically recycled, LIB recycling is only just beginning

Cobalt is already widely recycled. According to (25) the % of Co in the waste flow that is actually recycled (also defined as end-of-life recycling rate (EOL-RR)) is estimated at 35 %.

In the battery sphere, cobalt is the material of most interest to LIB recyclers, and is currently mainly recovered from electronic waste. It is known however that, today, although the efficiency of the recovery process is high, the overall recycling rate is limited due to poor collection rates (11).

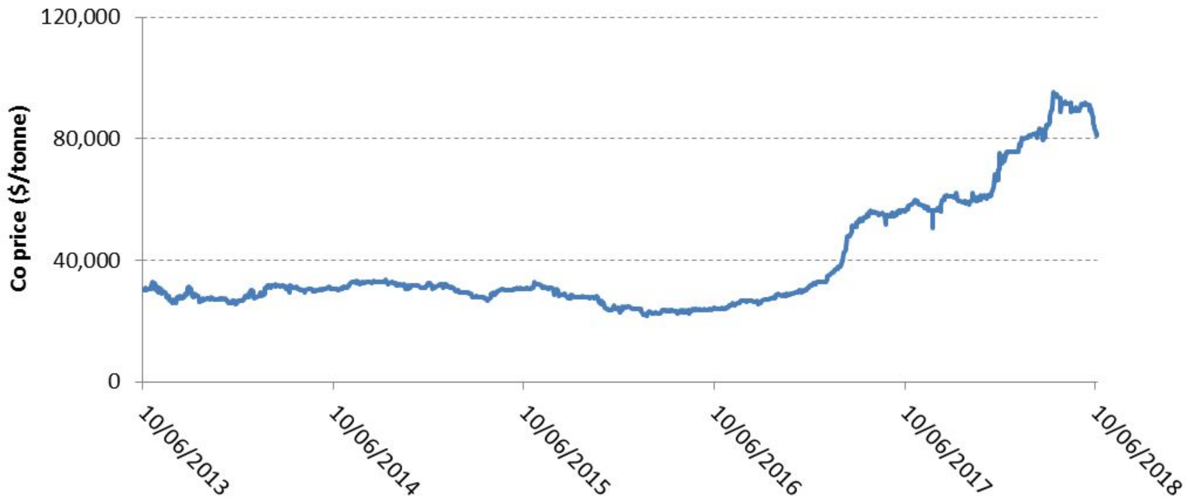
In turn, the recycling potential of EV batteries is significant as these batteries, due to their size, shall be subject to higher collection rates at the end of 1st life. However, given the recent introduction of EVs in global and European markets, large-scale recycling is not expected before 2020, and should only be more effectively realised beyond 2025 (10,40).

However, the declining use of cobalt in Li-ion chemistries may bring about specific challenges to recycling businesses which highlights the need to extend economic practicality of recycling to the other battery materials (10).

Cobalt prices reached peak levels in 2018

International cobalt prices have fluctuated significantly over the past decades. Although relatively stable since 2012, these nearly doubled on average to values around 56 000 $/tonne in 2017, reaching 81,500 $/tonne in June 2018 (Figure 13) (34).

Figure 13. Evolution of cobalt prices between 2013 and 2018 (34).



2.1.3 Nickel Value Chain

Some facts about Nickel - Box 4
According to the (44) Nickel (Ni, atomic number 28) is a silver white metal with typical metallic properties. In nature, it occurs mainly as isotopes of mass number 58 (68%) and 60 (26%). Further stable isotopes are of mass number 61, 62 and 64. Nickel alloys are characterised by strength, toughness and corrosion resistance over a wide temperature range. For instance, nickel-containing alloys played a key role in the development of materials for the aerospace industry and are essential to the iron and steel industry. Nickel deposits of economic importance occur in magmatic sulphides and laterites. Nickel concentrations of sulphide ores, which are the main source of mined nickel at present, range from 0.15% to around 8% nickel, but 93% of known deposits are in the range 0.2-2% nickel. The most important nickel sulphide mineral is pentlandite, which occurs mainly in iron- and magnesium-rich igneous rocks in Russia, South Africa, Canada and Australia. Lateritic ores, with an average nickel content of 1-1.6%, are formed by (sub-)tropical surface weathering. Their main nickel-bearing minerals

are garnierite and nickeliferous limonite, occurring in New Caledonia, Australia, the Philippines, Indonesia, Colombia and Greece.

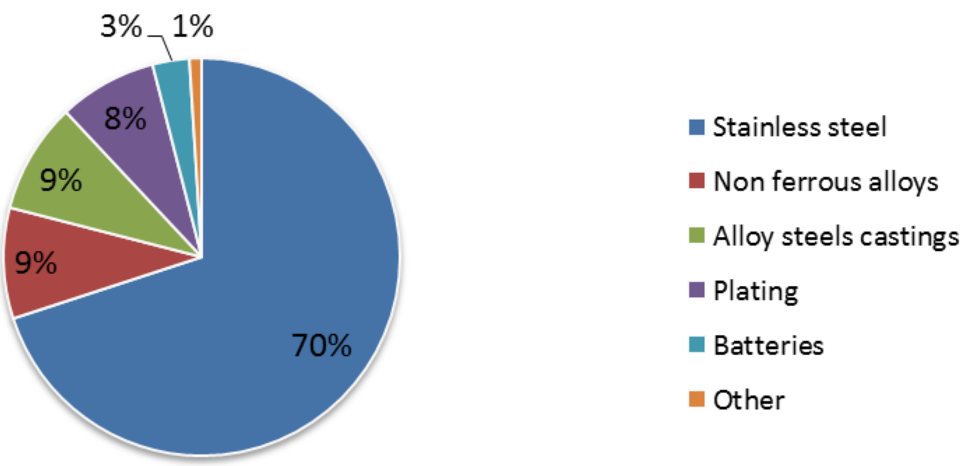
Today most Li-ion batteries rely on nickel which is expected to see a boom in demand as global automakers transition into producing electric vehicles

Nickel has long been used in mature battery rechargeable chemistries such as nickel metal-hydride (NiMH) and nickel-cadmium (NiCd) and was later incorporated in Li-ion batteries.

Today, most Li-ion batteries rely on nickel. Two of the most commonly-used types of batteries, Nickel Cobalt Aluminium (NCA) and Nickel Manganese Cobalt (NMC 111) use 50% and 20% nickel respectively of cathode powder weight (33). Additionally, newer formulations of NMC (NMC 811) are approaching 50% nickel (45).

Besides its application in batteries, nickel is used in the production of steels and alloys, plating, foundry, and a wide range of chemical processes (Figure 14).

Figure 14. Nickel applications (45).



Technology developments in the battery sector will likely reshape nickel demand as NCM and NCA cathodes are expected to become dominant technologies throughout the next decade. Having in mind that nickel will largely replace cobalt in battery applications, (33) estimates nickel demand in passenger EVs to increase 70 times between today and 2030.

According to (46), demand for nickel in lithium-ion batteries will soon make batteries the second-largest end-use application for nickel.

In 2017, nickel was produced in 92 mines around the world

Nickel production, contrary to cobalt for example, is not significantly geographically concentrated. According to (34), in 2017, nickel was produced in 92 mines around the world.

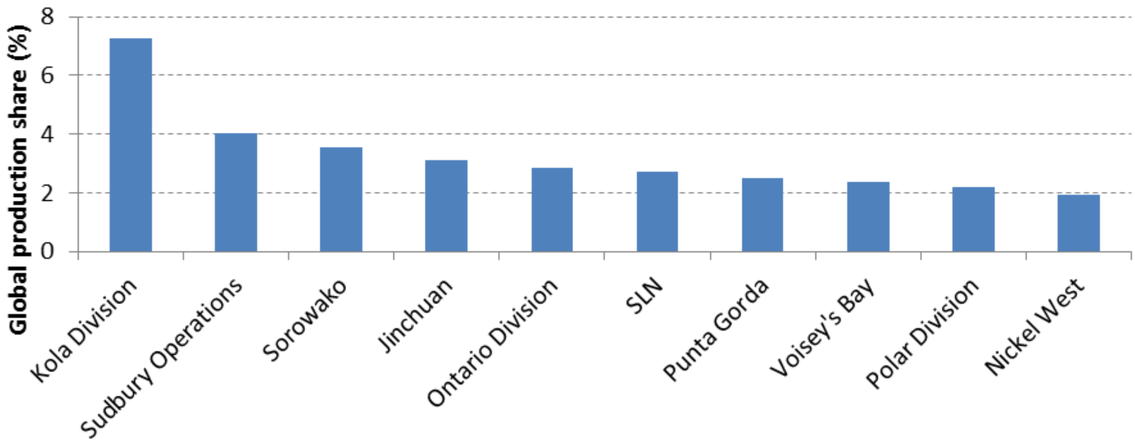
In 2017, nickel production amounted to around 2 million tonnes (35). Philippines and Indonesia accounted for 34 % of global mine output followed by Canada, New Caledonia and Russia (10% each). 10 mines were responsible for 32% of global nickel production (Figure 15) (34)[1].

That year, the EU produced approximately 56 000 tonnes at mines located in Finland, Greece and Poland (2.6% of the global output) (35) and refined 106 000 tonnes (5% of the global market) (47). Refining was undertaken in Finland, France, Austria and Greece.

[1] Estimates from S&P Global Market Intelligence however do not align with production totals from World Mining Data, due to a lack of reliable information for some countries.

With such production levels, it is estimated that the European import dependency for nickel refinery products is above 50%.

Figure 15. Top -10 nickel projects responsible for 32% of global production in 2017 (34).



Nickel resources are split between nickel sulphides and laterites with different processing requirements

Historically, nickel production has been dominated by sulphide ores, but this has shifted to laterites, which are more difficult to process requiring energy-intensive hydrometallurgical treatment (48).

Today sulphide deposits make up 38% of current production while nickel laterites account for 62% of current production (49).

The battery market requires nickel supplies in the form of a high-purity chemical product

The battery industry requires nickel sulphate which can be produced from a variety of feedstock material, such as crude nickel sulphate, briquettes, mixed sulphide precipitate, mixed hydroxide precipitate, carbonyl pellets and powder (46).

Today only 10% of nickel supply is in the form of sulphate suitable for use in batteries (49). Nevertheless, and despite the fact that efficient processing from low grade lateritic nickel ore is more challenging, the supply chain is already responding to the need for new nickel sulphate capacity, which according to (46) is rapidly being added in China.

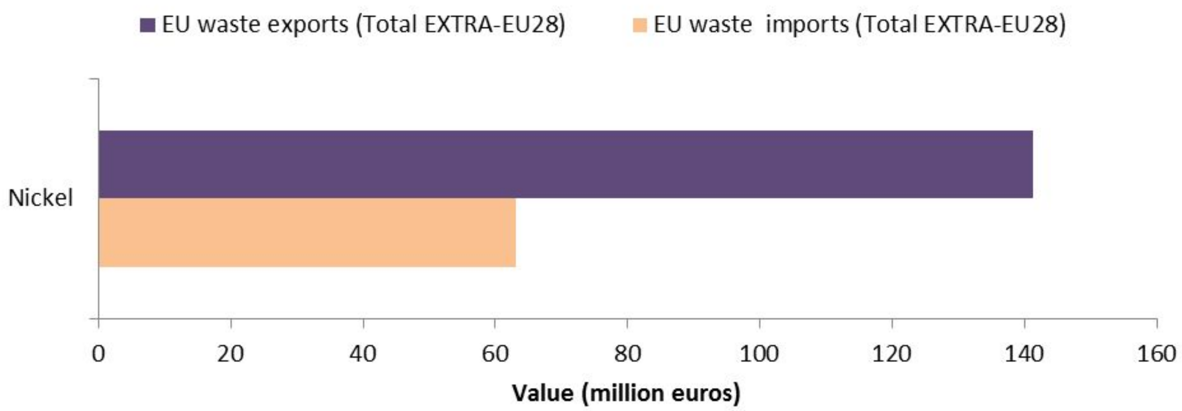
Nickel is fully recyclable but cross-border movements of waste from the EU are significant

Like many other metals, nickel is fully recyclable and most of its uses are not inherently dissipative (45,50).

In the EU, the end of life recycling input rate is estimated 34%, facilitated by dominant use of nickel as an alloying element which seems to facilitate waste collection and subsequent recycling (25). For that reason, nickel recycling has been undertaken directly by the steel industry (51).

While it is recognised that waste streams are important sources of nickel, with the potential to contribute to increase the security of supply and the circularity of the economy, today, cross-border movements of nickel waste from the EU are significant. In 2017 waste exports were significantly higher than imports both in terms of value and volume (52) (Figure 16).

Figure 16. Value of imports and exports of nickel waste materials in 2017 (52).



2.1.4 Graphite Value Chain

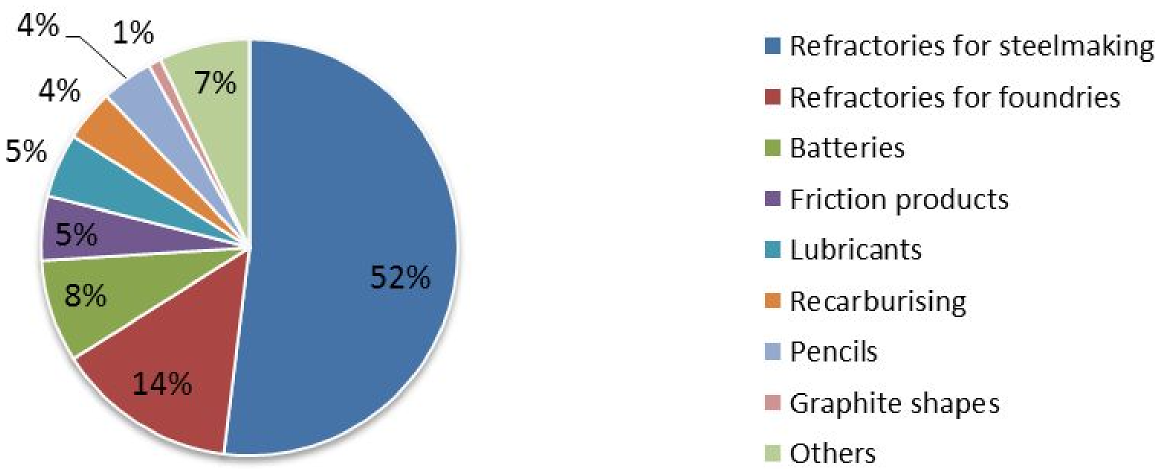
Some facts about Graphite - Box 5
According to the RMIS Raw Material profile (22): Carbon (C, atomic number 6) has a number of allotrope, graphite together with diamond and amorphous carbon (coal), and one of the forms of crystalline carbon. Because of its particular crystalline structure, it exhibits both metallic and non-metallic properties, which makes it one of the most versatile of non-metallic minerals used in many different industrial and technology applications. Graphite can be either mined (natural graphite) or synthetically manufactured from carbon precursors (e.g. petroleum coke) through a graphitising process at high temperatures (synthetic graphite). Graphite is the only non-metallic element that is an electrical and heat conductor. Natural graphite is not a homogeneous commodity. The end uses and associated commercial value are determined by the characteristics of the mined natural graphite and the subsequent processing of natural graphite concentrates. Besides amorphous and vein or lump graphite, flake graphite is coarse-grained crystalline graphite that consists of platelets of graphite layers (flakes). Flake graphite is of higher quality than amorphous carbon and has the broadest range of end uses. Commercial purity ranges from 85 % up to 97 % graphitic C. Flake graphite is marketed in different sized flakes (small, medium, large, jumbo), ranging between 40 μm and 1 cm in size (22). Due to its high electrical conductivity, inertness and reversible Li-ion intercalation between the basal planes of the crystal structure, flake graphite is a critical component of primary and rechargeable batteries, e.g. in cathodes of alkaline batteries as an additive, in anodes and cathodes of lead-acid batteries as an additive, in anodes of LIB as the main material.

In 2014, the battery market accounted for 8% of global natural graphite consumption and is projected to increase to 15% in the future

While the steel industry is the main driver for graphite demand, it is also used as anode material in lithium-ion batteries. In 2014, the battery market accounted for 8% of global natural graphite consumption (Figure 17) (25) and this is forecast to increase in the next years, on the back of maturing electric vehicle demand. By 2025, batteries can potentially make up 15% of global demand (53).

Projections of future graphite demand indicate an increase of nearly 50 times in the use of graphite for passenger EVs between 2017 and 2030 (33). In 2030, the demand for graphite in EV batteries will exceed current primary supply, by over 100%.

Figure 17. Global uses of natural graphite in 2014 (25)



Natural graphite is hardly produced in the EU

In 2017, production of graphite ore amounted to approximately 943 000 tonnes. China was the world leading supplier with approximately 71% of the global production, followed by Brazil which accounted for 9% (35).

Natural graphite production from the EU is very marginal. It is carried out in Austria and Germany but accounts for less than 0.1% of the global output (35).

With a very limited production and consumption of about 91,000 tonnes per year on average over the period 2010-2014, the EU fully relies on imports from third countries (25).

Both natural and synthetic forms of graphite can be used in lithium-ion batteries

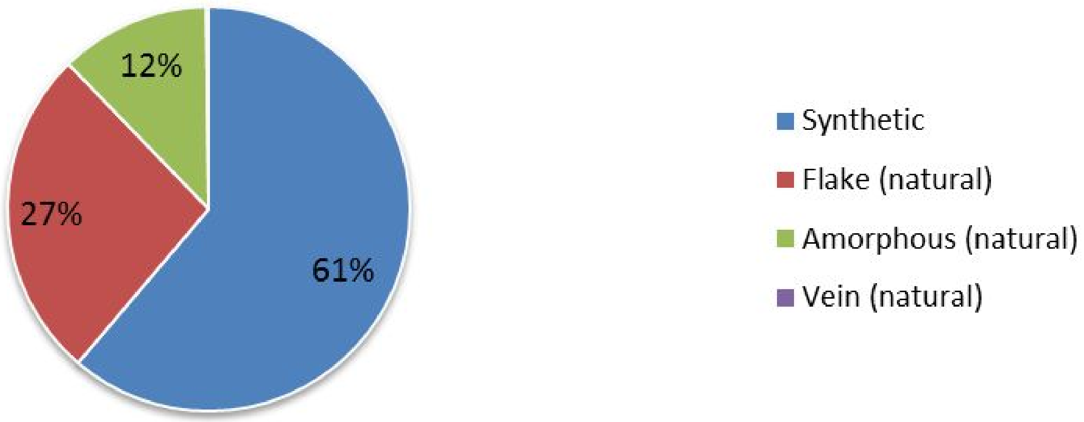
To be used in LIB, specialized graphite products with very strict quality requirements are needed. Battery-grade graphite is either produced from natural or synthetic forms.

Flake natural graphite is the precursor to the battery-grade quality for Li-ion anodes known as spherical graphite. Spherical graphite consists of high purity (> 99.95 % C and absence of metallic impurities) rounded particles with typical sizes in the range of 10-25 µm obtained from physically and chemically enhancing (micronizing, purifying, and rounding) flake graphite (25). This process increases the surface area and conductivity making it ideal for use in battery technologies (54). The spheroidal shape of the particles improves compaction and density within the battery compartment, which increases the energy and recharge capacity of the LIB (25,54).

Synthetic graphite on the other hand can be produced at a very high quality through artificially graphitising a carbon source (e.g petroleum coke). It is often used instead of natural graphite because of its very high carbon content, however synthetic graphite manufacturing is energy intensive and therefore entails a considerable cost.

In 2016 the global graphite market including natural and synthetic graphite was approximately 2.45 million tonnes. The largest portion of global demand was supplied by synthetic graphite which represented 61% (25,54) (Figure 18). Nevertheless, improvements in quality are helping natural graphite further entering high-end battery markets (55).

Figure 18. Global graphite market in 2016 (54).



Graphite use in EV batteries may be reduced in the future driven by substitution efforts

Silicon is a promising anode material to substitute graphite due to its higher specific capacity (almost 10-fold mAh/g), abundant availability and environmental friendliness. However, the huge volume expansion and the poor capacity retention over cycling are still significant drawbacks hindering the Si based anode LIB commercial applications (56). According to the (12) Si-based anode are expected to be available on the market around 2025 as Gen3b Li-ion battery technologies.

Whilst graphite anode materials are currently not recycled there are no obvious barriers to its recovery

In the EU, the end of life recycling input rate of graphite was estimated at 3% in 2012 (25). Besides some recycling of used refractory material, recycling of post-consumer products containing natural graphite has been inhibited by oversupply and low prices (25). Most LIB recycling processes have focused on the recovery of metallic ions while the carbon content of the batteries is either eliminated from the battery scrap by burning in furnaces or remains in after-filtration cakes as residue of the recycling process (57). Although the quality of secondary materials from battery wastes can vary substantially, from low performance to battery grade material, there are no obvious barriers to its recovery (10).

2.2 Li-ion battery criticality and resilience in the circular economy context

Key information gaps and issues:

9. Criticality of raw materials, i.e. likelihood of supply disruptions and the consequences, is by definition forward looking, though often estimated on average trends over recent past years. A resilience based approach should additionally anticipate future supply and demand balance mismatches and identify adequate mitigation strategies.
10. Recycling and substitution are key for both criticality and resilience, but it remains unclear up to which degree they provide a risk-mitigation filter in criticality, or are capable to enhance resilience to a satisfactory level.
11. Boosting of EU domestic production of relevant Li-ion battery materials is also key for mitigating their criticality and improving their resilience.

2.2.1 Criticality and the list of CRMs for the EU

Although all raw materials are important, as they are one of the basis of Europe's economy to ensure jobs and competitiveness, and they are essential for maintaining and improving quality of life, some of them are of more concern than others.

Securing a reliable, sustainable, and undistorted access to raw materials and their circular use in the economy is of growing concern within the EU (27,58) and globally. Recent years have seen a tremendous increase of the amount of materials extracted (59) and used together with a significant growth in the number of materials used in single products (product complexity). Global economic growth coupled with technological change (e.g., low-carbon energy and transportation systems, modern defence and communication systems) will increase the demand for many raw materials in the future (11,60).

"Criticality" combines the economic importance with the risk of supply disruption. In 2008 the U.S. National Research Council proposed a framework for evaluating material "criticality" based on a metal's[2] supply risk and the impact of a supply restriction (61). Since that time, a number of organizations worldwide have built upon that framework in various ways (58,62–68).

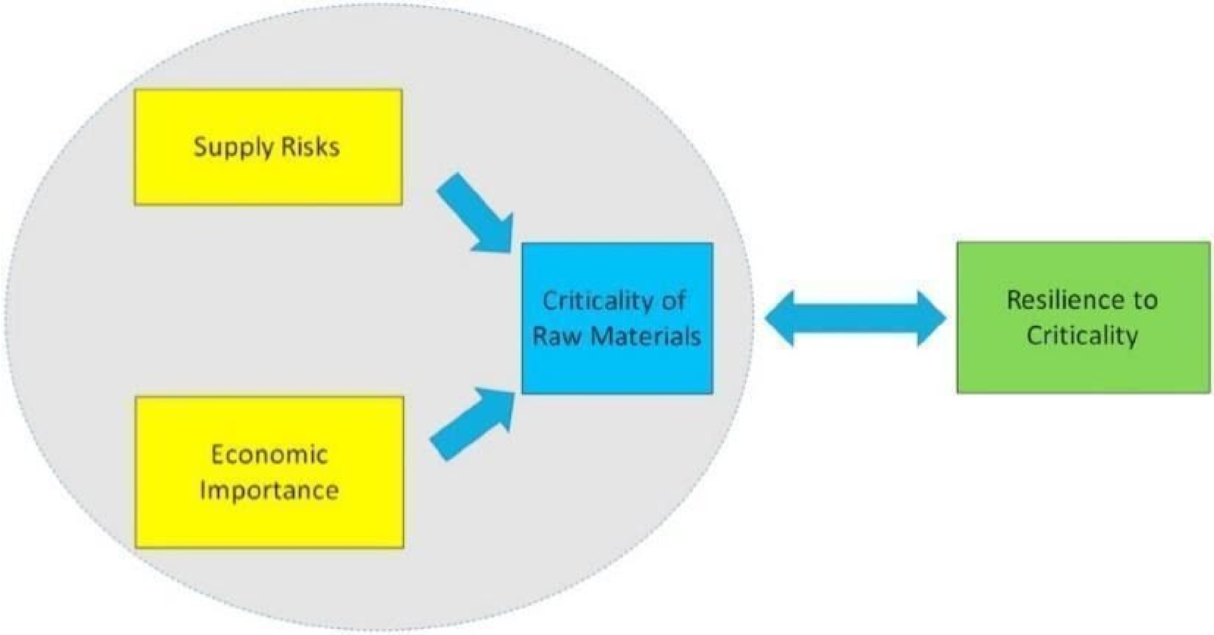
The list of critical raw materials (CRMs) for the EU, and the underlying European Commission (EC) criticality assessment methodology, are key instruments in the context of the EU raw materials policy (69).

The EU criticality assessment methodology was developed between April 2009 and June 2010 with the support of the European Commission's (EC) Ad-Hoc Working Group on Defining Critical Raw Materials (AHWG-CRM) within the Raw Material Initiative (RMI) in close cooperation with EU Member States (MS) and stakeholders (70). Such methodology was used twice; to create a list of 14 CRMs for the EU in 2011 (71) and an updated list of 20 CRMs in 2014 (72), then updated (73) and used to draw a list of 27 CRMs in 2017. The methodology is currently being used by the JRC to prepare the 2020 list of CRMs.

The clear separation between backward-looking and forward-looking approaches in the revision of the EC criticality methodology is particularly important. The revised EC criticality assessment methodology can be considered delivering a snapshot of the current situation, based on the recent past. Potential further analyses of future-orientated options, or forecasts, are not integrated. The sharp distinction between backward-looking and forward-looking approaches can also be presented in terms of the separation between criticality and resilience (74), where resilience is focused on the future response of the systems in the context of inadequate supply of a given material, the consequences, and options to reduce these (see Figure 19).

[2] Along this report metals, materials and minerals are used according to the relative reference (e.g. US focus was on metals in 2008. More recently (2018) it shifted also on non metal minerals. In the EU, focus is on raw materials: metals, industrial minerals, construction minerals, wood and wood-based)

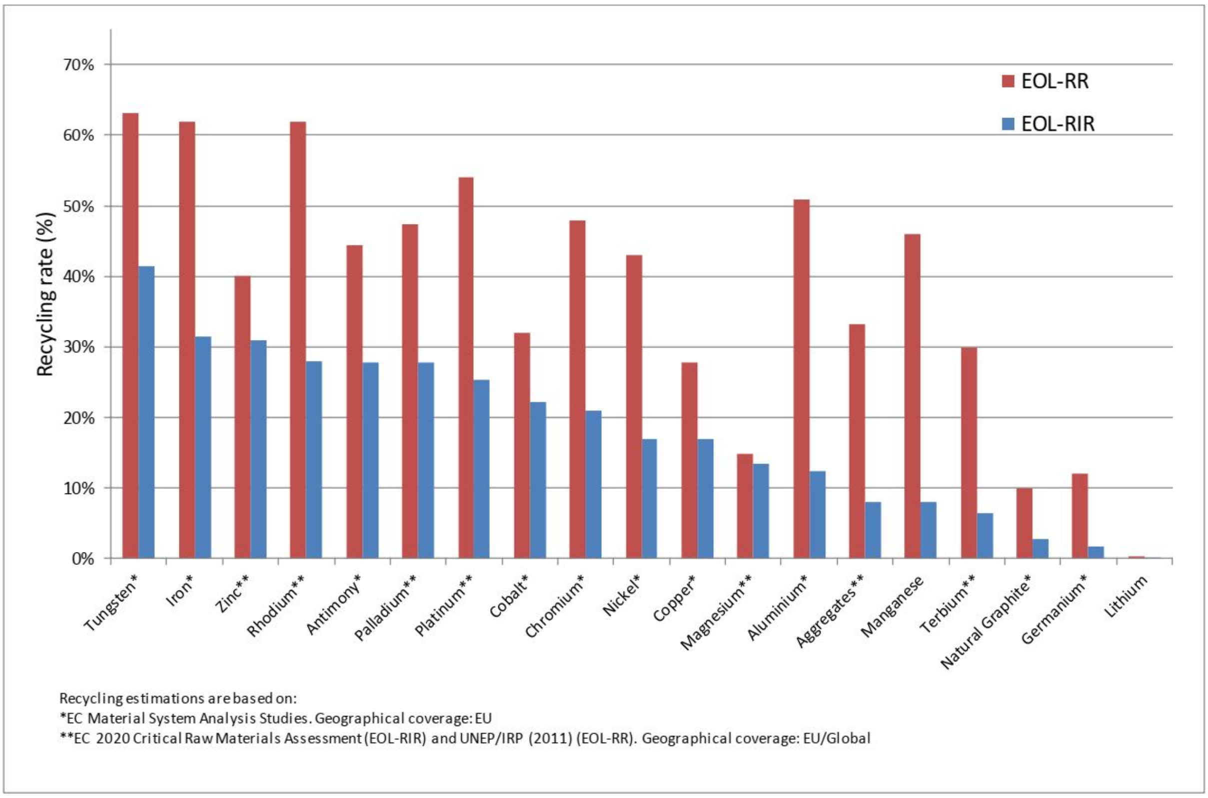
Figure 19. – Criticality vs resilience in the EC criticality assessment methodology (74)



2.2.2 Relevance of recycling in the list of CRMs for the EU

Recycling has a key role in the EC criticality assessment and the EU list. This is a rather unique feature, as recycling is often disregarded in criticality assessments outside the EU (74,75).

Figure 20. – Recycling rates and the List of CRMs for the EU



Recycling contributes to the security of supply of raw materials and helps improve the circularity of materials in the EU economy. It is seen as a risk-reducing filter in the EU Criticality Assessment (71,73,76,77) and in criticality frameworks used elsewhere (74).

The risk of supply disruptions, which is normally calculated based on supply concentration (HHI) and supplier country governance (WGI), is then filtered[3] by the end-of-life recycling input rate (**EOL-RIR**), which reflects how much of the total material input into the production system comes from recycling of post-consumer scrap (**input perspective**).As highlighted in the Raw Materials Scoreboard (27) and in the Circular Economy (CE) monitoring framework (10,78), the contribution of recycling to overall material inputs is generally low in the EU.

As shown in Figure 20[4], EOL-RIR (**input perspective**) can meaningfully be complemented by the information on end-of-life recycling rate (**EOL-RR**), which is the percentage of a material in waste flows that is actually recycled (**output perspective**). The two above recycling rates are obviously correlated, but, whereas EOL-RR indicates how much recycling of output flows is taking place, as a % of materials embedded in products at end-of-life, this does not necessarily correspond to an equal % contribution to meet demand for raw materials, which is measured by EOL-RIR.

The main factors that currently limit the contribution of recycling to partially meet demand for raw materials in the EU (27,78) can be summarised as: {1} demand for many materials is growing; {2} there is a lack of suitable technologies available for recycling; {3} recycling of many materials from end-of-life products and waste streams is currently not economically feasible; {4} some materials are embodied in products stocked in use for long time periods (e.g. buildings or wind turbines). .

For instance, in the case of lithium-ion battery, despite excellent performances in recycling industry in the EU, growing demand and growing stocks are likely limiting the contribution of recycling to meet demand and circularity in the next decade. As an illustration, a recent scientific paper quantifies how a new recovery option such as re-purposing of traction batteries in stationary application increases lifetime of batteries, hence increasing stocks of raw materials in society and eventually reducing the short term availability of secondary raw materials (79).

2.2.3 Different perspective on criticality

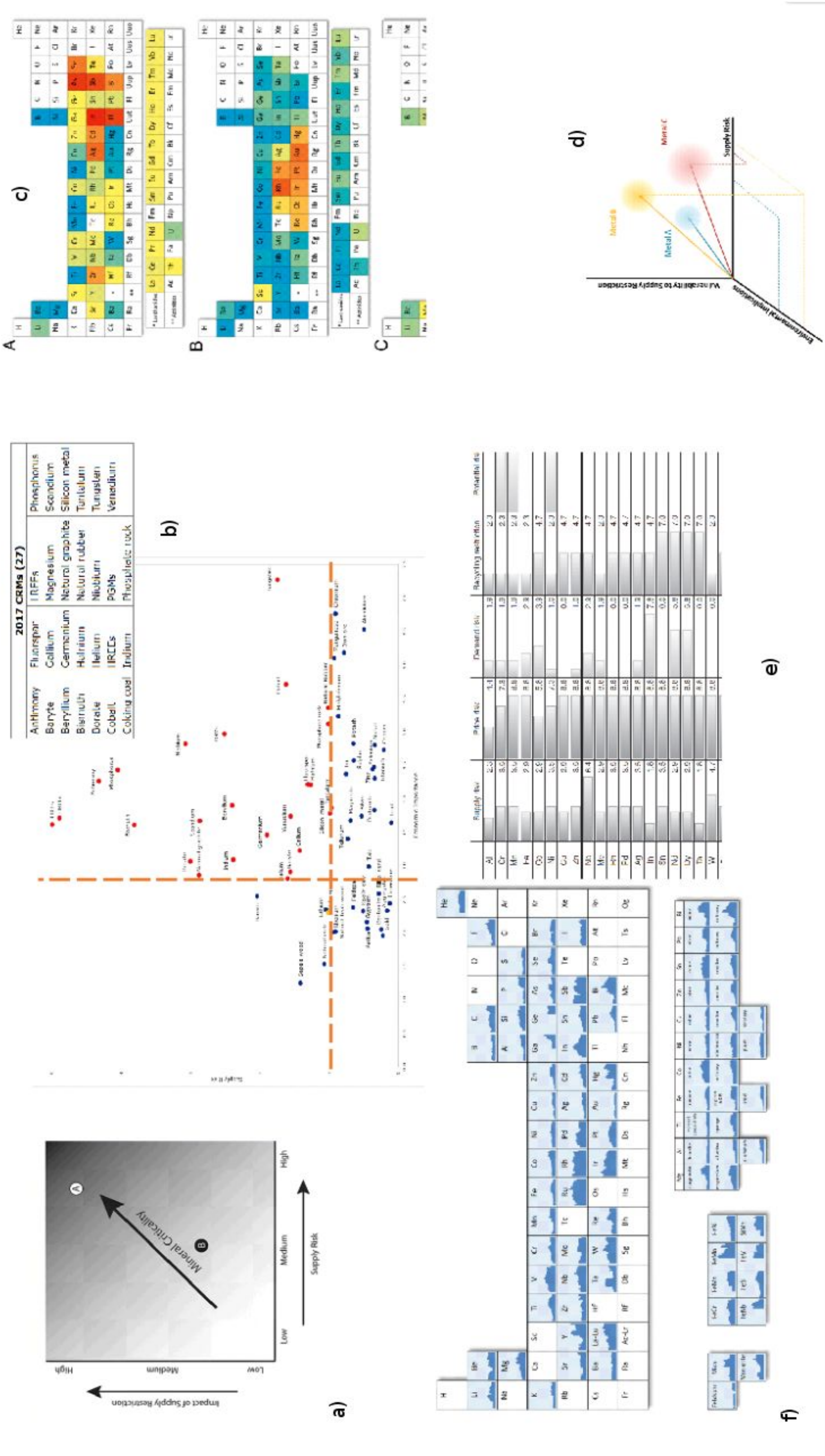
As Criticality heavily depends on who is asking the question, i.e. what is important, why or in which way there is a risk of supply disruption and what would be the consequences (80), it appears rather logical that not only the methodology is tailored to capture and combine the factors of relevance, but also the way in which the results are communicated, can be very stakeholder and user-specific.

Not that surprisingly, results presentation can take very different shapes (Figure 21).

[3] $SR = HHI_{WGI} \times (1\text{-EOL-RIR}) \times S_R$, where HHI=Herfindahl Hirschman Index; WGI = World Governance Indicator; EOL-RIR = end-of-life recycling input rate; S_R = Substitution Index

[4] Based on 2020 list of CRMs for the EU

Figure 21. – different perspectives on criticality (Clockwise): a) two-dimensional matrix of supply risk against impact of supply restriction (61); b) two-dimensional matrix of economic importance against supply risk with a threshold value for the establishment of a CRM list (732); c) relative scoring of raw materials for the dimensions of supply risk, environmental implications, and vulnerability to supply restriction (64); d) suggested presentation of a three-dimensional scoring using uncertainty ranges (64); e) raw material scoring per criticality indicator (82); f) evolution of criticality scoring over time (80)



A first important element is the use of the concept of critical vs non-critical raw material, based on which a list of CRMs can be drawn (71,72,76,81). The scientific community is generally less favourable to the adoption of a sharp on / off criticality criterion and more inclined to quantitative levels of criticality (30,33,51). The latter approach can also highlight that criticality is not an absolute status, but rather a relative condition (more / less critical than), as well as dynamic (criticality can come and go).

On their side, policymakers have historically shown a preference for sharp and simpler communication solutions (71,72,76), which are easier to understand for non experts and more practical to translate into effective policy actions at large scale. For instance, the EC adopted the two dimensions criticality matrix proposed in the 2008 NRC report (61) and adapted to the EU context alongside a list of CRMs presented in a rigorous alphabetical order to eliminate any references to critical levels, which is a specific policy need (73). The USGS generated a list of pre-critical materials for the US in 2018 (83).

A second macro distinction is that related to the level of detail of the assessment, which inevitably influences the communication of the results. As criticality assessment builds on a compromise between complexity (rigor) and simplicity (data available), sometimes criticality assessments end up in pre-screenings, which can be followed up with more detailed studies and assessments. The results of such criticality assessments should subsequently be regarded as a call for attention, not a source of 'panic' or the definitive word. It is in fact very unlikely that all aspects that could influence criticality can be squeezed into a screening methodology, while keeping the calculation equations short, simple, and objective (73).

The recent example of the early-warning screening of USGS (83) falls in the above category. USGS produced a list of potentially critical minerals for the US, to be followed by a second stage in-depth analysis. Another example is that of the EC, where single raw materials factsheets, with structured and detailed information and data, complement the 2011, 2014 and 2017 lists of CRMs for the EU. Raw materials factsheets show the data used in the assessment and bring further information and data that third parties might want to use in their ad hoc criticality studies (second stage).

A further interesting aspect is the level of aggregation of the criticality dimensions before communication. Several methodologies end up with a single criticality parameter. This is the case of the Yale methodology with the criticality vector (64), NEDO with the aggregated score (82) and USGS with criticality potential score (83). On the other hand, it is also acknowledged that, in applying the criticality assessment, understanding the respective components is more important than the aggregated results (82).

No aggregation is done in the EC methodology, where supply risk and economic importance are not merged at all, but need to simultaneously overcome a given threshold to reach the status of CRM.

Comparability with past exercises is often regarded as an essential asset (73,82), but only in a few cases trends are presented with sufficiently extended time horizons to be able to give also a function of early-warning (80).

Finally, it is rather logical that with such diverse approaches to criticality, also the role and the impact of recycling is very different. For instance, in the recently published list of 35 critical minerals for the US (83), recycling plays no role at all in determining what is critical and what is not. Very similarly, in the early-warning screening methodology set by the US National Science and Technology Council (80) there is no use of recycling indicators. On the contrary, Yale methodology (64) uses a recycling indicator as a mitigation factor of reserves/resources depletion, but the numerical impact on the final results of the criticality assessment is rather limited.

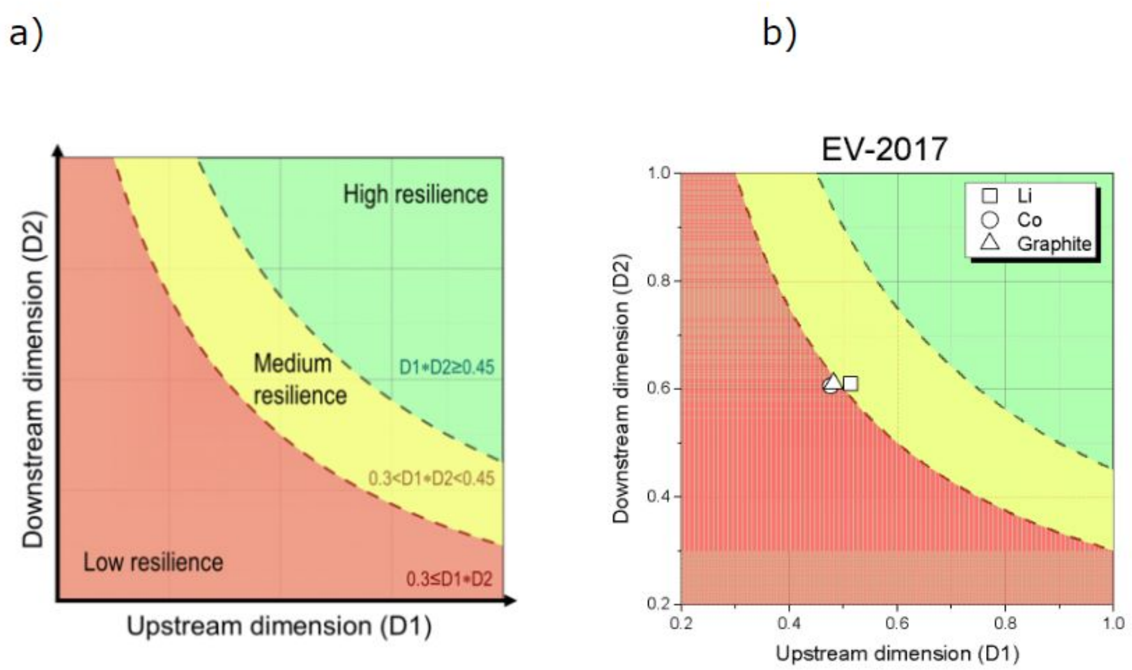
Though in a rather different manner, the role of recycling seems definitely more prominent in EU (73) and Japan (82) methodologies, as well as the impact on results. In the EC methodology recycling is implicitly considered riskless, and the selected recycling indicator is targeted on the current contribution of recycling to meet demand, so it is a risk-reducing factor. On the contrary, the NEDO methodology (82) strives to assess the risk that recycling cannot be deployed as a mitigation strategy, using a Recycling restriction parameter, based on techno-economic barriers to recycling.

2.2.4 Resilience

Quantification of **Resilience** in critical materials supply chain is a way to evaluate how vulnerable is a company, a sector or a country to potential constraints and supply disruptions along the whole supply chain. Hundreds of organisations and governments worldwide are dealing with criticality studies for different reasons, from raising awareness to forecasting purposes (73).

A recent JRC study (11) has evaluated the EU resilience along the materials supply chains for several technologies, including Li-ion batteries for electric mobility. The JRC in-house methodology relies on sets of indicators aggregated in two dimensions: upstream dimension (D1) provides an indication of EU secure and sustainable supply of raw materials, while downstream (D2) refers to the supply chain dependency beyond the raw materials step, namely supply of processed materials, components and final products. Dimensions are expected to evolve in time. The individual indicators range from 0 to 1 (critical to secure) and one can see for each material its position on a two-dimension graph (Figure 22) where constant product curves are used to define three different regions: green area (D1*D2 ≥ 0.45), the expectation is that no supply issues will be encountered along the supply chain; the middle yellow area (0.3 < D1*D2 < 0.45)[5] have a moderate likelihood of supply shortages; red area (D1*D2 ≤ 0.3) represent a high likelihood of supply shortages.

Figure 22. a) Resilience chart for materials b) Resilience chart for Li, Co and graphite used in EVs



Several mitigation measures have been proposed to alleviate supply risk along the whole supply chain. The methodology allows for a quantitative evaluation of the effect of each mitigation measure on the overall resilience.

Three materials were thoroughly assessed as potential bottlenecks for the deployment of Li-ion type batteries, namely **lithium**, **cobalt** and **graphite**. Current EU resilience to potential bottlenecks in the supply of lithium is assessed as medium; graphite is on the border line between low- and medium-resilience zones while cobalt is the red area of low resilience (The EU resilience to potential bottlenecks in the supply of materials is expected to evolve until 2030, driven by a number of factors. Besides growth in demand and expected evolution of supply actors over time, with variable impacts on the stability of the supply of both raw and processed materials, these factors encompass developments in recycling[6] (e.g. advanced methods to increase recovery rates or policy measures to increase collection rates) and substitution[7], as well as increase in the EU mine production[8]. The last three factors can contribute to increasing the EU resilience to supply of materials along the upstream dimension.

Lithium (Li)

The EU resilience of supply of all three materials will deteriorate until 2030 if no mitigation measures are undertaken at EU level (Figure 23). The performed analysis revealed that the EU resilience could be improved mainly by boosting the EU primary lithium production as well as, to a certain extent, by recycling, while no

[5] The threshold values (0.3 and 0.45) separating the various zones in the resilience chart are selected according to a given logic, reflecting also up-to-date common knowledge and well based assumptions.
[6] Developments in recycling could include different measures such as development of advanced recycling technics, allowing achieving higher recovery rates, policy measures to increase collection rates of end-of-life products among others.
[7] Substitution has different aspects: substitution at materials level (replacement of one materials with another material) or substitution at technological level (replacement of a component or a technology itself which serve the same purpose).
[8] In terms of ramping-up the production of the existing mines or opening new mines in order to increase the volumes of raw materials supplied within the EU.

significant impact from substitution of lithium is expected within the 2030 time frame. It is important to streamline policies and incentives supporting these mitigation measures to jointly cope with a higher demand for lithium in the future and the growing pile of batteries considered as waste. In the longer term – beyond 2030 – substitution might also play a substantial role for lithium. Therefore, supporting R&D activities in this direction is desirable.

Graphite (C)

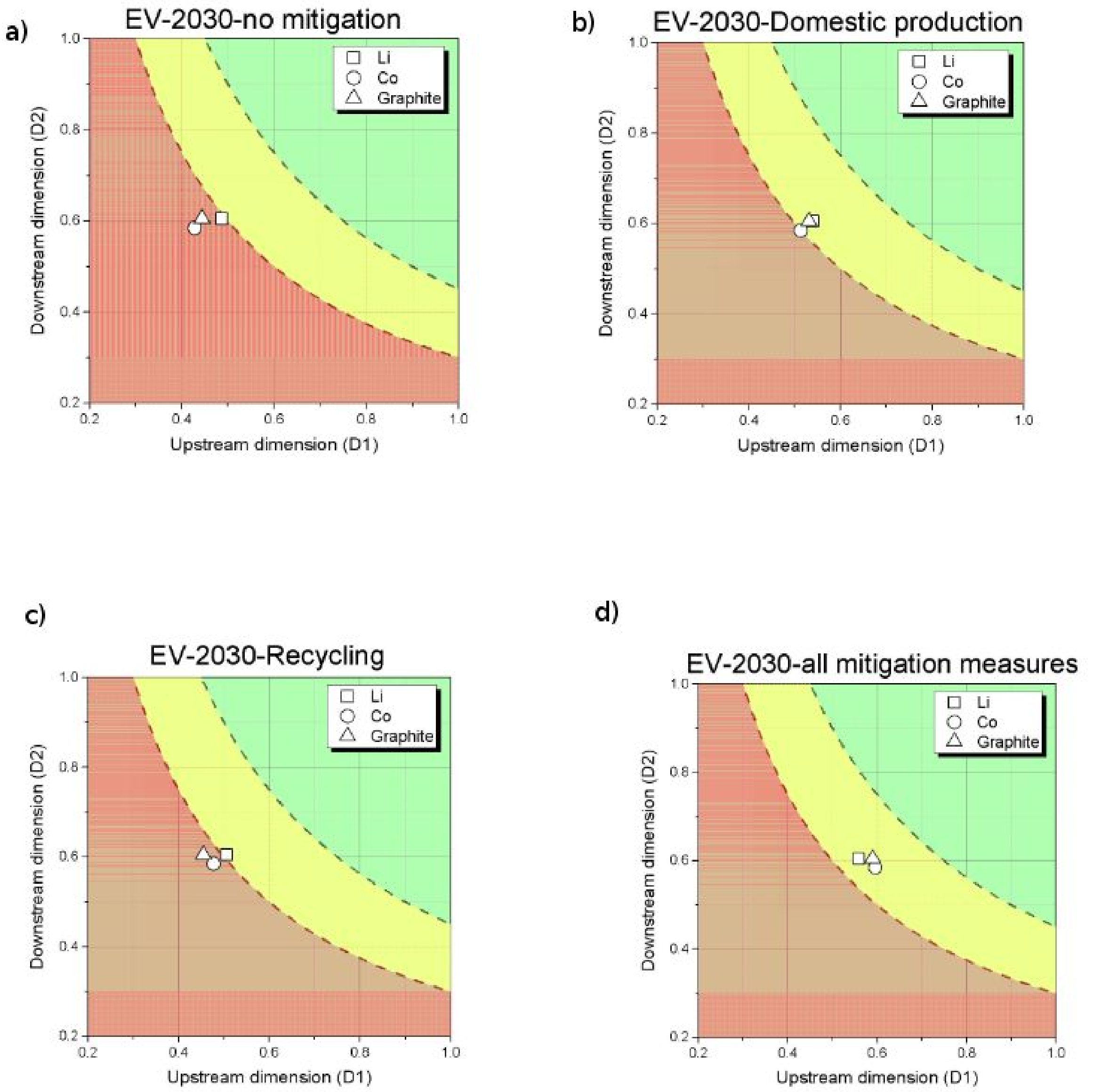
The EU resilience to supply of graphite (C) is low and is expected to deteriorate gradually until 2030 unless mitigation measures are put in place, in particular increase in domestic production, which have the potential to bring the resilience to the medium level (yellow area). Recycling has the potential to increase the EU resilience though not enough to reach medium yellow zone if applied alone. Substitution could further improve the situation by 2030. However, even applying all three mitigation measures, it will still not be enough to move the graphite to the "secure" green area of high resilience due to the expected substantial increase in demand for electric cars by 2030.

Cobalt (Co)

As for lithium and graphite, the EU resilience to the supply of cobalt is expected to deteriorate by 2030, remaining in the low-resilience zone if no mitigation measures are adopted and the most tangible mitigation measure for the given timeframe appears to be increasing the production of cobalt within the EU, followed by recycling. To be noted that recycling alone will not be able to move cobalt to the medium resilience area, due to rapidly increasing demand. In 2030, recycling of EV batteries deployed in the EU may provide for around 10% of the European consumption of cobalt in the EVs sector. To perform the analysis, minimum collection targets of 90% for BEV and 50% for PHEV and efficiency targets of 80% for auto batteries is assumed to be achieved in the EU. Future cobalt EU mine production can provide for around 6% of the European cobalt consumption in the EV sector in 2030[9]. In the EU the current mining infrastructure is limited, despite the high potential for its development. However with proper investments the amounts potentially produced can be even higher in the relevant timeframe.

[9] P. Alves Dias, D.T. Blagoeva, C.C. Pavel and N. Arvanitidis, 'Cobalt: demand-supply balances in the transition to electric mobility', 2018, to be published soon.

Figure 23. Resilience chart for Li, Co and graphite in 2030 for the case of: a) no mitigation measures undertaken at EU level; b) boosting the EU production; c) incentivising the recycling and d) applying all mitigation measures



Final remarks on resilience

If no mitigation measures are undertaken at EU level, the EU resilience will remain or become low for lithium, cobalt and graphite, required in batteries. Mitigation measures such as ramping-up the EU mine production, boosting of recycling and developing alternative materials (or design) could significantly improve the EU resilience though not sufficiently to reach high resilience level by 2030. To be noted that only passengers electric cars are considered for the assessment of the demand. The demand will be even higher if other vehicles such as busses, vans, 2-wheelers etc. are taken into account. Batteries for stationary storage will also add up to the demand figures in 2030.

This implies that strengthening the upstream supply of raw materials, including recycling and substitution, is necessary and very important but not sufficient condition to reach high level of resilience. The limited and not always coherent data related to future development of downstream capacities in the EU and globally is restricting the potential of the D2 dimension to affect the overall resilience, resulting in no- or very limited change along the D2 dimension. However, it is obvious that building and boosting manufacturing capacities along the whole supply chain (downstream dimension), in parallel with the upstream mitigation measures, is crucial to assure high EU resilience for Li-ion batteries deployment in the 2030 timeframe.

3 Time series for placed on market (POM) - Lifespans - Collection rates and trade flows - Recycling - Reuse and repurposing

The availability of SRM is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery that has been put on the market (POM) so far and on how much of it has been collected. The main difficulties encountered in this attempt are described considering the uncertainties of the available data. On top of it, the limits of the existing li-ion battery recycling processes and the EV battery second-use flow options are adding more uncertainty at the SRM value chain.

3.1 Evolution of battery market and time series for batteries placed on market (POM)

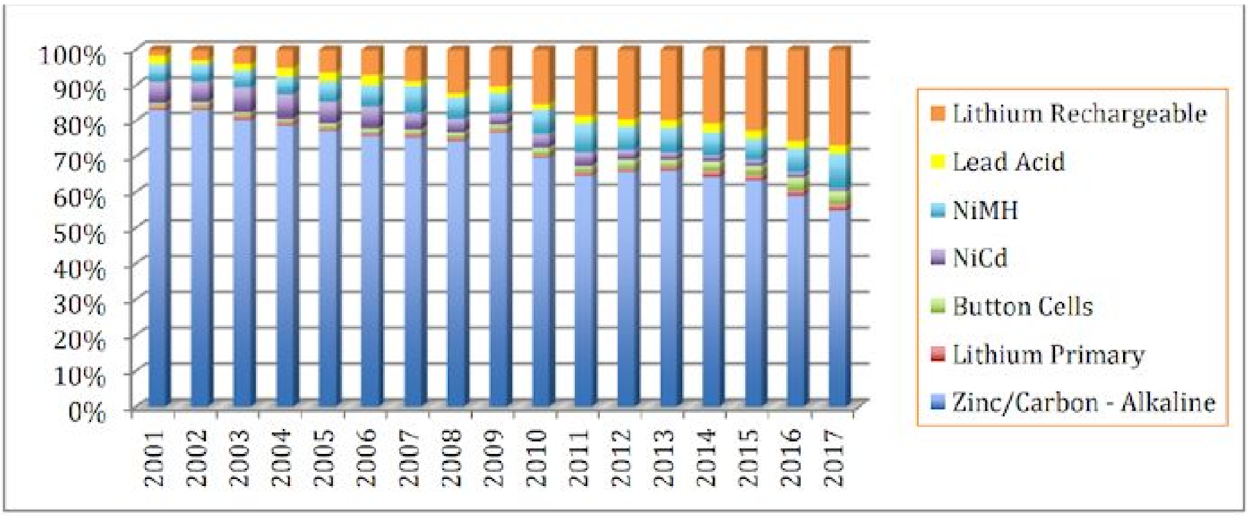
Key information gaps and issues:

12. Historic time series for battery volumes entering and leaving the market are predominantly based on industry sources. Member States are underreporting market inputs under the Battery Directive in particular for Industrial batteries.
13. A consistent use of a more detailed battery classification allows bridging between different official and non-official sources. This enables harmonisation, improving characterisation of the raw material content and ultimately the monitoring of collection and recycling performances (see Section 1.3.1).
14. Specific data on time-dependent chemistries is rather scarce or with high uncertainties. The conversion of units to weight and compositions introduces relatively large uncertainties in the materials stocks and flows information.

From the beginning of the years 2000' the battery market has evolved changing notably both in terms of number and weight of sale units, and chemistry and technology of battery POM.

In the first decade of 2000' the market evolution was prevalently attained at the portable batteries market. See for instance the evolution and the dramatic increase of portable rechargeable lithium batteries market share in the total portable battery mix from 2001 to 2017 (Figure 24) (84).

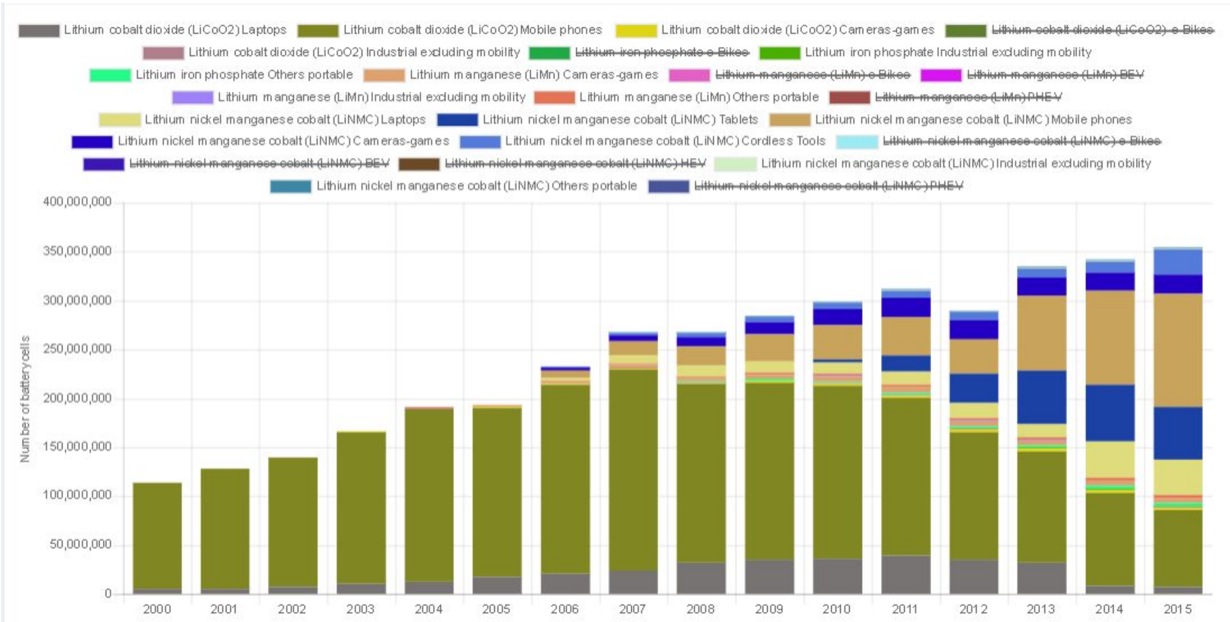
Figure 24. Evolution Portable Battery Mix POM (84).



In 2017, the ProSUM project published a complete inventory of the raw material content in batteries as well as electronics and vehicles, including time series for market inputs, stocks of in-use products and waste generation volumes at the www.urbanmineplatform.eu (21). The sales of batteries have increased significantly over the years especially in number of units (packs) sold.

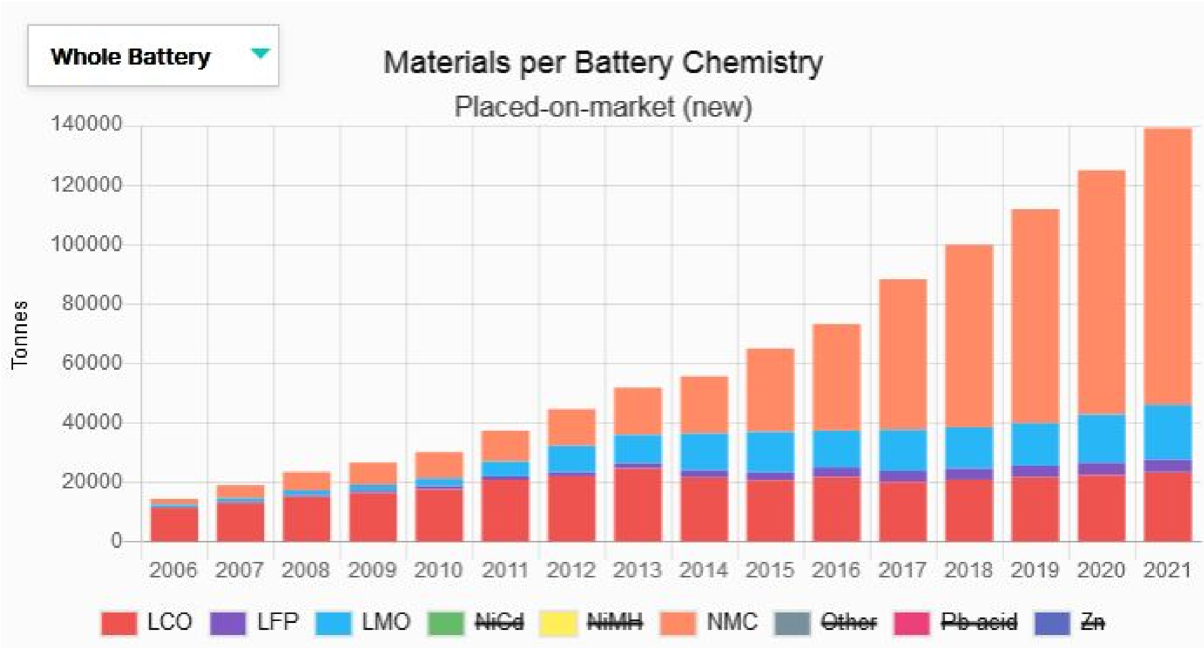
When excluding mobility applications, the use of rechargeable lithium-ion batteries in units sold has increased from over 100 million units in 2000, predominantly LCO, towards 350 million units in 2015 with a mix of different chemistries of which NMC having the largest growth over the last years as demonstrated in Figure 25 based on the ProSUM data until 2015 (21). This dataset has a high level of detail including all relevant chemistries for each application.

Figure 25. Market input of rechargeable lithium-ion batteries (excluding mobility) in units 2000 – 2015 (21).



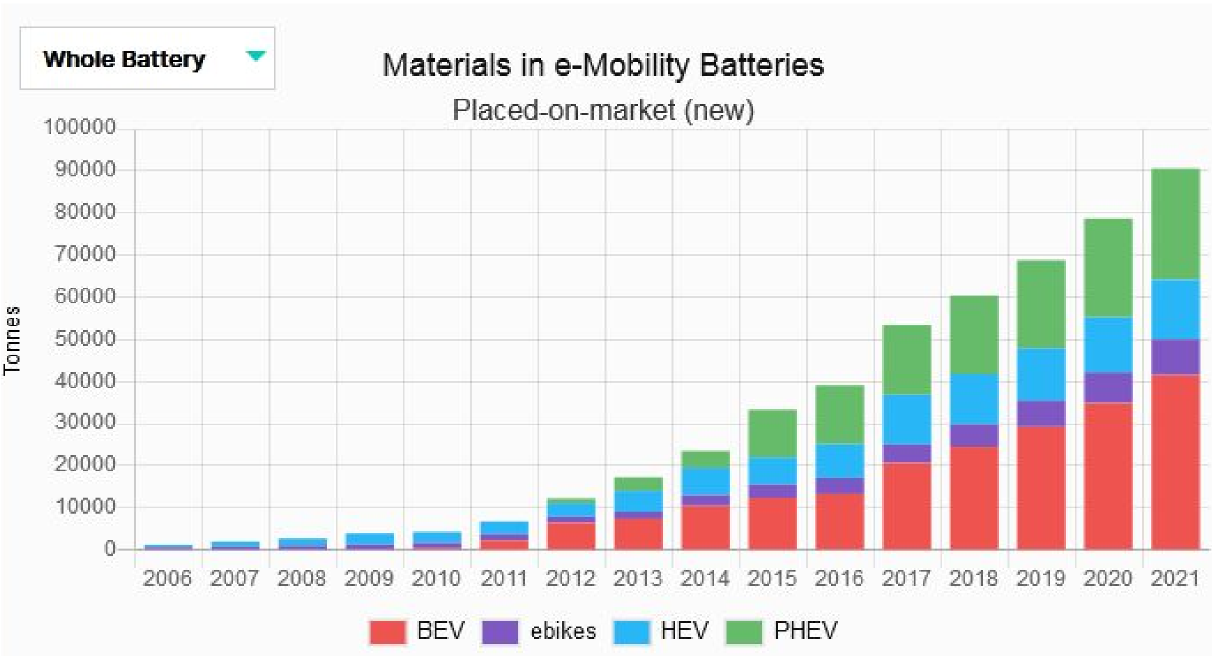
In 2019, Technische Universität Berlin and Recharge, commissioned by the JRC, reviewed, updated and consolidated data on secondary raw materials from batteries. The datasets included in RMIS (85) cover the years 2000–2016 and provide extrapolated trends up to 2021 for EU-27, UK, Switzerland and Norway, based on observed trends, market information and expert interviews. These data are the most recent update on the battery information provided by the ProSUM project and is aggregated at EU level by batteries weight. Figure 26 shows the data for all LIB batteries in tonnes for the EU-27, UK, Switzerland and Norway for the years 2006–2021 (85). The data from 2018 to 2021 are forecast. Apart from the active materials, other materials and components, such as electrolytes, packaging and the battery management system, are included in the total weight. The chart indicates recent changes at the chemistry level. LCO batteries are quickly losing market share to LMO and NMC batteries in particular. At the same time, in portable applications, LCO remains in use.

Figure 26. Market input of rechargeable lithium-ion batteries (all types) in weight 2006 – 2021 per chemistry (85)



The total amounts placed on the market per xEV drivetrain – hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) – are shown in Figure 27. Apart from Li-ion batteries, nickel-metal hydride (NiMH) batteries still play a role in HEVs and PHEVs. Apart from nickel, NiMH batteries contain a variety of CRMs such as cobalt and rare earth elements. Figure 27 shows the weight of LIB used for e-mobility (excluding Nickel based ones) in EV and e-bikes only. Until now, traction batteries have a relatively small share of the market, but these volumes will increase sharply and form a significant share of total battery volumes in the future.

Figure 27. Market input of rechargeable lithium-ion batteries (mobility only) in weight, EU-27 plus UK, Norway and Switzerland, 2006 – 2021 (85)



3.2 EU stocks and waste generation potential from past consumption of LIBs materials (2000 – 2020) - Raw materials used by LIBs chemistry and substitution effect

Key information gaps and issues:

15. Effect of substitution and other efficiency effects need to be taken into account (e.g. the change of one chemistry with another)
16. There is high uncertainty and very limited possession survey information available for batteries in electronics. Lifespan information is thus scarce, hindering sound estimates on the volumes becoming available for recycling.
17. Current datasets are not updated with actual market information and contain direct extrapolations without more robust market forecasts.

Based on the battery compositions research tool, created in the ProSUM project and further developed in the ORAMA project (18), market inputs and stocks and waste generation potential are computed. A sales-lifespan approach is taken for each chemistry-application combination by applying a specific set of Weibull parameters. These describe the lifespan distribution for each chemistry – application combination. The stocks accumulation of lithium-ion batteries increased significantly with the POM of EV batteries since the lifespan of vehicle batteries is much longer than for portable electronics as displayed in Figure 28 (85).

Figure 28. In-use stock of rechargeable lithium-ion batteries (all types) per chemistry in weight 2006 – 2021 (85)

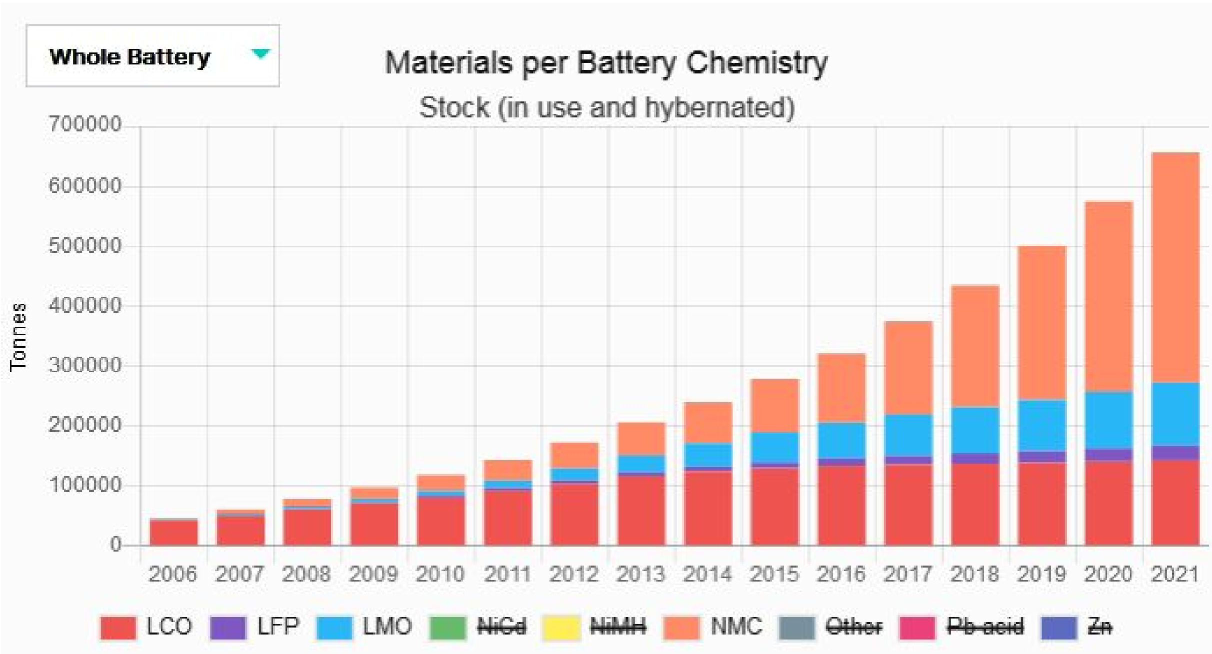


Figure 29. Waste generated of rechargeable lithium-ion batteries (all types) per chemistry in weight 2006 – 2021 (85)

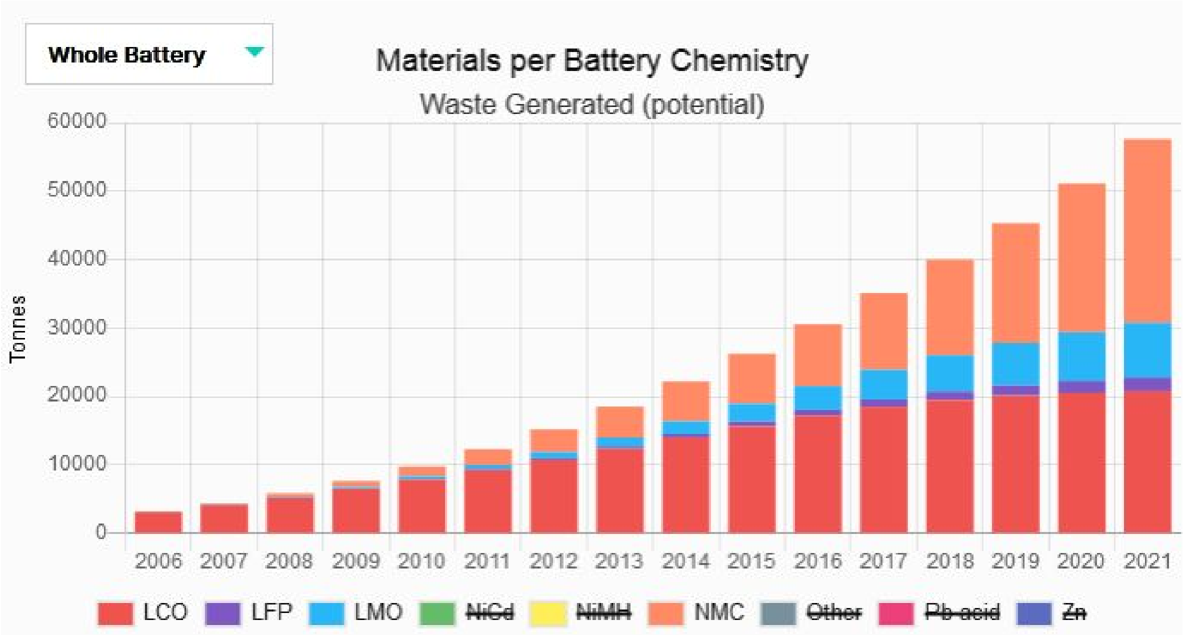
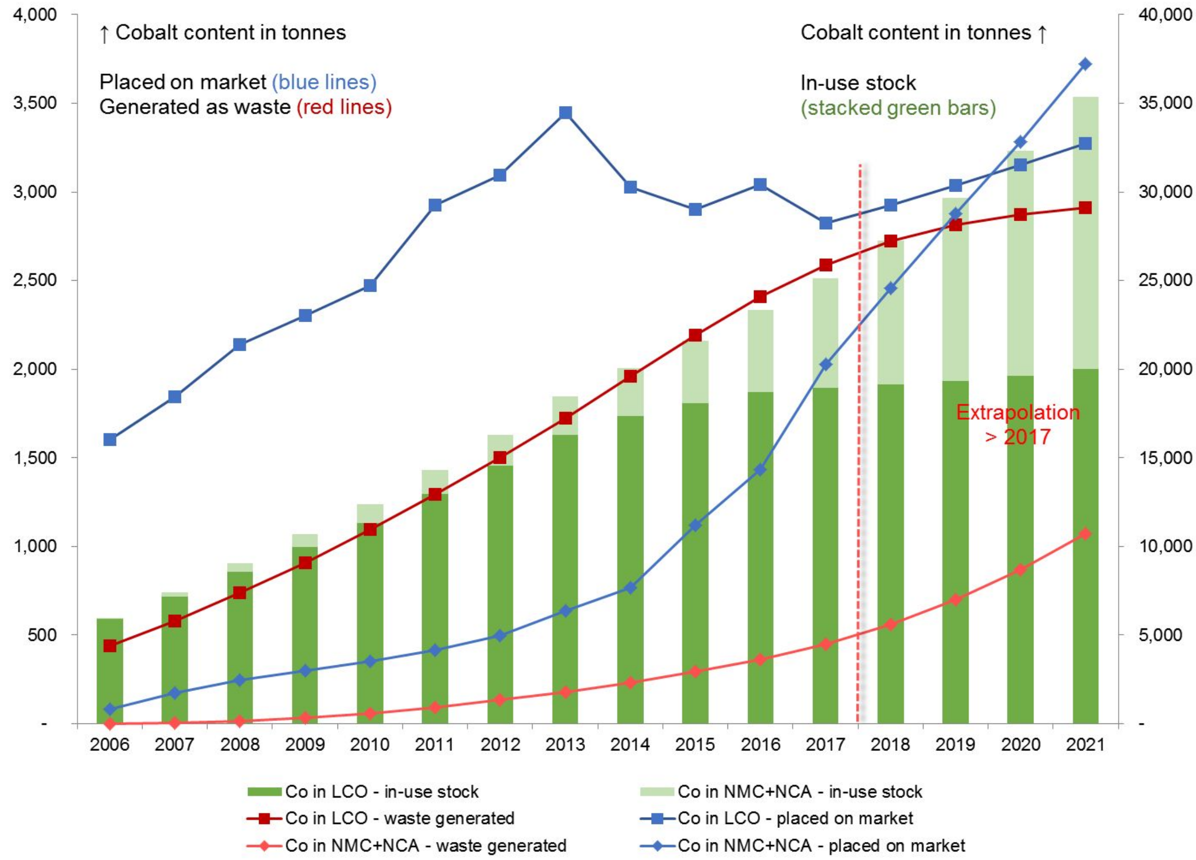


Figure 29 shows the amounts of waste LIB generated over time. There is significant growth over the years in the total amount of waste batteries potentially becoming available for collection and recycling. The lithium-ion battery waste generated is not only affected by battery lifespan, but also by the known hoarding effect where consumers tend to keep batteries for much longer time than their lifespan. Probably this is more evident with portable batteries rather than EV batteries.

Similar to the stock development figure presented in the Raw Materials Scoreboard (59), the specific trends per material are displayed from the RMIS data viewer. Figure 30 displays the market inputs of cobalt per chemistry from 2000 until 2015 and the identified trend extrapolated until 2020. In this figure the blue lines (left axis) represent the market input for respectively LCO (early market introduction) and NMC+NCA (later). The red lines represent the resulting generation as waste obviously lagging behind. The green bars represent the accumulating in-use stock including hoarding of these batteries on the right axis (note the 6 time large scale on the secondary vertical axis).

Figure 30. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (green stacked bars – right axis) of Cobalt in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)



With the rapidly decreasing cobalt content over time, the total volumes of cobalt are not increasing as fast as in unit sales previously shown in Figure 25. Interesting is the comparison with Figure 31 representing the same data for Lithium. Obviously for Lithium, present in all Lithium-ion battery chemistries, the upwards trend is much more significant. The same applies for the use of graphite as represented in Figure 32 below.

Figure 31. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (green stacked bars – right axis) of Lithium in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)

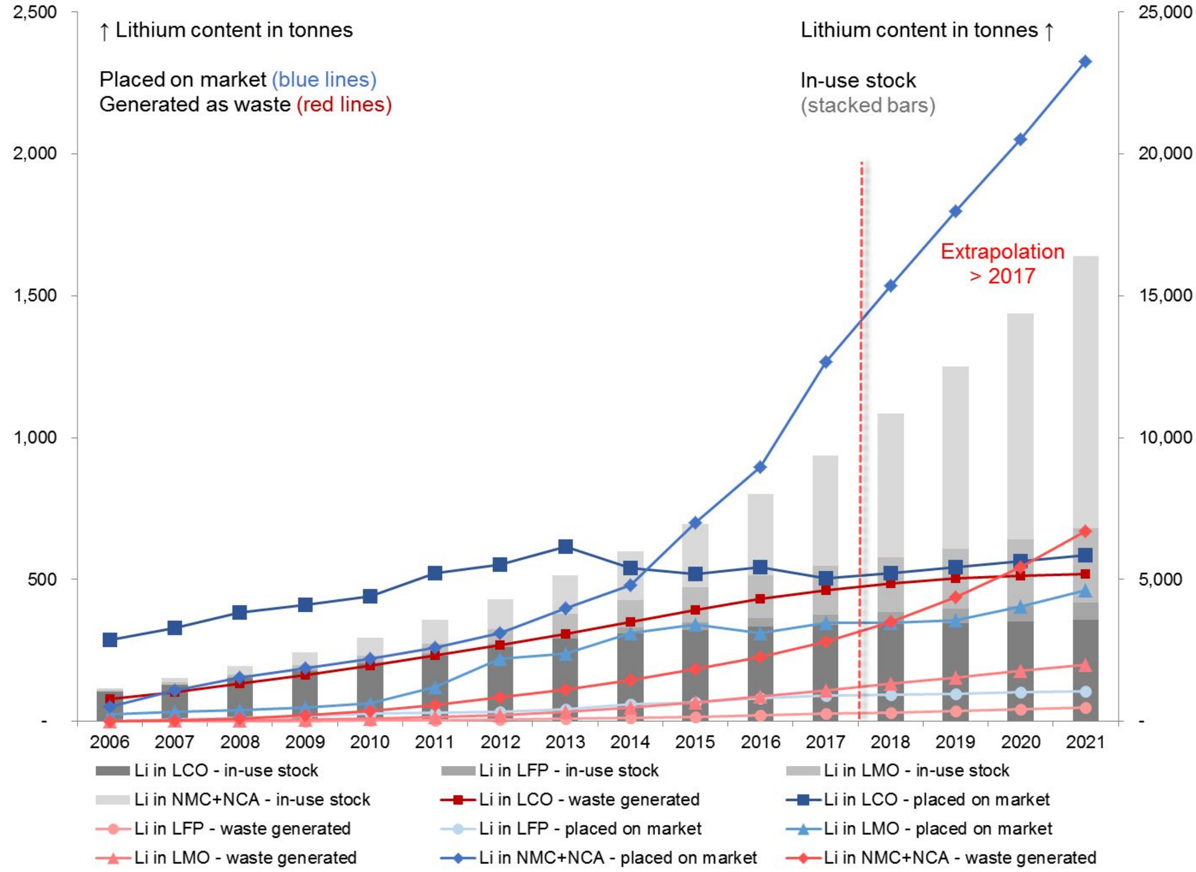
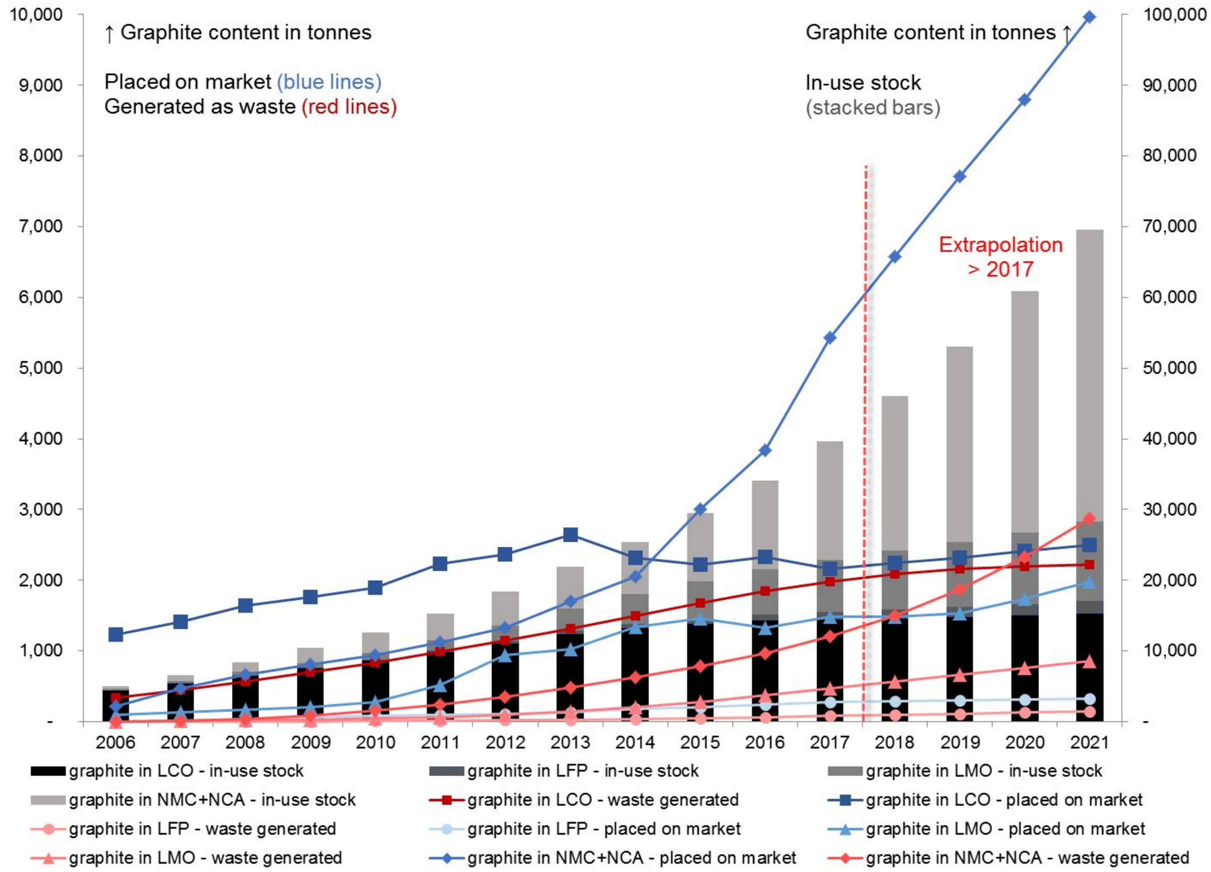


Figure 32. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (dark grey stacked bars – right axis) of Graphite in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)



Two elements relevant for reducing Cobalt content are Nickel and Manganese. Here Figure 33 and Figure 34 show the increase in use of both elements entirely related to the increase of NMC sales. Note, here the use of Nickel in older NiCd and NiMH chemistries is not displayed. These volumes however do play a significant role in the stocks and waste generated amounts with about 3 times the weight compared to their presence in LIB.

Figure 33. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (blue stacked bars – right axis) of Nickel in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)

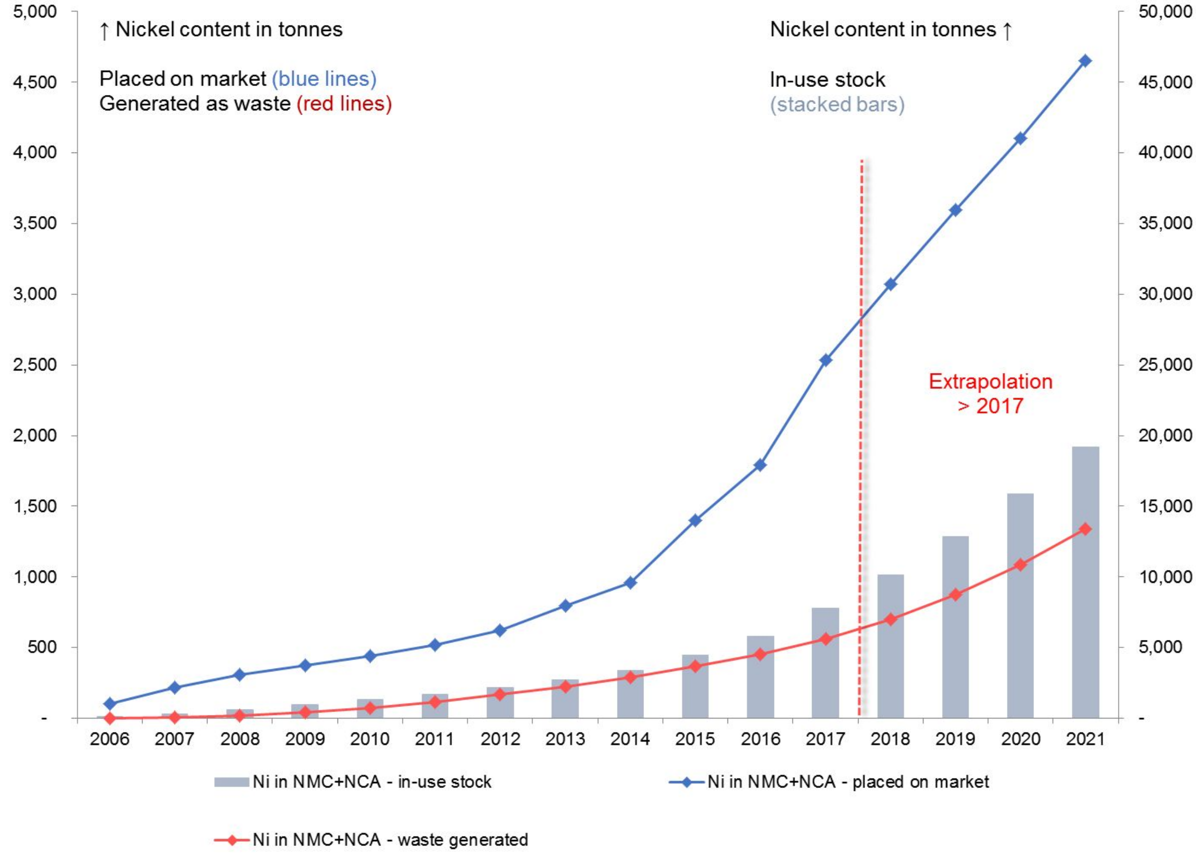
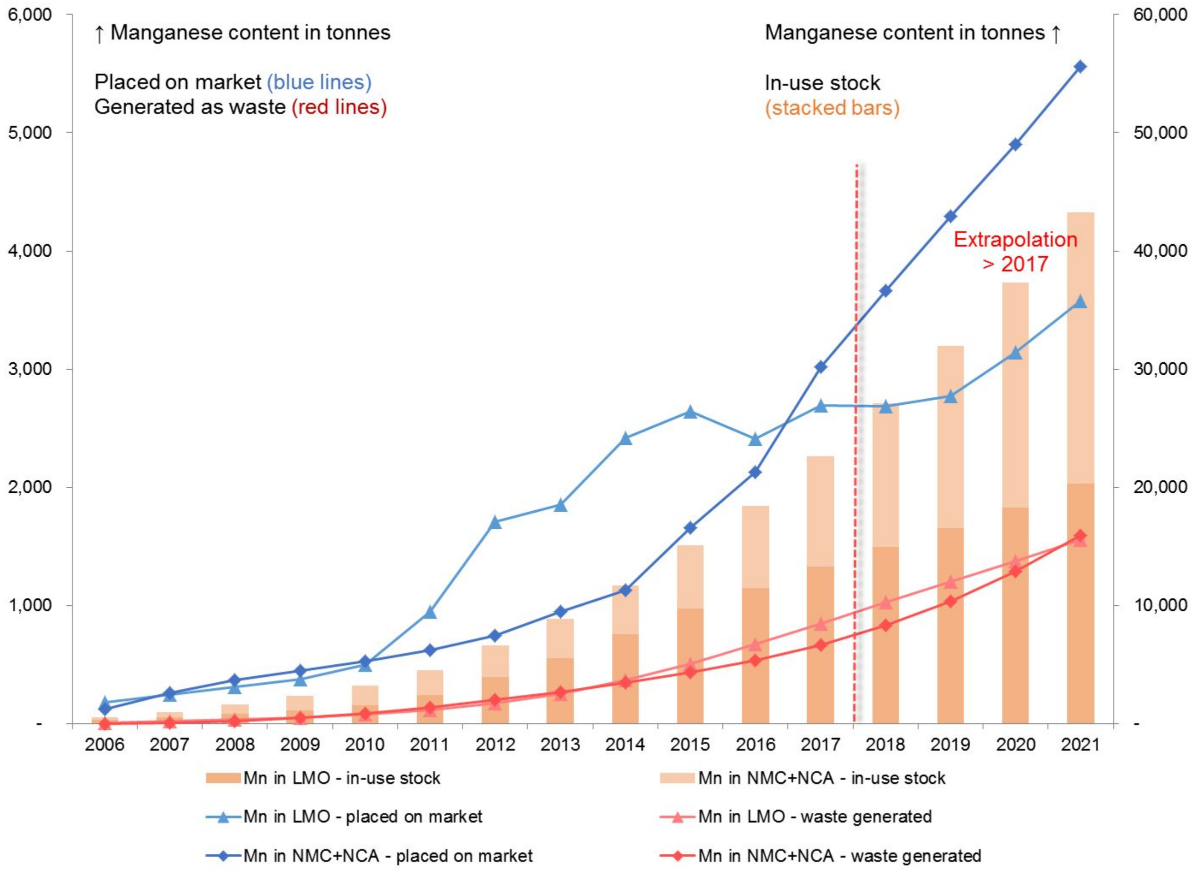
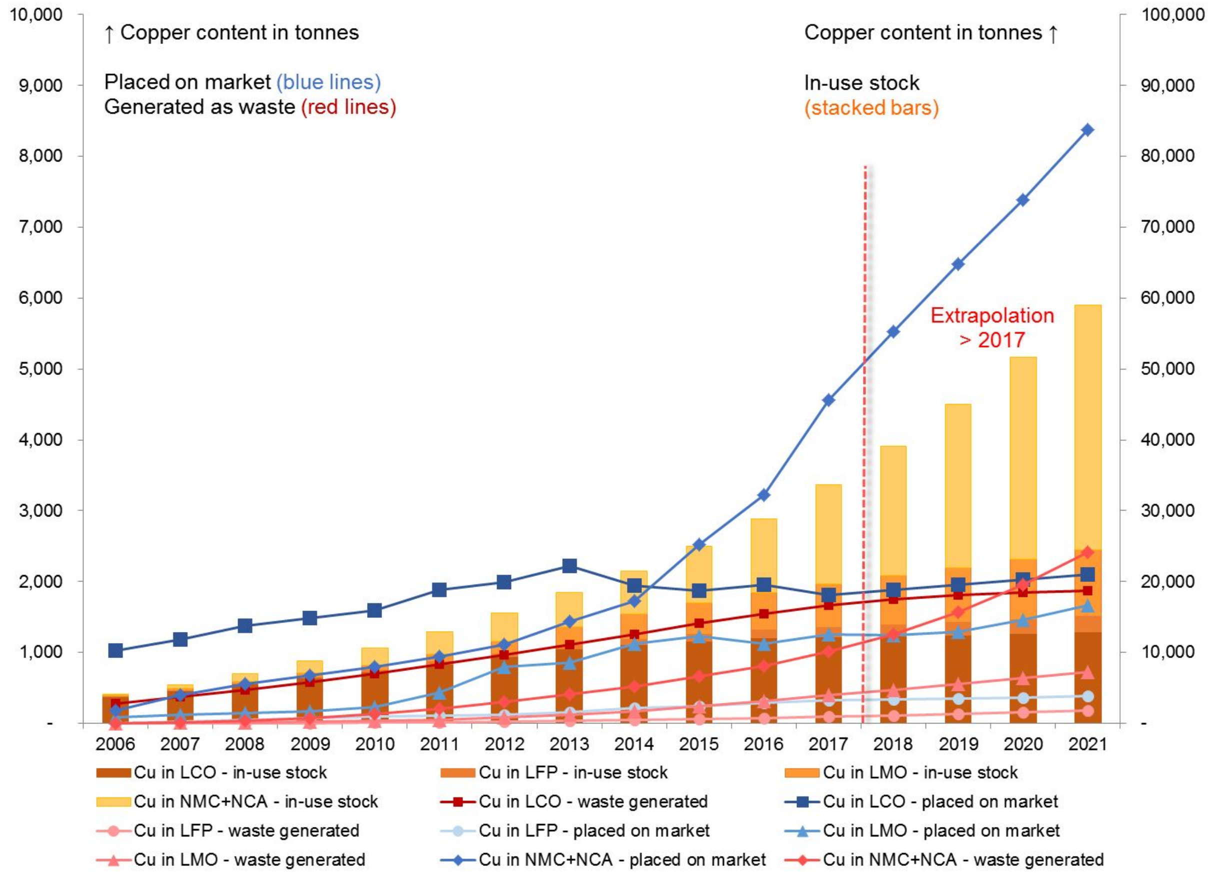


Figure 34. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (Orange stacked bars – right axis) of Manganese in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)



Finally, the increase in use of copper in all battery types is displayed in Figure 35.

Figure 35. Market input (grey lines – left axis), waste generation (red lines, left axis) and in-use stock (orange grey stacked bars – right axis) of Copper in lithium-ion batteries (all types) per chemistry, in tonnes 2000 – 2020 EU-28+2 (21)



Europe's capacity to produce xEV battery packs in 2021–2023 is expected to increase to 40 GWh, increasing from the 3 GWh currently in place. In particular, new companies such as Northvolt in Sweden, which is planning to ultimately realise 32 GWh of production capacity for battery packs, LG Chem in Poland and a few other developments will contribute to this planned production increase. Several of these production facilities are Asian investments. These European figures are in contrast to a current global capacity of 150 GWh, of which two thirds is located in China, and an expected capacity of 400–600 GWh in roughly only 5 years from now! For a more complete overview of planned production capacities (6).

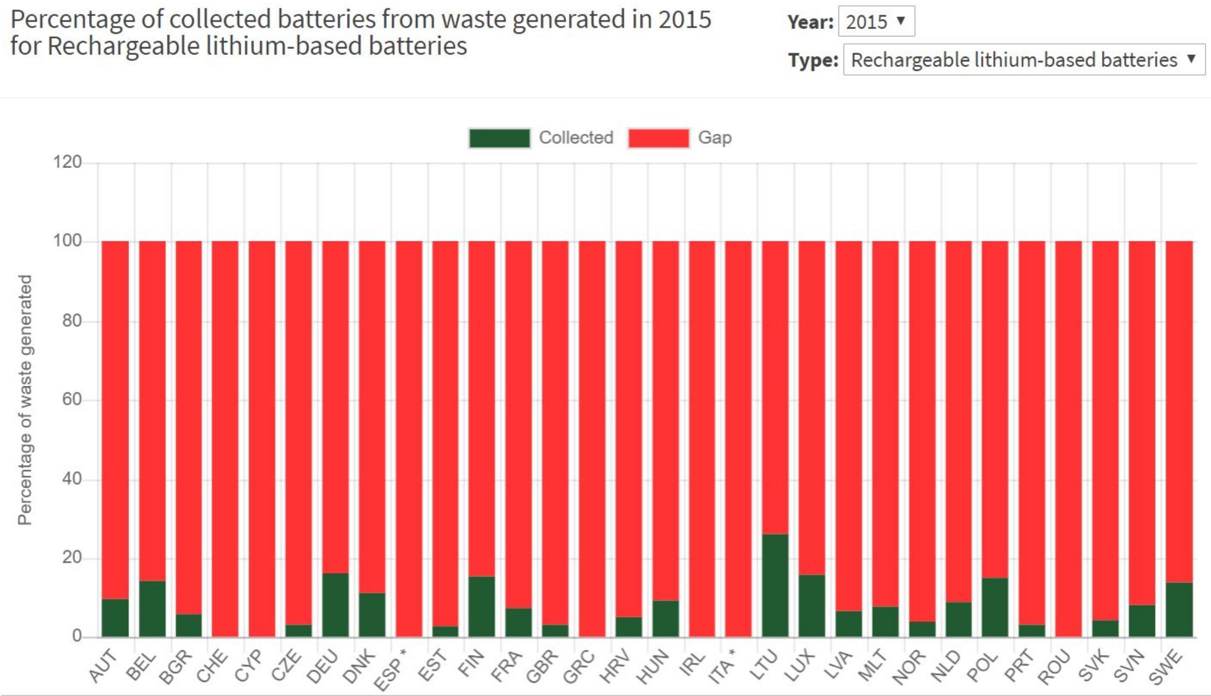
3.3 Collection rate and losses

Key information gaps and issues:

18. The trade and export of used cars and electronics is quite widespread. Officially reported collection volumes and trade flows are under-reported since many years.

The ratio of recycled battery materials compared to new materials contained in the POM batteries is a combination of two factors determining recycled volumes: collection rate of the batteries and recycling efficiency of the materials inside. Collection rate expresses the fraction of batteries placed on the market that are collected at their end-of-life, while recycling efficiency is expressed as the weight percentage of metals, metal compounds, plastics, and other products recovered from the collected waste that can be reused in battery production or in other applications or processes.

Figure 36. Collection rate of rechargeable lithium-ion batteries in 2015 (21)



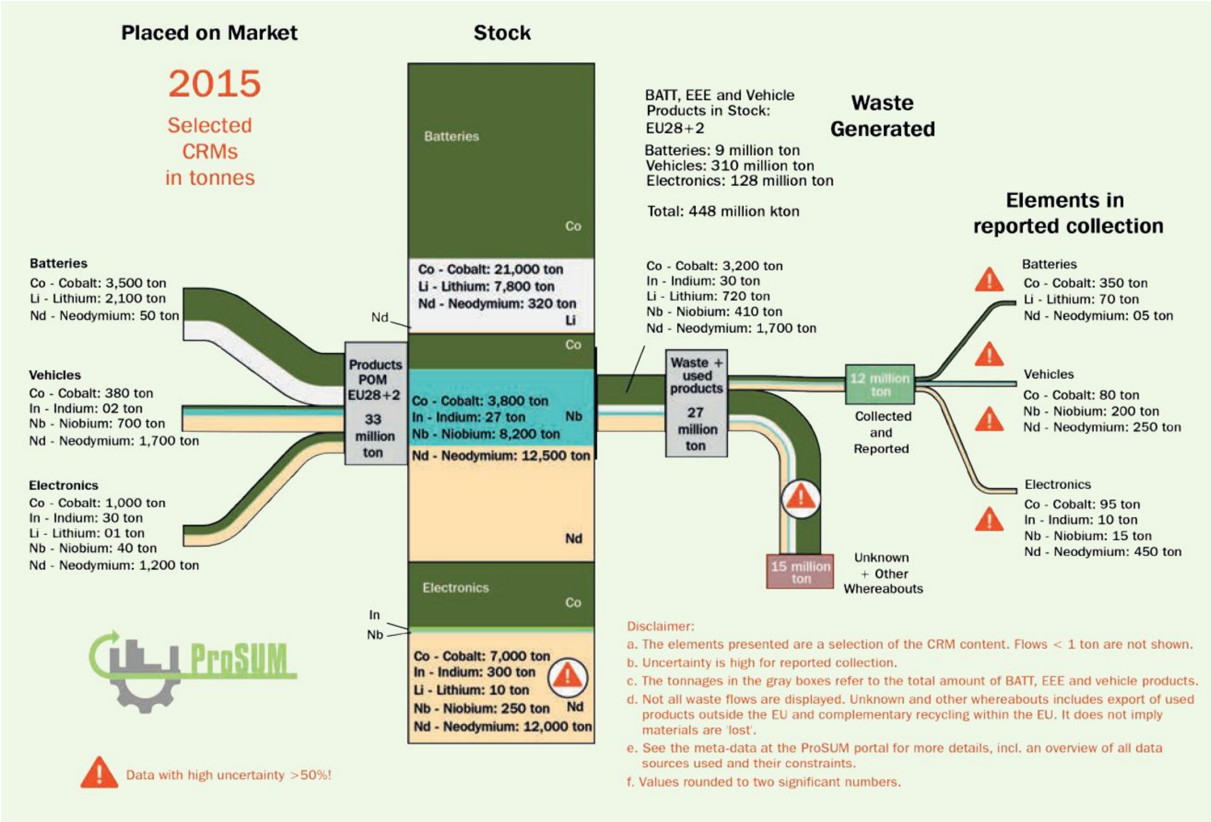
For an estimation of the efficiency of lithium-ion battery recycling in EU, the flow of lithium-ion batteries from the time they are placed on the market up to the recycling, passing through the collection phase, should be assessed. The source of available data is mainly based on information released by Member States in the frame of the battery directive 2006/66/EC requirements. Unfortunately, the quality of data is not consistent all over EU (Figure 36) and the information on lithium-ion batteries, when it exists, is often embedded and hidden in the "other batteries" category. Consequently, the analysis risks to be based on calculation derived largely from assumptions rather than using measured data (19).

Actual collection rates of waste batteries depend on the battery technology/type (e.g. rechargeable/non-rechargeable batteries, Lithium/Ni-Cd batteries), on the lifetime of batteries, and on the end-user behaviour. End-user behaviour is considered to be the main cause for the lowest collection rates of Lithium-ion (especially those with the highest content of cobalt (e.g. NMC, LCO and NCA) and NiMH batteries (84,86), while for automotive batteries an important cause will be their lifetime (average lifetime of 10 years) (10,87,88).

According to the Waste Batteries Directive evaluation, the collection rate of 14 EU Member States in 2016 was higher than 45%, and the average EU collection rate is 43.8 % (increase of 2.8 percentage points compared to 2015). However, these data are aggregated and, since a specific Li-ion batteries classification is not available in the MS reporting, it is not possible to define the percentage of collected LIBs

Figure 37 shows the documented and estimated non-documented volumes of materials entering and leaving our societies for a range of CRMs. It explicitly shows the sizeable stocks as well as the large gap in unknown whereabouts.

Figure 37. Sankey diagram for market input, stocks, waste generation and waste flows for selected CRMs, 2015, EU28+2 (21)



3.4 EU lithium-ion battery recycling industry

Key information gaps and issues:

19. There are only a few large recyclers in Europe. Information on actual treatment volumes (not capacities) is not available.
20. Future capacities and competitiveness of EU recyclers is difficult to determine in the current emerging market with high price volatility and uncertainty on the volumes becoming available for recycling.
21. There is significant uncertainty about costs and environmental and social benefits of recycling to be expected. This is due to volumes becoming available later, the costs of removing environmentally relevant substances, the costs of safe collection, storing, handling and treatment, uncertain economies of scale and unknown future metal prices (in particular for Cobalt).
22. Data on actual recovery rates and RIRs (Recycling Input Rates) from scraps is scarce and anecdotal.
23. More robust MFA's are needed to determine the actual material efficiency levels, including also the level of dilution/ downgrading of materials.
24. There is a clear need to define more intelligent collection and recycling targets, reflecting environmental and societal recovery value for the most relevant batteries and materials.

Across the world, once batteries reach their end of life, the way how they are treated is very much depending on both national battery waste legislation, when it exists and profitable business opportunities that may be envisaged. Several types of batteries are available on the market, each of them based on specific electrochemical process and chemical composition. Some of them may include toxic and hazardous chemicals (e.g. Lead, Mercury, Cadmium, organic electrolyte). Consequently, battery waste legislation has been developed to minimize the negative impacts that erroneous disposal would have on the environment (e.g.

mixed in municipal waste and/or landfill). This is the case of the EU Battery Directive (89) that, besides the gradual banning of specific elements such as mercury and cadmium, and promotion of a high level of collection and recycling of waste batteries, also introduced the Extended Producer Responsibility (EPR) concept. The EPR enforces battery producers, or third parties acting on their behalf, to finance the net cost of collecting, treating and recycling waste batteries. Since its approval the directive worked reasonably well for Lead-Acid batteries also because besides EPR, recovery of lead is usually profitable and the logistics for collection is quite well structured.

3.4.1 Issues for the LIB's recycling industry. Recycling efficiency Vs Recycling rate

In the EU, for the relatively new Lithium-ion batteries technology, the battery directive 2006/66/EC does not work as well as for the Lead-acid technology. The main issue is that the existing Directive cannot deal with new battery technologies and the LIB indeed shows clearly how challenging can be its actuation.

Let's take for instance how the recycling efficiency in the Directive 2006/66 is set. The recycling efficiency is expressed in terms of weight percentage. The Battery directive 2006/66/EC fixes a minimum recycling efficiency expressed as 50% in weight. The Directive fixes also detailed rules on how to calculate such recycling efficiencies (90). However, the Directive doesn't capture the relevant value for the recycling industry, which would be better represented by the recovery rate of relevant materials. A generic minimum value of 50% seemed quite an easy target to be reached and the methodology for its calculation is neither focusing on the most valuable materials nor on recovery of the most environmentally relevant materials. Although higher efficiency generally brings higher environmental benefits, the recycling efficiency measured in terms of recovery rate of the different materials composing the lithium-ion batteries entering the recycling facility seems more appropriate.

Beside the requirements of environmental legislation, the recycling industry concentrates its effort on the most profitable source of raw materials looking for higher recovery rate only for those materials that can maximize their benefit (e.g. cobalt, nickel, copper). However, higher recovery rate comes also with higher cost.

The profitability of the recycling industry is linked to the competitiveness of the recycled SRM in a driven PRM market. At the present, the effect of the total lithium/nickel/aluminium/copper recovered from batteries (and to be reused for LIBs manufacturing) does not importantly affect the raw material market. Cobalt seems to be the exception. However, cobalt is used in long lasting batteries (e.g. ESS and traction LIBs), so that its recovery will occur in 10-20 years and flows in the market are changing compared to past flows (mainly related to portable batteries, which have shorter lifetime) (91). The market value of recycled product and the batteries availability (according to the chemistry) are important aspects affecting the recycling market and also affect the dynamics of both the collection and the choice of downstream routes (91).

A sustainable way to assess the value of SRM should be to compare its unitary cost and environmental impacts (e.g. € and CO_2 per kg) with the competing PRM of the same industrial grade.

The Battery directive 2006/66/EC (89) is at present under revision. The new version should tackle those issues being more material focused and considering the profitability of the recycling industry.

Costs and environmental impacts of SRM are not only related to the core recycling processes below listed, but they are also greatly influenced by all the steps in the value chain and that are bringing the batteries in the recycling facility. Battery waste has to be prepared for the recycling process. Dismantling and pre-treatment of large battery packs (e.g. EV, EES) to reach sizes compatible with recycling processes add additional complexity, especially considering that the battery pack design is usually not meant for easy dismantling and recycling. Also, the absence of a standardised product across the lithium-ion battery market brings a great variety of chemistries and format and often the absence of a clear labelling (e.g. Chemistry) is not helping the recycling industry. A supportive legislation focusing on those aspects could fill the gap.

Despite the fact that the EU recycling industry has a strong and dominant position in the battery recycling sector, it is currently struggling to prepare for the expected great increased volumes of lithium-ion battery waste. The current collection processes for portable batteries are not so effective (e.g. only 10% of lithium-ion portable batteries put on the market in 2011 were recollected in 2016) and when it will come to deal with increasing number of larger battery packs, additional logistic and safety issues may hinder the collection process further more (e.g. discharging, dismantling, transport and sorting).

In all cases, once recollected, the lithium-ion battery waste is then recycled and although chemical and metallurgical processes are up and running, there is still room for improvement of the processes cost-efficiency and their environmental impact.

3.4.2 Existing LIBs recycling technologies

Currently, several processes are employed for the recycling of lithium ion batteries: dismantling and mechanical (pre)treatment, thermal, pyrometallurgical and hydrometallurgical (end)processing (92).

Mechanical treatment includes crushing and physical separation of components and recovery of the black mass which contains valuable metals such as cobalt, nickel, manganese, lithium.

In pyrometallurgical processes spent Li-ion cells are processed at high temperature without any mechanical pre-treatment as batteries are loaded into the furnace directly. This class of recycling process recovers cobalt, nickel, copper and iron in form of a metal alloy. Metals such as aluminium, manganese, and lithium are lost in the slag and plastic and other organic components are incinerated (38,91).

Hydrometallurgical methods include mechanical pre-treatment and metal recovery from the black mass by means of leaching, precipitation, solvent extraction, ion-exchange and bioleaching. In addition to cobalt, nickel, copper and iron, hydrometallurgical processes enable recovery of lithium with high purity. A hydrometallurgical process is often preceded by a thermal pre-treatment step to remove organic compounds and graphite which adversely affect leaching and solid-liquid separation steps of the recycling process.

In EU several companies have designed a set of technologies based on those processes, and installed in different battery recycling plants. The capacity regarding Lithium ion battery, ownership, location and main process of those plants is resumed in the following Table 2:

Table 2. Main EU battery recycling plants and recycling capacity of batteries per year

(*T - Thermal process; P - pyrometallurgical process; M - Mechanical process; H - hydrometallurgical process; * no declared capacity*: *small plant/pilot projects*)

Company: **(HQ location)**	**Recycling plant** **location**	**Processes**	**Estimated/declared recycling volume, tons of batteries per year**
Umicore Battery Recycling (Belgium)	Hoboken (Belgium)	P + H	7000 (capacity)
Accurec Recycling GmbH (Germany)	Krefeld (Germany)	T + M	2500 (Li-ion) 1500 (NiCd) 500 (NiMH)
NICKELHÜTTE AUE GMBH (Germany)	Aue (Germany)	P + H	1000
Fortum/Crisolteq (Finland)	Harjavalta (Finland)	M + H	*
Duesenfeld (Germany)	Wendeburg (Germany)	M + H	*
Snam (France)	Viviez (France)	P + H	*
EDI/Sarpi-Veolia	Dieuze (France)	M + H	*

3.5 Repurposing and second use of EVs batteries

Key information gaps and issues:

25. Lifespan information of e-mobility batteries is only indicative at the moment due to the very recent market introduction and lack of experience. This affects the assessment of the potentials for second use application like in ESS.
26. There are very few cases on End of Life EV batteries going into ESS.
27. The efficiency related to environmental, economic and safety aspects of re-use and re-purposing practices is not yet properly assessed.
28. The existing EU regulatory framework for battery waste (Battery directive 2006/66/EC and Waste Directive) limits the Extended Producer Responsibility (EPR) transfer and the “End of Waste” status, which are dimmed necessary for a better functioning of the second-use option in EU.
29. If EV batteries go through a second life, the key raw materials contained in those batteries will be retained in applications and not available for more years to come. This will lower the volume of available batteries for the recycling industry, possibly limiting their revenues. This may also impede the immediate use of key and valuable raw materials (e.g. Co) to produce more resource efficient batteries and also possibly affecting the price of SRM, limiting the EU cell manufacturing industry to access a potential domestic source of raw material.

Compliant with the current legislation, once waste batteries are collected, usually they are usually recycled. However, for electric vehicle battery, when the Lithium-ion battery no longer meets the original EV requirement, e.g. when their energy storage capacity has decreased by approximately 20 to 30 %, they could be repurposed and employed in second use applications, such as stationary energy storage systems (93) or remanufactured and put back in the market for less demanding traction purpose to support new business such as EV car sharing schemes or battery leasing[10].

The clear advantage offered by the second use of a retired xEV Lithium-ion battery and the extension of its total lifetime is the improvement of its environmental impact as shown in preliminary studies (94). The second use option may help to improve the EV's overall economic efficiency sharing the cost of battery between the primary and secondary users (95). At present, car manufacturers are using the second use option in an attempt to expand their portfolio and enter in the stationary battery market. In cooperation with utility companies and/or other specific partners they are launching several xEV battery second use pilot projects (96–99).

However, despite these promising opportunities, there are still several unclear technical, legal and economic issues that may hinder the second use option of xEV battery. Primarily, there are not yet enough EV LIB that have reached the end of their first life. Furthermore, the design of EV battery packs is not optimized for an easy dismantling approach, which may be also an obstacle for the recycling industry. Also, a standardized methodology for the SoH (State of Health) assessment of aged Lithium-ion batteries is still not properly developed. As well, the safety implications of a repurposed battery system is not yet tackled properly as it is for the new battery products. On top of that, especially because of the existing EU regulatory framework for battery waste (Battery directive 2006/66/EC and Waste Directive) there are legal obstacles limiting the Extended Producer Responsibility (EPR) transfer and the “End of Waste” status, which are dimmed necessary for a better functioning of the second-use option in EU. But there are also many economic aspects adding uncertainty to the repurposed battery scenario. The repurposed battery will compete with new advanced batteries and it is not clear how price and warranty policies will be able to cope with it. Furthermore, if EV batteries go through a second life, the key raw materials contained in those batteries will be retained in applications and not available for more years to come. This will lower the volume of available batteries for the recycling industry, possibly limiting their revenues. This may also impede the immediate use of key and valuable raw materials (e.g. Co) to produce more resource efficient batteries and also possibly affecting the price of SRM, limiting the EU cell manufacturing industry to access a potential domestic source of raw material.

[10] H2020 projects: CarE-Service (http://www.careserviceproject.eu/);

4 SRM in EU to feed the future growing demand of lithium-ion batteries

Recovering and recycling of materials embedded in LIBs can partially satisfy the demand for raw materials for LIBs in the future. However various aspects have to be considered for assessing the future SRM potentiality; the availability of embedded materials for recycling and the quality of recovered materials are two examples that could importantly affect the flows of SRMs to be used again in the batteries' sector.

Some forecasts on materials flows for batteries are already available in the literature. It is worthy to note that geographical and temporal boundaries are relevant when assessing EoL scenarios of specific technologies (100). However, most of the studies perform analysis at global level without focusing of specific regions and/or countries, e.g. (79,101–106). On the demand side this likely means increasing competition for the same raw materials. On the supply side this means that the place of discarding might be different than the place of the original sale. This affects collection targets and the realisation of circular economy loops.

Also, the assessment of a complex system in which both products and recycling technologies are developing quite fast entails uncertainties (102) that should be considered and estimated. Moreover, the potential second-use of LIBs can change the EoL scenarios extending the lifetime of batteries in the stock and delaying the availability for recycling, with a consequential delay in SRMs available for new production cycles in either closed or open loops (79).

In this chapter some relevant information and sources of data that can help to estimate the amount of SRMs that, in a specific system, participate in satisfying the demand of LIBs. Future flows of LIBs within the EU are identified and discussed focusing on both the already available information and the knowledge needed to provide reliable forecasts.

Some relevant aspects considered in the following sections are hereinafter listed:

- Demand of batteries according to the different batteries available in the EU market
    - Different applications: traction, portable, ESS
    - Different chemistries and therefore different materials content. Evolution in time of the material content for a given chemistry (e.g. cobalt content in NMC chemistries)
- Lifetime/residence time of batteries depending of several factors:
    - Evolution of lifetime in time, considering the development of batteries performance, the needs of different applications and the development of chemistries;
    - Second-hand market (e.g. embedded LIBs in EEE);
    - Possible extension of the lifetime of some type of batteries (e.g. remanufacturing and/or second-use of traction batteries);
    - User behaviours in waste battery collection when no more usable (e.g. stocked in houses, hoarding).
    - size of export/second-hand flows, which represent the losses (e.g. amount of batteries not entering in the EOL flows)
- End-of-Life of batteries:
    - Combination of sales projection for each application and lifetime distribution to estimate the batteries waste generated per application;
    - Improvements in collection, sorting and recycling processes (evolution of existing regulations and availability of incentives);
    - Improvement in the recycling technology (higher efficiency of processes; recovery of additional materials; higher quality of recovered materials, etc.);
    - Development of new EoL options for some types of batteries, e.g. remanufacturing and reuse options.
- Knowledge of the main processes along the whole batteries value chain in order to

- Monitor the foreseen changes in the lithium-ion technology in terms of chemistry/application and performance and consider any substitution effect;
- Monitor the flows of both batteries and materials;
- Identify the main losses.

Finally a simplified Materials Flow Analysis (MFA) model based on the previous elements applied to the LIB value chain is presented. Due to the data gaps, only a qualitative analysis will be provided and relevant data requirements and needs will be underlined for future and more complete analyses.

4.1 Sales projections

Key scenarios and developments:

30. Data on future sales of LIBs per application and chemistry are needed. Available data are often aggregated (per application, per geographical area, etc.) and therefore hardly comparable.
31. According to the sector, different drivers should be considered in forecasting LIB sales, e.g. user behaviour for portables, regulatory framework and incentives for traction batteries and ESS.
32. Substitution scenarios should consider the fast development of the battery technology. Specific uncertainty relates to the possible substitution of PbA with LiB for SLI batteries.

Due to the novelty of the Li-ion technology and its fast development, data about sales batteries projections are often lacking or based on assumptions and estimations, therefore difficult to be compared. Most of the forecasts refer to global sales or specific Member States and in most cases are aggregated (e.g. by application, by chemistry), hence it is difficult to extrapolate specific data. In the literature, some projections are available for specific sectors (e.g. Li-ion in electric vehicles, in appliances, in energy storage systems) or chemistry (e.g. NMC, NCA). To perform a complete material flow analysis, information from different studies need to be adopted.

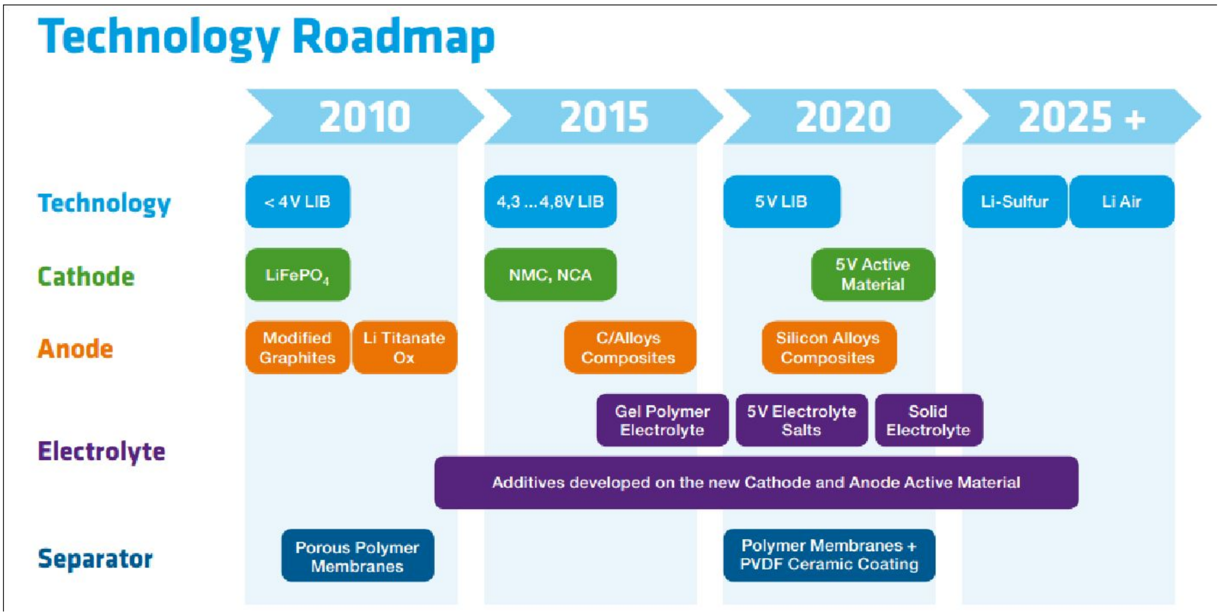
In general, the expected increase of LIBs in Europe will be dominated by xEV traction batteries; portable and industrial batteries are also expected to increase, though to lesser extent (21). (107) provides a similar trend, even though the flow of LIB POM is halved compared to that reported by ProSUM (70 kton VS 140 kton[11] in 2020). These trends are also confirmed by other studies in the literature, e.g. (24). Also (109) states that electric mobility is expected to cover about 56% of the Li-ion batteries sales in 2025, alongside stationary applications and mobile or portable electronic products.

The **main drivers for the development of LIB markets** are respectively the societal drive for portables and the regulatory driver for both xEV and ESS (108).

In various studies, projections are available in terms of power and/or energy capacity of batteries. Especially in these types of forecasts, the **expected improvement of batteries performance** in the next decades as stated by available batteries' technology roadmaps (e.g. (109–112)) represents a relevant aspect to be assessed. Note that the technological development entails changes in all the batteries components, i.e. cathode, anode, electrolyte, separator, materials, etc (Figure 38) (110).

[11] Norway and Switzerland are included only in ProSUM forecasts (https://rmis.jrc.ec.europa.eu/apps/bvc/#/v/chemistry)

Figure 38. Example of technology roadmap available for the EU (110)



From a regulatory perspective, to "become competitive in the global battery sector to drive e-mobility forward" specific performance targets up to 2030 for traction batteries are defined in the action n.7 of the Strategic Energy Technology Plan (113); in the Implementation Plan of Action n.7, both performance and costs targets for 2020 and 2030 are illustrated (5).

Based on available roadmaps and costs estimations, some authors provide estimations of future perspective of the LIB market based on past development and (See Figure 39) (112).

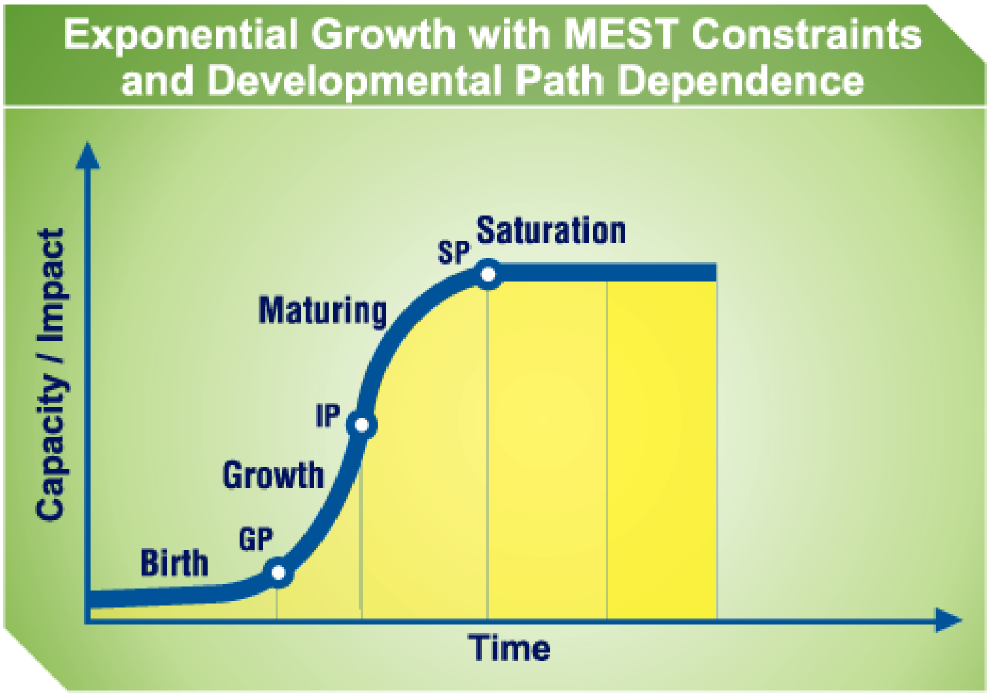
Figure 39. Li-ion battery market in GWh/year, past evolution and perspectives until 2030 (112)

	2010	2015	2020	2025	2030
Cell phones	6	11	17	28	44
Tablets	1	7	12	17	25
PC	12	9	9	9	11
Portable electronics, other	3	4	7	12	20
Portable electronics, total	**21**	**31**	**45**	**66**	**100**
EV	0	11	65	115	200
PHEV	0	2	8	13	25
HEV	0	0	2	7	15
Road-transport, other	0	0	1	2	5
Road-transport, total	**0**	**13**	**76**	**137**	**245**
Storage in power supply	**0**	**0**	**2**	**10**	**30**
Other applications	**1**	**1**	**2**	**7**	**15**
Total	**22**	**45**	**125**	**220**	**390**

Finally, the uptake of new technologies could be described by specific function following an S-curve. These models have an initially slow trend of the penetration of the considered technology due to various factors (e.g.

high cost of the technology, more risk-oriented people); then, a steeper curve and finally a slowdown to reach a saturation stage (e.g. when other technologies can potentially replace it) (114). The main difficulty in modelling such curves is the speed of the progress along the curve and the emerging of possible e.g. incentive measures (86). An example of the S-curve is shown in Figure 40.

Figure 40. S-curve (http://www.foresightguide.com/logistic-growth-s-curves). GP = growth point, IP = inflection point, SP = saturation point



4.1.1 Projections of portable LIB

Sales of portable batteries in Europe increased in the last decades and the same trend is expected for the next decades. IT applications are "the most dynamic markets for portable batteries" (115).

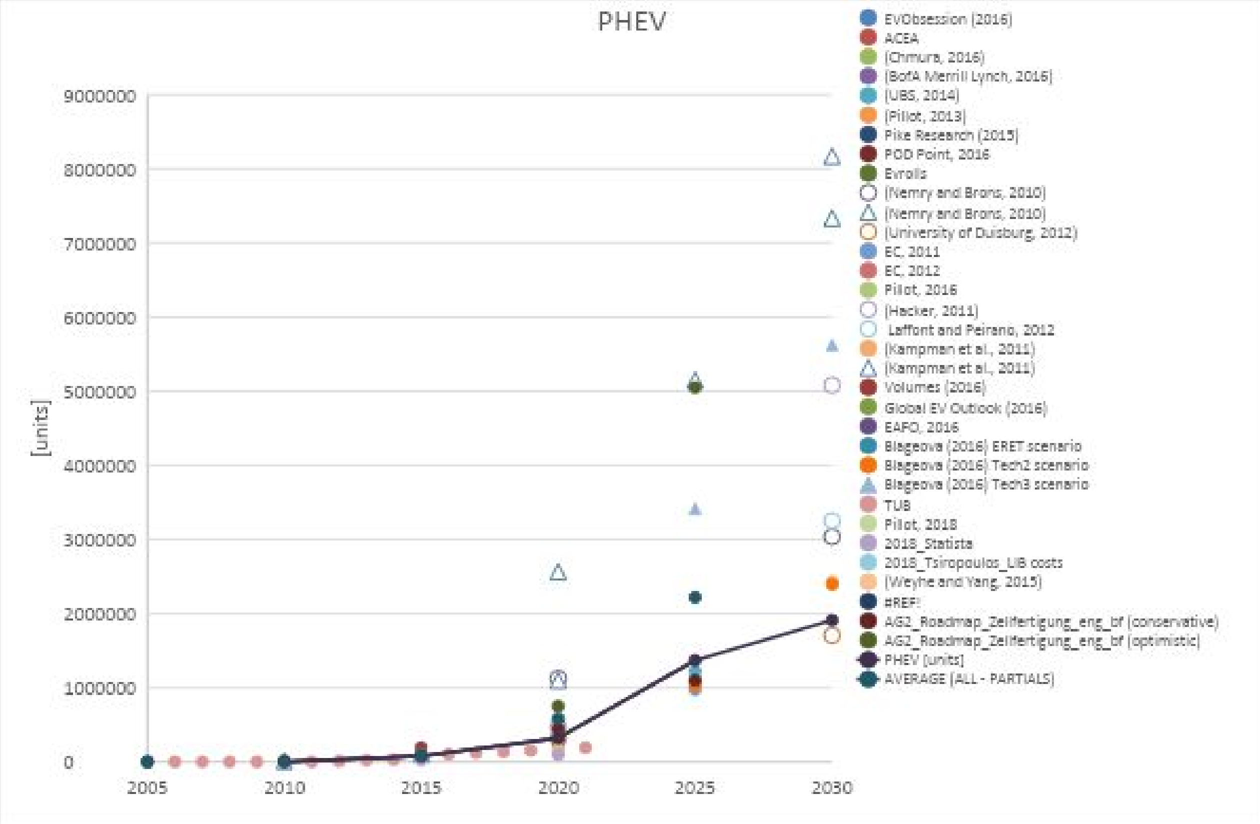
Very few data are available for portable market projections, and often refer to specific sectors or products, e.g. portable PCs or tablets. For instance, Chancerel et al. (16) estimated that the overall volume of LIB for tablets and notebooks in 2020 will be almost 90 million units, most of which are NMC chemistry. Pillot (116) estimated an increase of portable devices from 2015 to 2025 of about +6% per year, detailing an increase of +4% for cellular phones between 2010 and 2025 (from around 200 million units in 2010 to 300 million units in Europe) and an almost stable trend for portable PCs between 2016 and 2025. Jaffe (117) estimated that the batteries for consumer electronics in Europe will correspond to about 10 GWh in 2020.

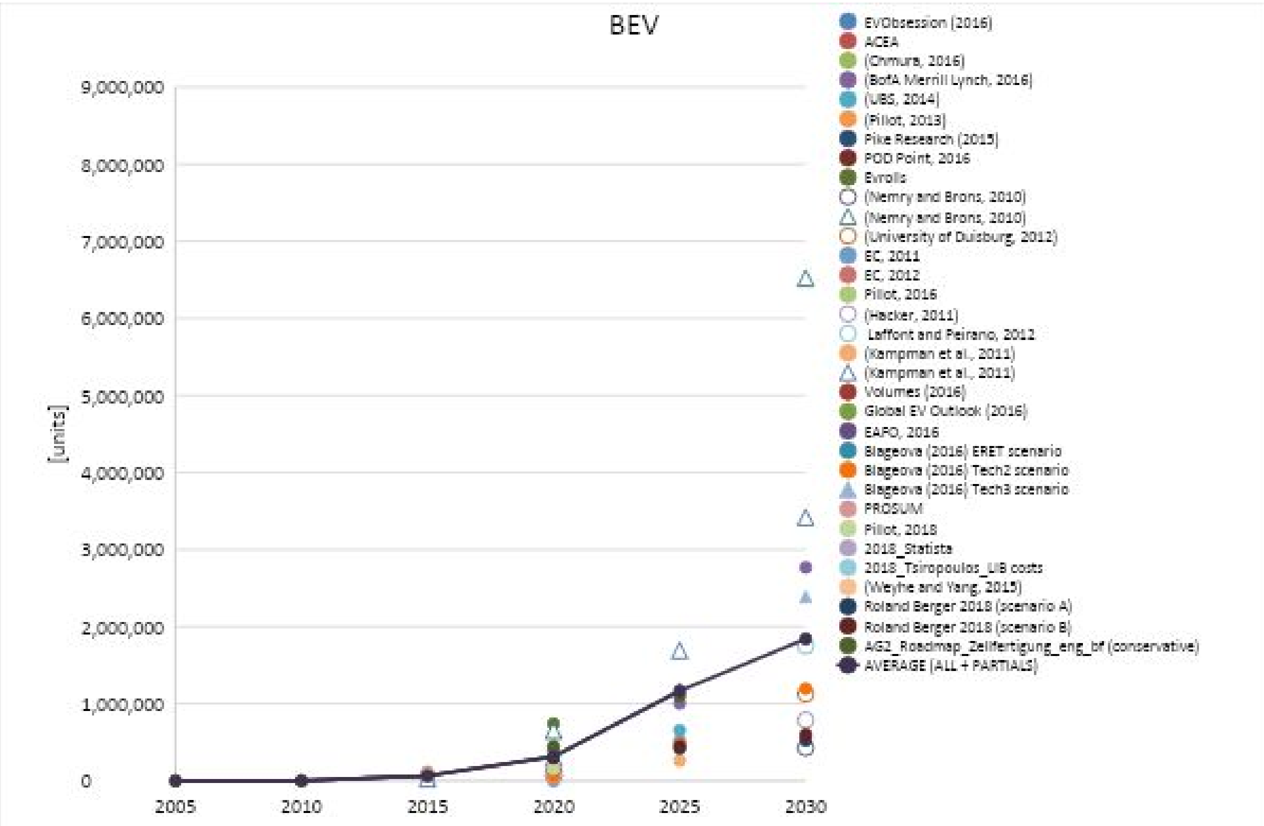
4.1.2 Projections of automotive and traction batteries

Projection of xEV sales in Europe are available from different studies, as reported in Figure 41 (own elaboration)[12]. According to the considered scenarios and assumptions of the consulted sources, sales of PHEVs in Europe in 2025 range between 975,000 and 5,150,000 units, and will be about 5 times higher in 2030. Similarly for BEVs, European sales range between 260,000 and 430,000 in 2020; between 1,690,000 and 6,525,000 in 2030.

[12] Updated until 2018 sources

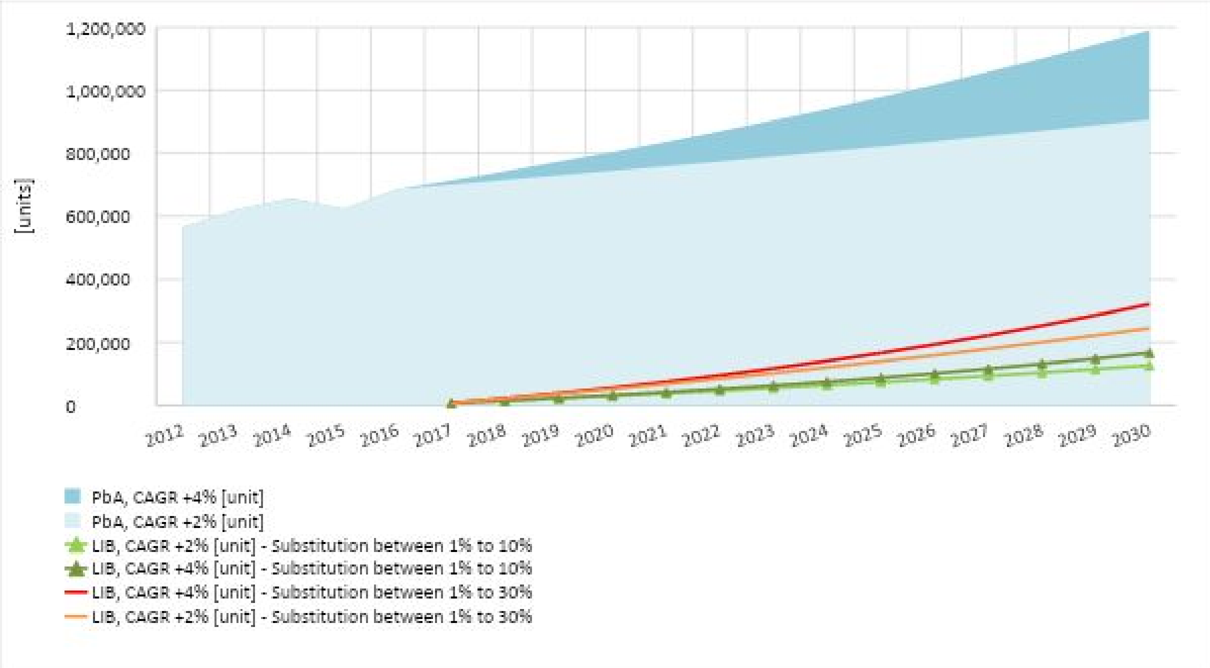
Figure 41. Forecast of PHEV and BEV sales in Europe up to 2030 according to several sources (own elaboration)





According to Baes (118), in the future Lead-Acid batteries for starter, lighting & ignition (SLI) may be substituted by Li-ion chemistries. Some examples of Li-ion chemistry for SLI batteries already exist for certain vehicle OEMs and geographical locations; especially in Europe, the replacement could occur for medium-to high-end conventional vehicles (119). Among LIBs, LFP chemistry is the best candidate to potentially substitute Lead-Acid SLI batteries for their technical characteristics and costs (119,120). Eurobat (88) considered the possibility of replacing Lead-Acid SLI batteries with LIB in the next future and roughly estimates the quantity of Li potentially needed to this change; however, the strong market position of Lead-Acid SLI batteries and the prohibitive costs related to change the vehicle charging system will assure them a high level of competitiveness (121). Based on PROSUM data, considering that the lead-acid battery market will grow by 2-4% to 2025 (121), several LIBs replacement scenarios can be superimposed to the expected increase of SLI units (in 2030 SLI will range between 900,000 and 1.2 million units) (Figure 42).

Figure 42. Forecast of SLI until 2030 in Europe and possible replacement with LIBs (own elaboration based on ProSUM data)



Some issues were identified in collecting data on xEV batteries projections:

- among the available sources, different documents refer to the same data sources. It is recommended to identify the original sources of data and the data obtained from elaborations;
- in many cases data are aggregated and it is difficult to understand the origin and the elaborations made by authors;
- according to the developed scenarios, different technologies could be involved in forecasting the development of the mobility in the EU and increase the uncertainty of estimations. For instance the potential development of fuel cell electric vehicles (FCEVs) could importantly affect the estimation of future demand of traction batteries for xEVs, considering that the demand of vehicles will reach the market saturation (see S-curve models Figure 40);
- geographical representativeness should be considered in order to ease the comparison of sources and the data elaboration, e.g. considering EU27 or EU27+3.

4.1.3 Energy Storage System (ESS) LIB projections

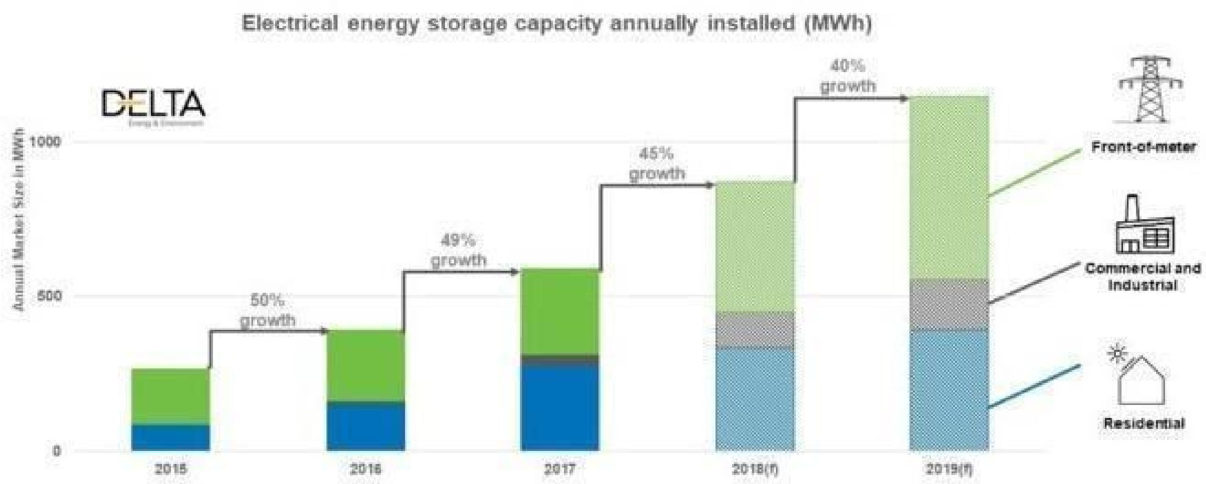
Energy Storage in the EU 1) supports the increase of renewable energy share in the EU[13] reducing the level of curtailments occurring in Europe, 2) supports the increase of energy efficiency especially for high

[13] From 24% in 2030 to 56% in 2050 of the electricity generation in Europe (122)

energy-intensive industrial processes and 3) improves the links between energy carriers (122,123). Focusing on storage behind-the-meter[14], the expected growth of such storage systems is contributing to maximising the self-consumption, reducing consumers' bills, providing voltage and frequency support, reducing peak loads in the system and enhancing sustainability through the replacement of diesel generators (124). In line with these considerations, ESS applications in EU will rise from 5.3 GW[15] in 2016 up to 7.6-9.8 GW in 2020 and 11.5-14.5 GW in 2025 (125), of which almost 30% will be for behind-the-meter storage . Compared to other chemistries, Li-ion batteries in 2013-2014 have the highest increase in terms of installed battery capacity (126). In 2016, according to (127), ¾ of the electro-chemical capacity installed in Europe are Li-ion batteries (125), and an increasing trend is observed in the EU. Despite the main technology today available for ESS is PbA, the market penetration of this chemistry is already at the "recession" stage while Li-ion batteries are still at the beginning of their maturity (especially for non LFP chemistries) (86,112). According to the application, LIBs are expected to achieve mass production around 2020 for large ESS and before 2030 for ESS over 5 MW (86).

The main applications segments for ESS development in Europe are residential sector, commercial & Industrial and front-of meter (Figure 43)[16]

Figure 43. ESS market figures and forecasts



4.2 Lifetime/residence time of LIBs

Key scenarios and developments:

33. The estimation of average lifetime of LIBs in different applications is quite uncertain due to the limited information currently available, e.g. due to the few Li-ion batteries that have reached their EoL or the different behaviour of batteries in different applications.
34. Available studies made assumptions based on warranties and producers indications. Due to the high level of uncertainty, the adoption of a LIB lifespan distribution function is recommended.

In the battery market lifetime belongs to the relevant factors affecting the choice of the batteries chemistry (86). However, to predict the service lifetime of LIBs in various applications is complex since it is related to 1) **the application** in which they are adopted and 2) the **consumer behaviour** (10,128,129). Moreover, the technology is quickly developing and batteries are always more performant, which means that their lifetime is rapidly increasing.

[14] According to (124) behind –the-meter batteries are "connected behind the utility meter of commercial, industrial or residential customers, primarily aiming at electricity bill savings"; they "range in size from 3 kilowatts to 5 megawatts and are typically installed with rooftop solar PV"

[15] "*The power capacity (GW) of storage cannot directly be translated into energy capacity (GWh) because this depends on the discharge time and the number of charge-discharge cycles*" (12)

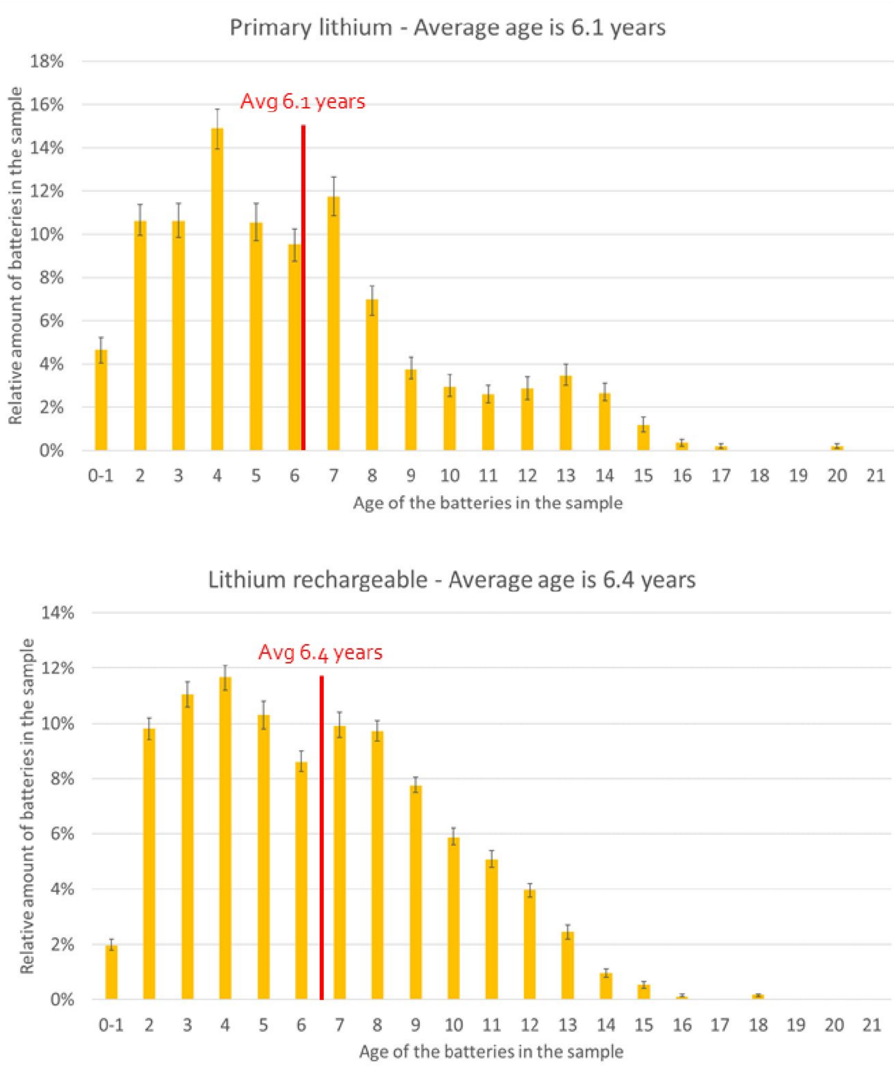
[16] Available at http://www.energy-log.in/90-of-european-energy-storage-installations-were-based-on-lithium-ion-batteries/

4.2.1 Portable LIBs

According to manufacturers, after the production of portable batteries, 3 months are needed to be sold (130).The average lifetime of primary lithium batteries is 6.1 years (5.9 the average usage and 0.2 of hoarding term), whereas it is 6.4 years for lithium rechargeable batteries (6.2 the average usage and 0.2 of hoarding term) (130) (Figure 45).

Due to the uncertainty related to lifetime of batteries, several studies not based on primary data recommend to adopt a statistical distribution for the lifetime, e.g. the Weibull distribution, according to the application in which batteries are used.

Figure 45. Average lifetime of portable Li-ion batteries (130)



Despite the fact that in the Waste Batteries Directive the calculation methodology of collection rates is based on three years, the average service life of batteries is much longer than three years. This is especially true for rechargeable batteries (115,131). Also, small rechargeable batteries could be part of a second-hand market through their reuse (still rare option) through the second-hand market of WEEE. For this reason, in assessing the flows of batteries, it has to be considered that the EoL of LIB could occur out of the EU. As a result, not all the flows of batteries can be properly traced within the EU, e.g. for changes of ownership (132) or export of LIB to “developing countries” (133).

The end of the operating lifetime (to have an overview of the difference between the different “life” terminologies see Figure 5) does not necessarily correspond to lifetime when arriving to recycling facilities for LIBs. In fact, portable batteries are often stored in households (‘hoarding’ by end-users) (91,115,128,130). This entails a delay in batteries available for recycling, and therefore of SRMs.

Besides “hoarding”, portable LIBs could remain in EEE and enter in a second-hand market or collected together WEEE where they are not always removed to the depollution level required according to standards. In this case, these flows of batteries cannot be accounted for as portable LIBs available for collection and recycling, but they represent a “lost” in the LIB system.

4.2.2 Traction LIBs

The traction LIBs lifetime varies between 5 and 15 years according to various factors, e.g. driving style, frequency of charging (93,95,134–136). The warranties that car manufacturers offer for their EV batteries are within this range. For instance Tesla is offering a warranty of 8 years or 200.000 km for the battery of the Model 3 with 70% of residual capacity and Nissan warranty for the Leaf’s battery is 8 years/100,000 miles until the 80% of residual capacity. It is supposed that the battery can live at least 10 years (or about 70,000 km before the battery ranges 80% of its initial capacity). A survey carried out by Tesla[17] state that most of the sample batteries lost 10% of their capacity after 270,000 km. A similar survey made for the Nissan Leaf shows that the original 24 kWh pack lost on average 20% of its capacity only after 60.000 – 70.000 km.

In estimating the lifetime of traction LIB, it is worth noting that the degradation of batteries is dependent on the combination of calendar (stand-by) ageing and cycling (charging and driving) ageing (137) and it is affected by several external factors, e.g. temperature (137,138). Furthermore, uncertainty related to lifetime of traction LIBs is also related to the fast development of the technology and to the limited number of exhausted batteries to have a representative sample of lifetime values. For analysing the lifetime of traction LIBs, a lifetime distribution is recommended rather than fixed values. As an example, the Weibull distribution is considered appropriate to describe this (139).

Li-ion SLI battery (88) estimates average lifetime ranges between 5 and 7 years.

4.2.3 ESS LIBs

LIBs in ESS are used in power supply systems (off-grid and grid-connected) and their development depends on the development of Renewable Energy Sources (RES) (112).

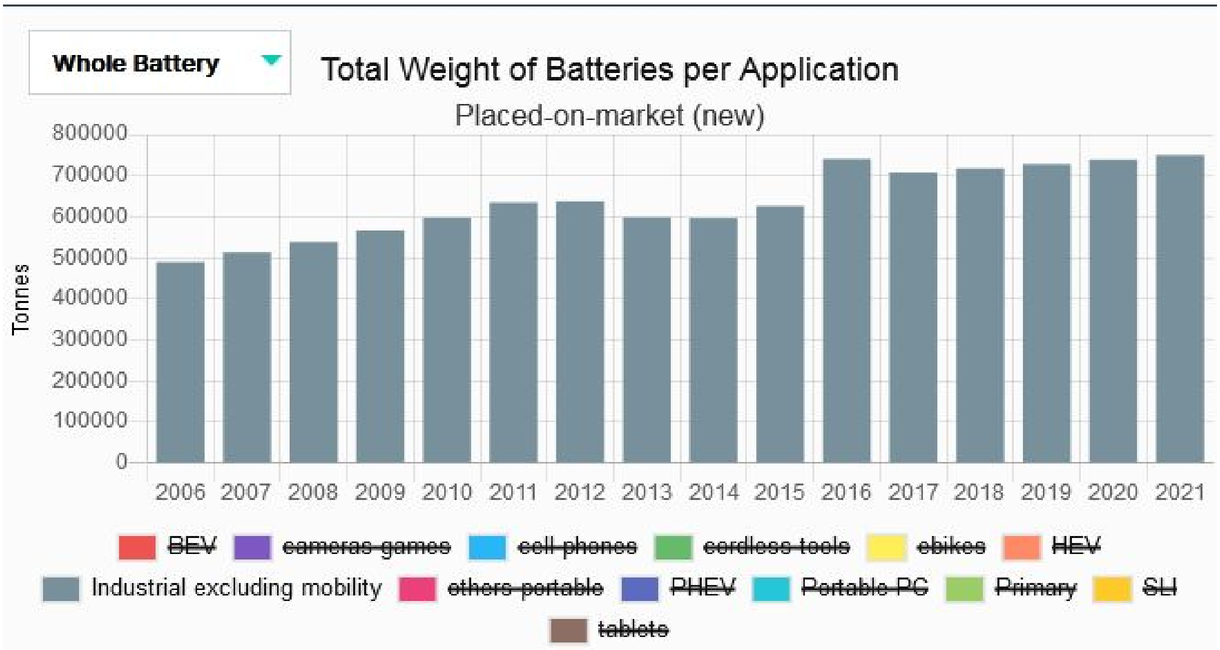
As for traction LIBs, lifetime of ESS LIBs is application-dependent, so that an average value of lifetime for those batteries is highly uncertain. In general, batteries for industrial applications can reach 20 years (115). This is also confirmed by the fact that most of the Li-ion storage projects in the US DOE's (Department of Energy) database consider a lifetime ranging between 15 and 20 years (6). Also, NREL said: *"Without active thermal management, 7 years lifetime is possible provided the battery is cycled within a restricted 47% DOD operating range. With active thermal management, 10 years lifetime is possible provided the battery is cycled within a restricted 54% operating range,"* (140) and *“Assumed 25 years system for grid-connected photovoltaic systems (Optimal sizing of a lithium battery energy storage)”*. BLAST (Battery Lifetime Analysis and Simulation Tool)[18] is a toolkit developed by NREL aiming to estimate the lifetime of batteries for different applications, including behind-the-meter applications. For instance, a variant (i.e. BLAST-BTM) specifically addresses peak shaving applications and the BLAST-S variant addresses other utility-scale applications.

According to Hesse et al. (141), reaching 20 years for state-of-art LIB systems, especially used in PV applications, is still a challenge of the 2020s.

In terms of flows, starting from the industrial LIBs placed on the market and the current stocks, the waste of industrial batteries until 2020 are provided by the ProSUM project and updated for the EU in the RMIS (see Figure 46 below). The values presented based on industry data are considerably higher than those reported by Eurostat.

[17] https://docs.google.com/spreadsheets/d/t024bMoRiDPIDialGnuKPsg/edit#gid=1710185683
[18] https://www.nrel.gov/transportation/blast.html

Figure 46. Market input of Industrial LiB (all non-portable and non-automotive applications incl. ESS)



4.3 The future of recycling industry and the role of remanufacturing and repurposing

Key information gaps and issues:

35. Innovation in the recycling industry is necessary, however, size matters and an economy of scale of the battery recycling plants need to be reached
36. In the circular economy context the aim should be to develop sustainable recycling processes that rely on fewer external inputs and lower waste generation.
37. The difficulty in predicting the volumes of LIBs in waste flows is strictly related to the uncertainty in the lifetime of LIBs
38. A standardized methodology for the SoH assessment of aged Lithium-ion batteries is still not properly developed. This leads to uncertainty in the estimation of LIBs' lifetime in second-use applications.
39. The missing regulatory framework for extending the lifetime of batteries through their remanufacturing/second-use is adding more elements of uncertainty.

The recycling industry in the EU is strong but it may not be ready to accommodate the incoming flow of LIB waste (e.g.). Innovation is necessary although uncertain revenue and economy of scale and unknown future raw material price may make difficult investments. Innovation in the lithium-ion recycling industry is looking for the most efficient and best combination of recycling processes to minimize costs and increase the recovery rate of SRM. The challenge is to transfer those innovations into a processing plant, where size matters and an economy of scale of the battery recycling plants need to be reached. Furthermore, in the circular economy context the aim should be to develop sustainable recycling processes that rely on fewer external inputs and lower waste generation (142). The innovation should not only rely on the improvement of chemical and mechanical processes, but also should be supported through the improvement of the logistic process and legislatory framework. For instance there is a widespread consensus that a simple enforcement of standardized Lithium-ion battery labeling system could be of great help. Scrap recycling facilities built besides battery cell manufacturing plants could be ideal for testing and busting the required innovation in the recycling processes (e.g. Innoenergy and NorthVolt investment (143). This will offer the chance not only to improve the known pyro-hydro and mechanical processes, but also to test the so called 'direct recycling' which would allow the direct recovery of the majority of battery components (i.e. cathode, anode, electrolyte, metals) with the advantage to keep some of the material properties' vs. recycling into raw materials (back into individual metals/ precursors).

The possibility to reuse LIBs through their remanufacturing and/or repurposing and second-use will extend their lifetime and delay their collection as waste batteries. Although reuse of batteries is not yet developed in the EU (94), this delay should be considered to forecast future waste flows in the EU. In case of remanufacturing, batteries (or batteries' modules) will be reused again in xEV, whereas in case of repurposing and second-use, batteries will be adopted in applications other than EVs. Due to the novelty of the topic and the high level of uncertainty related to both the application and the used battery performance in a specific application, more research efforts are needed to establish the lifetime of LIBs in second-use applications. Based on the literature, the batteries lifetime in second-use applications ranges between 5 and 10 years (94). In a recent JRC (Joint Research Centre of the European Commission) study, the lifetime is estimated through an energy model considering both the system and the battery characteristics; for both applications (peak shaving and increase of PV self-consumption), the second-life is estimated to be about 4 years (144). Also in case of second-use, the estimation of second-life is application-dependent (93), so that experimental data are needed to well describe a lifetime distribution of LIBs in their second-use applications. The correct estimation of potential lifetime requires also a proper methodology for the assessment of State of Health (SoH) of batteries at the end of their first life. Unfortunately, a standardized methodology for the SoH assessment does not yet exist although numerous projects and research works are dealing with this technical challenge (e.g. CarE-Service and LibforSecUse)[19].

Note that the high value of SRMs in the market could discourage the second-use of batteries in the system (economic driver) and as mentioned in the previous chapter the missing regulatory framework for extending the lifetime of batteries through their remanufacturing/second-use is adding more elements of uncertainty.

4.4 Are there changes foreseen in the lithium-ion technology in terms of chemistry/application and performance?

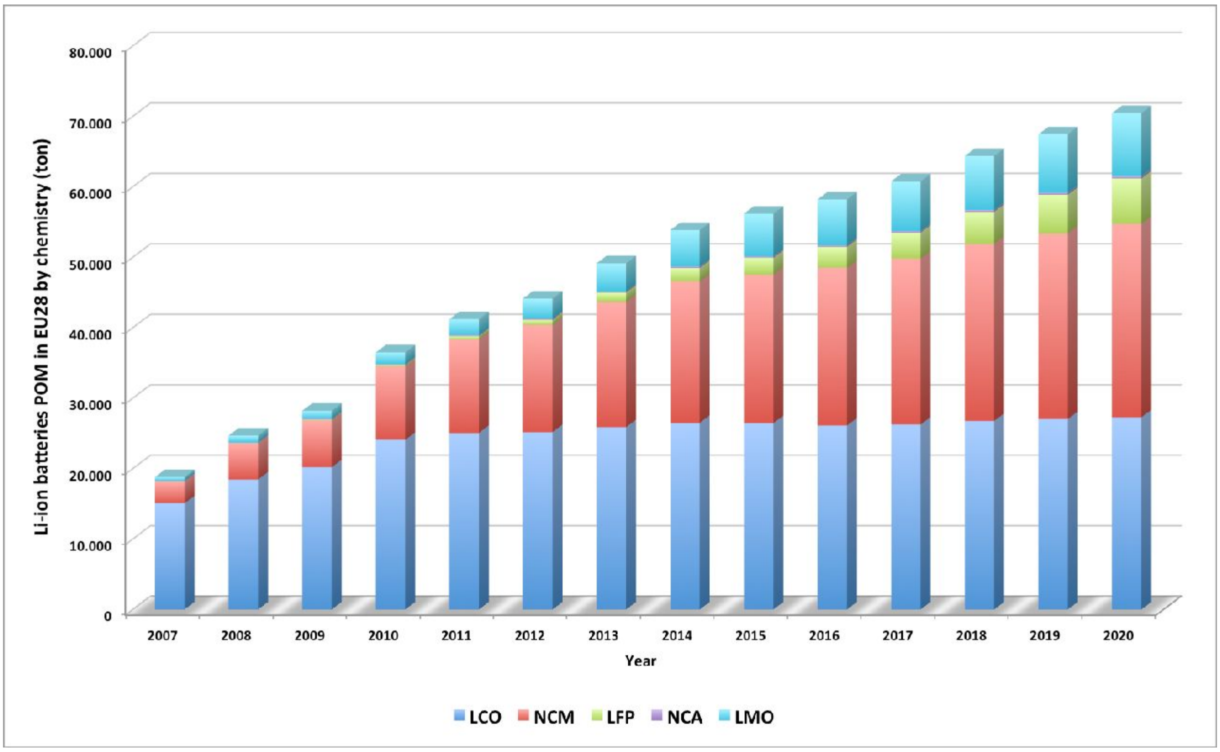
Key information gaps and issues:

40. The LIBs market in 2030 is very likely to be mainly dominated by NMC with decreasing amount of Co
41. No specific data are available on the evolution of specific chemistries to be used for portable batteries in Europe.
42. New battery technologies, beyond Lithium-ion are not foreseen to be commercialized before 2030.

Focusing on the LIBs chemistries available in the market and expected in the European market in the next years, LCO is not expected to increase up to 2020, whereas NMC is expected to increase very fast to be mainly used in traction LIBs (107) (Figure 47)[20] . Accordingly, PROSUM estimates a decrease of LCO chemistries and a strong increase of NMC chemistry in the waste flow up to 2020.

[19] H2020 projects: CarE-Service (http://www.careserviceproject.eu/); Joint European Metrology Project: LibforSecUse (https://www.ptb.de/empir2018/libforsecuse/home/)
[20] Also available at https://accurec.de/battery-market

Figure 47. POM of lithium-ion batteries in EU28 by chemistry (2007-2020) (107)



In general, the LCO market is expected to decrease under 15% in 2030 since LCO is mainly used in portable LIBs; whereas NMC is expected to dominate the LIB market already in 2025 (112). NCA and LFP will be used in specific sector but without a big role as NMC; overall, the LIBs market in 2030 is "*is very likely to be NMC in first place with a 35% market share, followed by LFP and NCA with a 40% combined market share, and finally LCO and LMO*" (112).

Also according to Pillot (116), the main difference in the development of LIBs chemistries will depend on NMC chemistry.

4.4.1 Portable LIBs

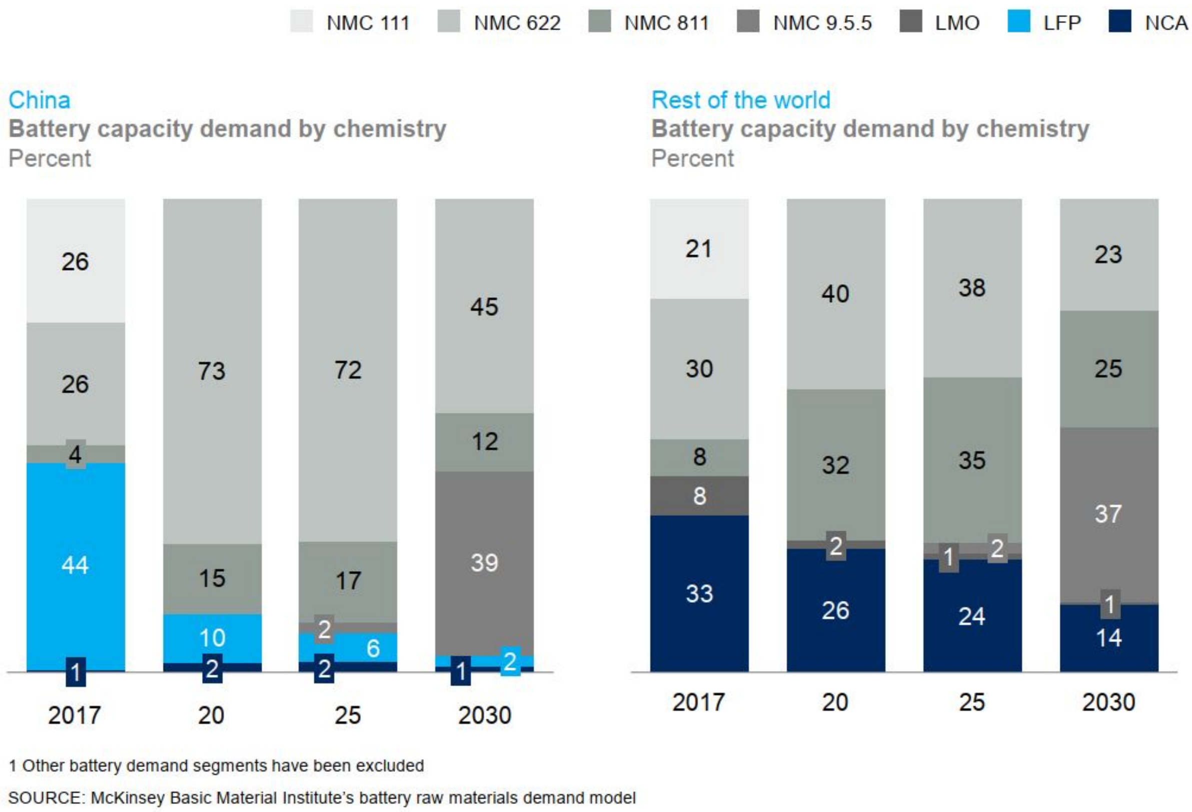
No specific data are available on the evolution of specific chemistries to be used for portable batteries in Europe. Several sources state that LCO will continue to be the most used chemistry for portable LIB due to its good performance and the high level of safety. NCA could also substitute the expensive LCO cathode (145).

4.4.2 Traction LIBs

Looking at the current market and its main actors, the main chemistry used for traction LIBs is NMC. However, due the high price of Co, the development of low Co NMC are under development (112). In 2025 it is forecasted that the LMO batteries will no longer be used for traction batteries whereas 10%-15% of LIBs sold for EV will be NCA, 0%-20% LFP, and the remaining 70%-85% NMC chemistry. Most of the NMC chemistry is low cobalt NMC, i.e. most NMC622, NMC811 and NMC9.5.5[21] (145,146) (see figure 48).

[21] NMC9.5.5 has 9 part of Ni and 0.5 of cobalt and manganese (145)

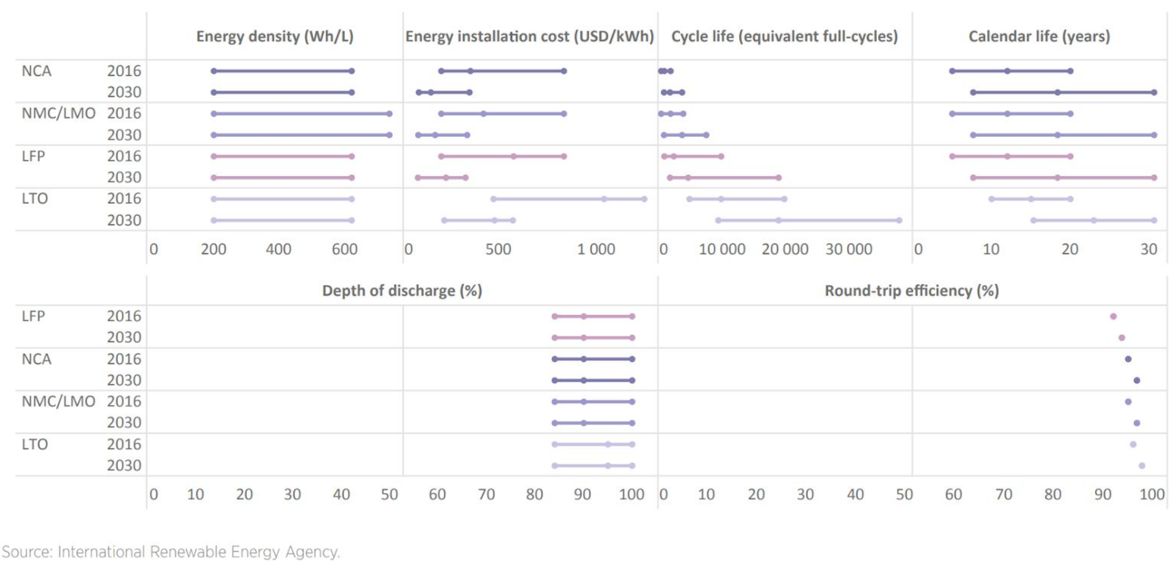
Figure 48. Projections for distribution of EV by battery chemistry (145)



4.4.3 ESS LIBs

The most relevant characteristics for ESS batteries are long lifetime and high safety (147). Therefore, LFP is a suitable chemistry for ESS also due to its low costs compared to other Li-ion chemistries. Despite its higher cost, also LTO chemistry is expected to have a relevant market share up to 2030, because of its long lifetime and its high round-trip efficiency (148) (Figure 49).

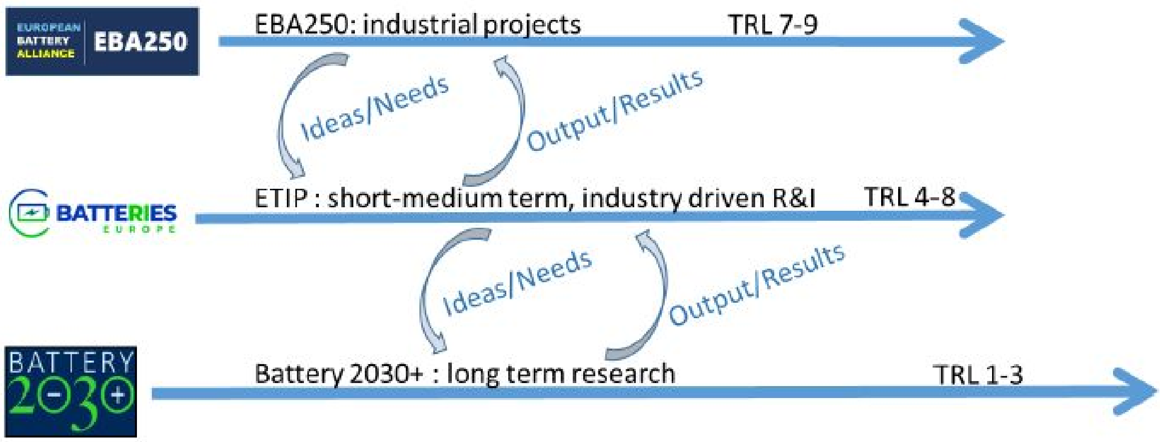
Figure 49. Properties of selected chemistries of lithium-ion battery electricity storage systems, 2016 and 2030 (148)



4.4.4 Evolution of performances for LIB and beyond Li-ion technology

In the EU, the Strategic Energy Technology (SET) Plan is a "*key stepping-stone to boost the transition towards a climate neutral energy system through the development of low-carbon technologies in a fast and cost-competitive way*"[22]. Batteries are mentioned among the key actions for research and innovation of the SET Plan ("*competitiveness in global battery sector and e-mobility*") (5). In this framework, European platforms and alliances are working on the topic: European Battery Alliance (3), Batteries Europe (4)[23], Battery 2030+ (149). Among these, BATTERY 2030+ is adopting the longest-term approach (Figure 50).

Figure 50. Complementarity between three the European Battery Alliance, Batteries Europe and Battery2030+ (150)



The enhance and speed up innovation in the batteries sector, research areas covered by the BATTERY 2030+ are (1) materials acceleration platforms to accelerate the discovery and development of new materials/electrolytes/interfaces-interphases; (2) battery interface genome to improve the knowledge of controlling interphases and interfaces during the operational lifetime of batteries; (3) sensing and (4) self-healing to improve durability and sustainability of batteries.

Roadmaps of the development of Li-ion technology are available in the literature and mainly state that the Li-Co based chemistries will be the most adopted chemistries in the next decades in the EU (11,21). New chemistries not yet available at industrial scale are expected to enter the EU market depending on their application, e.g. NaS, Li-S, Li-air (110,112). The need for longer lifetime, improved performances and competitive cost are important drivers for new technologies that are expected to enter the market up to 2030 (110,112,150).

Some projects are focusing on various post Lithium-ion technologies, e.g. Li-air, Li-sulphur (111,151). However, Li-air is at prototype level (laboratory status) and improvements are needed before its massive use; Li-S will more probably replace LIB in the next 5-10 years in Europe due to both the low cost materials and its energy density (122). Also, new batteries should reduce the gap existing between the real specific energy density and the theoretical one, as reported in Figure 51 (150). Figure 52 shows the roadmap presented by Energy Materials Industrial Research Initiative in a 2018 workshop.

[22] https://ec.europa.eu/energy/topics/technology-and-innovation/strategic-energy-technology-plan_en

[23] https://batterieseurope.eu/

Figure 51. Practical and theoretical energy density for different batteries chemistries (148).

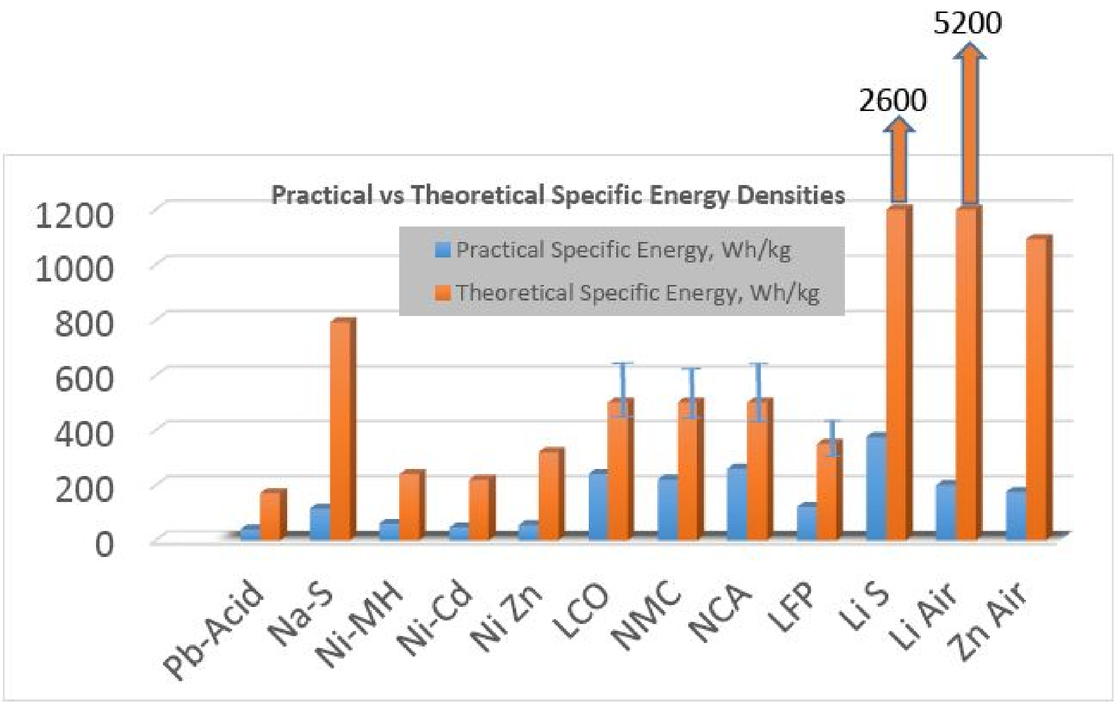
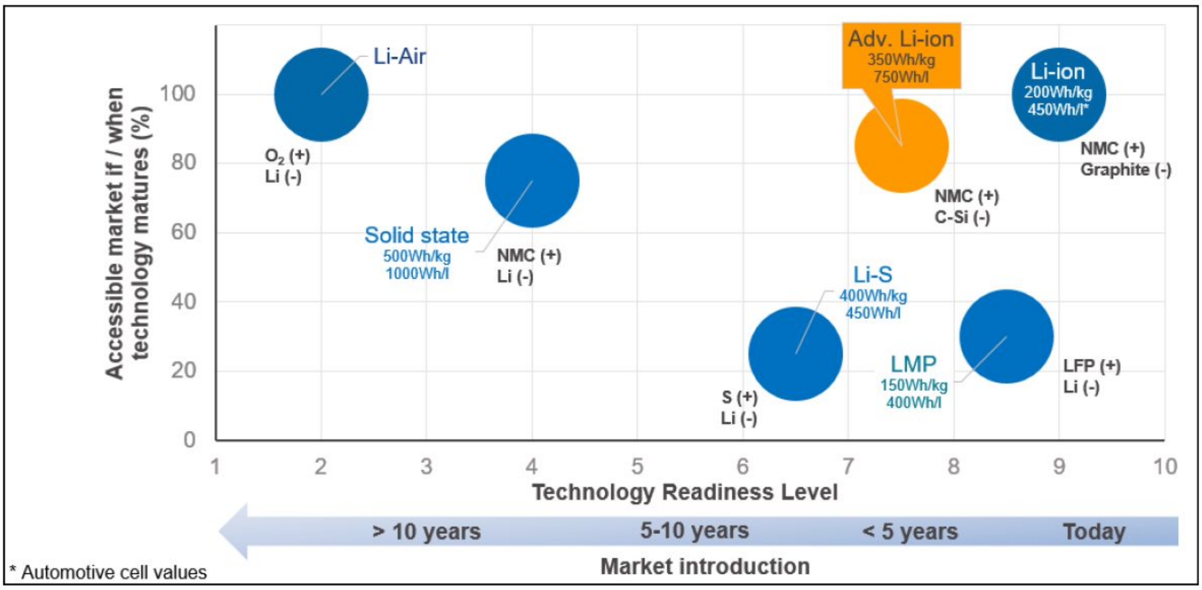


Figure 52. Roadmap of future batteries in the market, and the chemistries according to their energy density and technological maturity (110)



It also reported that super-capacitor is a technology that can reach higher power density than LIBs (e.g. 10-20 kW/kg) and can very rapidly change and discharge over many cycles. However, current super capacitors in the market have poor energy (<8 Wh/kg) and cannot compete with LIBs (122,152). Despite being a relatively new technology, super-capacitors are commercialised already in hybrid buses, control systems and uninterrupted power supplies and it is expected that the energy density will reach 50 Wh/kg in 2030 (122).

4.5 Raw materials flow analysis model. A zoom on Cobalt in traction LIBs

Key information gaps:

43. Material Flow Analysis (MFA) model may be a useful tool to grasp the multiple and interconnected factors affecting the flow of LIBs' raw materials in EU in different timeframes.
44. The uncertainty of the available data inputs is quite important and should be addressed through {1} an extensive data collection, involving different actors of the values-chain and {2} performing different scenarios in order to identify key parameters affecting stocks and flows of materials

According to the previous sections, more efforts are necessary in collecting information and data on batteries to better understand their evolution in time. Also, an in-depth knowledge of the whole value-chain of LIBs is essential to identify the stocks and flows of LIBs and, consequently, of materials embedded in LIBs. In fact, the in-depth knowledge of flows of LIBs allow to identify the processes in which materials are stocked and when they will be available e.g. for recycling. This is particularly relevant in case of CRMs for the EU or materials for which the demand is expected to rapidly increase. Accordingly, in this section a qualitative analysis of stocks and flows of LIBs in the EU is provided; to better illustrate the analysis model, examples are provided referring to cobalt embedded in traction LIBs.

Figure 53 shows a simplified model that allows to estimate the stocks and flows of materials embedded in LIBs. Such a model is based on the dynamic MFA model proposed by (79), which describes the value-chain of traction LIBs in the EU mainly focusing on current and future EoL options. The MFA model reported in Figure 53 was enlarged to cover all the value-chain of LIBs: the most relevant processes (boxes) from the primary raw materials extraction to the landfilling are included. The flows of materials embedded in the LIBs are represented by the arrows; they include the flows between processes, losses of materials and import/export flows. The value-chain was modelled based on the information gathered from both stakeholders and literature data, and it refers to the current EU value-chain (109).

An example of information that can be gathered from the dynamic MFA model is the quantification of SRMs that can be kept in the EU through the extension of the lifetime of LIBS (e.g. reuse practices) or their adoption again in manufacturing new LIBs. Especially for some processes/flows, the uncertainty of data is quite high; this is for instance the case of recycling process: efficiency of recycling and quality of recycled materials are key parameters to be considered in estimating the amount of SRMs flow. Concerning Cobalt, several sources state that the cobalt is already recovered through recycling and the efficiency of such a process is quite high (109,153); this is related to the high economic value of the recovered material (112,154). For other materials like Lithium, recycling is currently quite limited even though technically feasible (10); hence, especially in this second case, changes are expected in future and the MFA can capture the potential relevance of this increasing flows of SRMs.

The first step of the assessment is the definition of the geographical boundaries of the analysis (dashed box in Figure 53). The inclusion or exclusion of processes and/or flows will be reflected in the size of the flows, that will change according to the system under analysis, the input and the adopted assumptions (e.g. different recycling technologies result in different recovery rate, countries that are net importer/exporter of LIBs have big import/export flows).

Hereinafter a more detailed description of the processes and flows is provided, in relation to the lack of data highlighted in previous sections and focusing on traction xEVs for which more information are available compared to ESS and portable batteries. The model could be adapted also to the value-chain of other types of batteries. This will imply an update of the model in terms of adding new modules (processes and flows) or delete some modules now in the MFA model. Note that the adoption of a modular model, with parameters allows to not consider some of the modules in the model simply putting corresponding flows equal to zero.

Raw/Processed materials stages (grey boxes)

PRMs, together with SRMs, are inputs of the raw and processed materials stages. The EU is dependent on third Countries about the supply of key raw materials for LIBs (section 2.2), e.g. cobalt is mainly provided by the Democratic Republic of Congo (section 2.2.2). Therefore, flows of import/export are included in the system. Note that, even though the export of PRMs of LIBs is null (equal to zero in the mathematical model), this flow is included in the MFA model to allow the assessment of different scenarios or possible changes in future. For instance, a flow that could become more relevant in the future is the flow of SRMs, i.e. materials from recycling of LIBs (section 4.3).

This stage is split in "raw materials" and "processed materials" to better represent the value-chain of materials, to clearly visualize different flows and to take into account specific characteristics of processes (e.g. losses between processes or processes efficiency).

Key aspects that can potentially change in future are: potential strengthening of the EU domestic refining of raw materials for LIBs, including SRMs in the process; materials content in different chemistries; emerging of new LIBs chemistries.

LIBs manufacturing (blue boxes)

According to the manufactured chemistry (section 4.4.2), different quantities of materials will enter and be processed in the EU. Such materials can be provided by both domestic production (from grey processes) and from third Countries (as mainly occurring nowadays, see section 2.2). Also, the possibility of improving manufacturing of both components and LIBs in the EU is included in the system through the flows quantifying the export of export cells and LIBs.

To capture the technological changes in terms of both chemistries and quantities, the output of the "LIBs cells manufacturing" process is a set of flows representing different LIBs chemistries. For instance, focusing on cobalt, Co-based cathodes are currently the most representative chemistry in the EU market (e.g. NMC111, NMC811, NCA), but there are expected to decrease in the future (section 4.4.2). The number of flows reflect the number of chemistries available in the market, currently and expected in the future; their size of flows provide an overview of the most common chemistries available in the EU at the analysed year.

Key aspects that can potentially change in future are: potential strengthening of the EU domestic manufacturing of LIBs and their key components; materials content in different chemistries; emerging of new LIBs chemistries.

LIB in EVs (yellow box)

LIBs are mounted in the product for which they were built, in this case EVs. In this process, import and export. Also, materials embedded in LIBs that are imported/exported is included. Materials in LIBs are stocked according to their lifetime ("Stock I" in Figure 53). The stock of materials embedded in LIBs is expected to increase according to the improving performances of batteries and therefore their longer lifetime compared to LIBs that are currently in the EU fleet (section 4.2.2). Due to the complexity of determining the lifetime of a fleet of LIBs used in different applications (i.e. PHEV and BEV), the adoption of a distribution function like the Weibull distribution is recommended. Also, the uncertainty should be addressed through e.g. the variation of parameters adopted in the adopted distribution (155).

From the performed literature review, it emerged that most of the available forecast refers to future mobility focusing mainly on EVs placed on market, and on the uptake of EVs in the future EU fleet (section 4.1.2). Based on past trends of import/export and industrial information about the evolution of automotive industry in the EU, it is possible to define the share of imported/exported vehicles and manufactured vehicles in the EU. An important source of uncertainty on forecast is that future mobility is heavily affected by several factors (156,157), and therefore available forecasts of LIBs in the mobility sector depend on various types of assumptions, e.g. environmental targets, price of key components, economic incentives, in fractures, etc. This results in a very different share of EVs in the next future.

Also, the amount of LIBs in the system does not always reflect the number of EVs in the market. In fact, the flow of LIBs place od market could increase also due to the possible increase of second-hand market of EVs in which new LIBs will be placed (95,158) and LIBs replacement depending on their warranty conditions (95).

Key aspects that can potentially change in future are: change in the mobility system; increased LIBs; second-hand market of EVs/LIBs; warranty conditions.

LIBs EoL

Based on the results of the lifetime distribution (mentioned above), the amount of LIBs extracted from EVs is the sum of the output flows of the process "LIBs placed on market (POM) and used in EVs". After their use, batteries are collected through car dealers (e.g. due to recalls, malfunctions of accidents) or dismantlers (when no more suitable for xEVs) (159). When extracted from xEVs, batteries can be tested in order to know their residual capacity or directly addressed to recycling. It is also worth noting that not all the batteries are properly removed and collected (160); this aspect is considered through flows of lost LIBs (dashed flows). Batteries replaced e.g. based on their warranty (95), that do not yet reach their EoL in terms of performances, can be still used in xEV or other applications after proper testing, remanufacturing and/or repurposing (79).

Example of remanufactured batteries are already available worldwide[24], for instance the Nissan Leaf[25] or Spiers New Technologies[26]; in case of warranty service for the Tesla Model S/Model X, the battery could be replaced by Tesla or substituted with a "factory reconditioned unit" (Tesla, 2017). In case of remanufacturing, an internal loop is created; if LIBs are repurposed and used in second-use applications, a new stock of LIBs within the system should be considered ("Stock II" in Figure 53). As a consequence, recycling of batteries is delayed according to extended lifetime of LIBs and also the recovery of SRMs. When LIBs cannot be used either in EVs or second-use applications, they are addressed to recycling to recover SRMs. An recirculation of SRMs within the battery sector, which means that SRMs are used to manufacture new LIBs depends on the quality of the recovered material. There are examples of cobalt recirculated in a closed-loop (161) According to the assessed material and the recycling technology, the quality of the recovered materials is essential for its recirculation in the battery sector.

Note that in the EU exhausted batteries have to be recycled according to in force Directives (89), so that incineration and landfill disposal is not considered in this model.

Key aspects that can potentially change in future are: improvement of the collection rate of LIBs; increase of import/export of used LIBs; development of remanufacturing and second-use of LIBs; increase of recycling (both efficiency of the process and quality of the recovered materials).

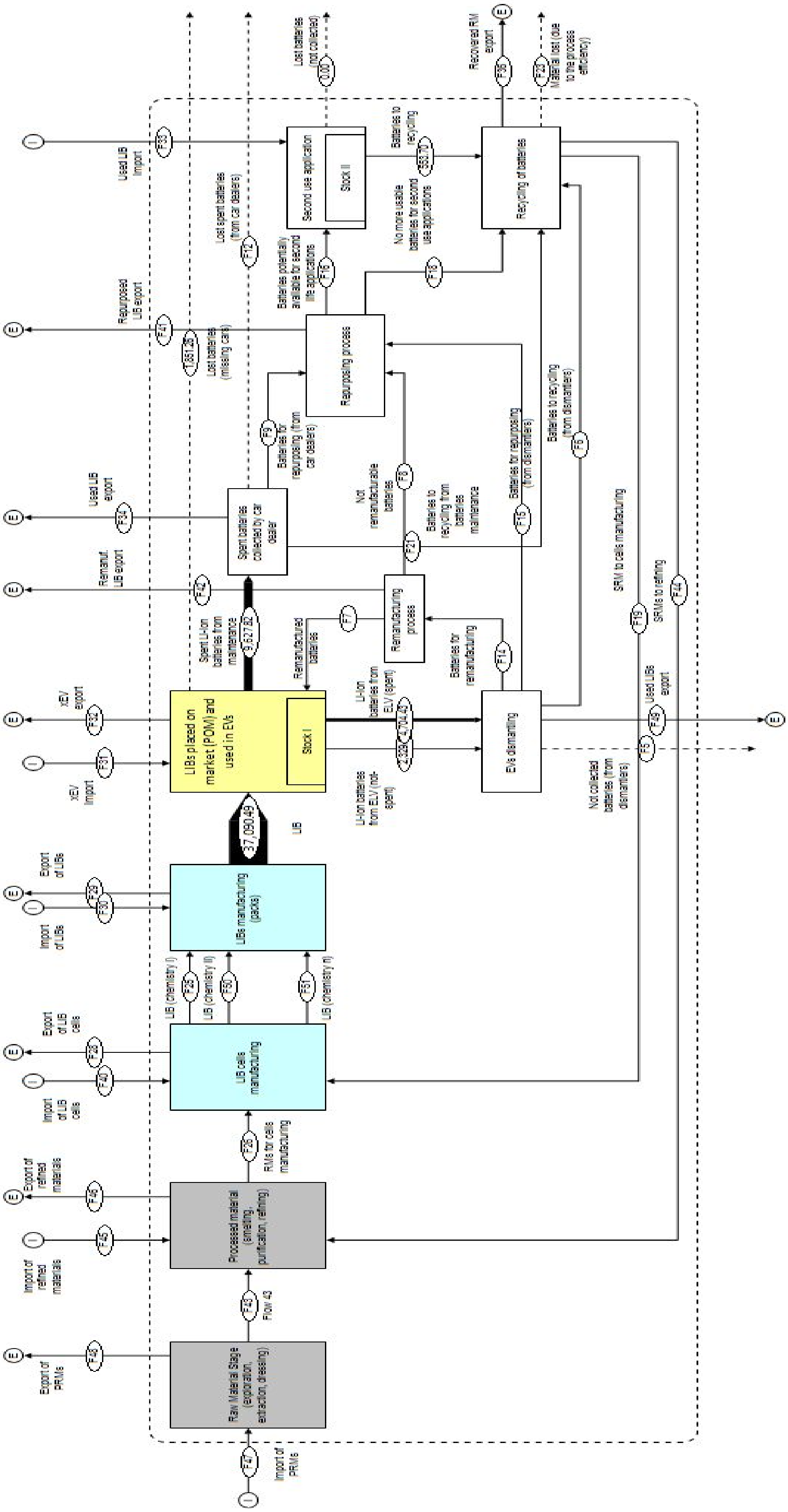
In case of second-use, a new stock of materials embedded in LIBs within the system should be considered ("Stock II" in Figure 53).

[24] E.g. http://www.globalbatterysolutions.com/

[25] https://insideevs.com/nissan-introduces-refabricated-batteries-for-older-leaf-in-japan-from-new-4r-plant/

[26] http://www.spiersnewtechnologies.com/#lifecycle-management. Note that in the website the term "remanufacturing" is used for "Remanufacturing vehicle battery packs and modules for second life deployment in non-vehicle applications", whereas "repair" for "Repair and Refurbishment of vehicle battery packs for redeployment in vehicles"

Figure 53. simplified model for a MFA along the LIB value chain. Source: JRC, (2020)



5 Conclusions and policy implications

The EC Vice-President Maroš Šefčovič called the European stakeholder for actions to build a competitive European battery industry: "… *We need to establish a whole value chain in Europe. A value chain focused on green batteries, from security of supply to production processes recyclability and second use, to gain competitiveness and economies of scale*…".

In this report we tried to highlight bottlenecks and gaps that are actually preventing turning this vision into reality, including strategies to overcome these bottlenecks.

Still today the worldwide usual business in the Li-ion battery value chain follows the traditional linear economy approach, and the vision above stated can only become true if the growing EU Li-ion battery industry moves to a sustainable circular economy paradigm. This means also that a competitive European lithium-ion cell manufacturing industry can only materialize if Europe can secure access to sustainable and responsibly sourced battery raw materials at reasonable price.

We followed the actual Lithium-Ion batteries materials flow timeline progression to identify the processes in which materials are stocked and when they will be available. In our analysis the mobility scenario is often employed to describe the problems and we focused on the four most emblematic materials used in the Li-ion battery production: Co, Li, Ni and natural graphite. These materials are derived mainly from PRM mined from the earth's crust, either from the surface or underground. Unfortunately, in the actual circumstances this traditional source of raw materials is not reliable for the EU LIBs industry. The most obvious reason is that PRM domestic production is not nearly sufficient to meet the actual and forecasted LIBs EU industry demand. Moreover, their prices are extremely volatile and their evolution is very difficult to predict. Market actors for mining and processing activities are very dynamically changing and resources and reserves data of PRM is always very uncertain due to variations in reporting methodologies and the not consistent statistics among various sources.

A circular economy approach requires keeping product and materials value in the loop in an attempt to mitigate the Li-ion battery raw materials criticality and improving their resilience. Criticality of raw materials is by definition forward looking, though often estimated on average trends over recent past years. A resilience based approach should additionally anticipate future supply and demand balance mismatches and identify adequate mitigation strategies.

Using the recycling of LIB as SRM source and efforts to substitute specific materials (e.g. lower Co content, Si enriched anode, change of one chemistry with another) are probably not enough to bring the European material supply for the Li-ion manufacturing industry to reach a high level of resilience, but they are necessary and very important steps that will certainly mitigate supply issues. As well, new battery technologies, beyond Lithium-ion are not foreseen to be commercialized before 2030. Consequently PRM sourcinge is and will be still necessary. On the other hand, boosting EU domestic mining production of relevant Li-ion battery materials may also contribute to mitigate their criticality and improve their resilience although the unclear and not uniform regulatory context for mining in the EU may be a limiting factor.

The availability of SRM is first conditioned by the access to the waste li-ion battery, which is obviously linked to the amount of li-ion battery that has been put on the market so far and on how much of it has been collected. However, historic time series for battery volumes entering and leaving the market are predominantly based on industry sources which are not harmonized as well as EU Member States reporting that, although complying with the Battery Directive, is also not fully reliable because of underreporting market inputs. Consequently, specific data on time-dependent chemistries is rather scarce or with high uncertainties. Furthermore, the conversion of units to weight and compositions introduces relatively large uncertainties in the materials stocks and flows information. The difficulty in predicting the volumes of LIBs in waste flows is strictly related to the uncertainty in the lifetime of LIBs. The estimation of average lifetime of LIBs in EV and ESS is quite uncertain due to the limited information currently available, due to the few EV and ESS Li-ion batteries that have reached their EoL or the different behaviour of batteries in such different applications. Available studies made assumptions based on warranties and producers indications. Due to the high level of uncertainty, the adoption of a LIB lifespan distribution function is recommended. All these factors are hindering sound estimates on the volumes becoming available for recycling. Also, current datasets are not updated with actual market information and contain direct extrapolations without more robust market forecasts. A consistent use of a more detailed battery classification may bridge between different official and non-official sources. This may enable harmonisation, improving characterisation of the raw material content and ultimately the monitoring of collection and recycling performances.

There are only a few large recyclers in Europe. However, information on actual treatment volumes of LIBs (not capacities) is not available. There is scarce and only anecdotal data on actual recovery rates and RIRs (Recycling Input Rates) from scraps, which clearly require to define more intelligent collection and recycling targets, reflecting environmental and societal recovery value for the most relevant batteries and materials. Future capacities and competitiveness of EU recyclers is difficult to determine in the current emerging market with high price volatility and uncertainty on the volumes becoming available for recycling. Data on future sales of LIBs per application and chemistry are by definition not certain. Available data are often aggregated (per application, per geographical area, etc.) and therefore hardly comparable. Different drivers should be considered in forecasting LIB sales, e.g. user behaviour for portables, regulatory framework and incentives for traction batteries and ESS. Also, substitution scenarios should consider the fast development of the battery technology. A clear legislative framework to enforce an easy dismantling/recycling and labelling of LIBs battery packs may help the recycling industry at least for all the preparatory steps previous to the recycling process. But still significant uncertainty about overall costs and environmental and social benefits of recycling are expected. Big volumes will only become available in the future adding uncertain economies of scale to unknown future metal prices (in particular for Cobalt). Size matters and an economy of scale of the battery recycling plants need to be reached. The recycling industry should keep pursuing technological innovation to develop sustainable recycling processes that rely on fewer external inputs (e.g. energy) and lower waste generation and environmental impact and at the same time flexible enough to cope with variable volume and composition of LIBs waste inputs.

For EV batteries, besides recycling, the remanufacturing for reuse in less demanding traction applications or repurposing in a second use for e.g. ESS applications is another circular economy approach capable of keeping the material and product value in the loop. However, The efficiency related to environmental, economic and safety aspects of reuse and repurposing practices is not yet properly assessed. A standardized methodology for the SoH assessment of aged Lithium-ion batteries is still not properly developed. This leads to uncertainty in the estimation of LIBs' lifetime in second-use applications. Moreover, the existing EU regulatory framework for battery waste (Battery directive 2006/66/EC and Waste Directive) limits the Extended Producer Responsibility (EPR) transfer and the "End of Waste" status, which are dimmed necessary for a better functioning of the second-use option in the EU adding more elements of uncertainty. Furthermore, the repurposed battery will compete with new advanced batteries and it is not clear how price and warranty policies will be able to cope with it. On top of that, if EV batteries go through a second life, the key raw materials contained in those batteries will be retained in applications and not available for more years to come. This will lower the volume of available batteries for the recycling industry, possibly limiting their revenues. This may also impede the immediate use of key and valuable raw materials (e.g. Co) to produce more resource efficient batteries and also possibly affecting the price of SRM, limiting the EU cell manufacturing industry to access a potential domestic source of raw material.

It is of paramount importance to be able to quantify the present and future availability of SRM. A robust Material Flow Analysis model is necessary. In this report we proposed a simplified MFA model that allows us to estimate the stocks and flows of materials embedded in LIBs. The MFA model is a useful tool to grasp the multiple and interconnected factors affecting the flow of LIBs' raw materials in EU in different timeframes, although the uncertainty of the available data inputs is quite important and should be addressed through {1} an extensive data collection, involving different actors of the LIBs values-chain and {2} performing different scenarios in order to identify key parameters affecting stocks and flows of materials.

Future works

The estimation of SRM available for the LIB industry is a difficult exercise. However considering the limitations highlighted in this report, a preliminary quantitative assessment could be performed. The MFA model could be used looking at different raw materials.

Environmental considerations related to all LIB supply chain stages should be reviewed as well. Conducting LCA work was out of scope of this report, but the analysis of information performed in this report is key for subsequent impact assessment work which in turn is crucial for policy making.

The same counts for evaluation of economic considerations including analysis of the cost and benefits of recycling and of the primary versus secondary raw materials; the consequences of organisational, technical and other changes in the value chain including increasing vertical integration, the effects of cost reductions and increasing economies of scale over time, etc. Furthermore, social consideration at EU level, like job creation, and non EU level, like the impact of circular economy on mining countries and responsible sourcing deserve careful attention and detailed scrutiny.

Finally, the options to enhance the competitiveness of products with higher environmental and social standards should be analysed. How to set a fair market where responsible sourcing and circular economy strategies are economically awarded? How to set higher standards, more transparency about the supply chains and measures to improve product quality, repairability, inter-operability, removability and recyclability with higher collection and recycling rates?

List of abbreviations and definitions

EBA (European Battery Alliance)

LIBs (Lithium-ion batteries)

EU (European Union)

MS (EU Member States)

US (United States)

EVs (Electric Vehicles)

BEV (Full battery EVs)

HEV (Hybrid EVs)

PHEV (Plug-in Hybrid EVs)

xEVs (Generic Electric Vehicles that include BEV, HEV and PHEV)

ESS (Electrical Stationary Storage)

EEE (Electrical & Electronic Equipment)

PRM (Primary Raw Materials)

SRM (Secondary Raw Material)

CRMs (Critical Raw Materials)

MFA (Material Flow Analysis)

LCA (Life Cycle Assessment)

Li (Lithium)

Ni (Nickel)

Co (Cobalt)

Mn (Manganese)

Al (Aluminium)

Cu (copper)

Si (Silicon)

C (natural and synthetic graphite)

Fe (Iron)

S (Sulphur)

CO2 (Carbon dioxide)

LFP (Lithium-Iron-Phosphate oxide LIB cathode)

NMC (Lithium-Nickel-Manganese-Cobalt oxide LIB cathode)

LMO (Lithium-Manganese oxide LIB cathode)

NCA (Lithium-Cobalt-Aluminium oxide LIB cathode)

LCO (Lithium-Cobalt oxide LIB cathode)

SoH (State of Health)

EoL (End of Life)

EPR (Extended Producer Responsibility)

NiMH (Nickel-Metal Hydride)

NiCd (Nickel-Cadmium battery)

PbA (Lead Acid battery)

SLI (Start-Light-Ignition low voltage automotive batteries)

POM (Placed On the Market)

WEEE (Waste Electrical & Electronic Equipment)

LCE (Lithium Carbonate Equivalent)

List of figures

List of tables

References

1. COM(2018) 293 final - EUROPE ON THE MOVE Sustainable Mobility for Europe: safe, connected, and clean - COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS [Internet]. 2018. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A293%3AFIN
2. Sefcovic M. Statement by Vice-President for Energy Union Maroš Šefčovic following the high-level meeting on battery development and production in Europe. 2017; Available from: https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_17_3861
3. EBA. EBA@250 - European Battery Alliance [Internet]. 2018. Available from: https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
4. BatteRIes Europe. BatteRIes Europe kick-off meeting. 2019; Available from: https://ec.europa.eu/energy/topics/technology-and-innovation/energy-storage/batteries-europe_en/
5. European Commission. Integrated SET-Plan Action 7 - Implementation Plan: “Become competitive in the global battery sector to drive e-mobility and stationary storage forward.” 2017.
6. Tsiropoulos I, Tarvydas D, Lebedeva N. Li-ion batteries for mobility and stationary storage applications – Scenarios for costs and market growth, EUR 29440 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97254-6, doi:10.2760/87175, JRC113360. 2018;
7. Wentker M, Greenwood M, Leker J. A Bottom-Up Approach to Lithium-Ion Battery Cost Modeling with a Focus on Cathode Active Materials. Energies. 2019;12(3):504.
8. Bleischwitz R. International raw materials markets: Rising prices and growing conflict potential. 2007;
9. European Commission. COM(2014) 297 final. “On the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative”. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. 2014.
10. Mathieux F, Ardente F, Bobba S, Nuss P, Blengini G, Alves Dias P, et al. Critical Raw Materials and the Circular Economy – Background report. JRC Science-for-policy report, EUR 28832 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-74282-8 doi:10.2760/378123 JRC108710. 2017.
11. Blagoeva D, Alves Dias P, Marmier A, Pavel C. Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030; EUR 28192 EN; doi:10.2790/08169. 2016.
12. Steen M, Natalia L, Di Persio F, Boon-Brett L. EU Competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications –Opportunities and Actions, European Commission, Petten, 2017, JRC108043. 2017.
13. Martinez-Laserna E, Gandiaga I, Sarasketa-Zabala E, Badeda J, Stroe D-I, Swierczynski M, et al. Battery second life: Hype, hope or reality? A critical review of the state of the art. Renew Sustain Energy Rev. 2018;93:701–18.
14. Bakker C, Wang F, Huisman J, Den Hollander M. Products that go round: exploring product life extension through design. J Clean Prod. 2014;69:10–6.
15. H2020 Prosum project [Internet]. Prospecting Secondary raw materials in the Urban mine and Mining wastes. Available from: http://www.prosumproject.eu/
16. Chancerel P, Mählitz P, Chanson C, Binnemans P, Huisman J, Brechu MG, et al. Stocks and flows of critical materials in batteries: Data collection and data uses. In IEEE; 2016. p. 1–8.
17. H2020 Orama project [Internet]. Optimising data collection for Primary and Secondary Raw Materials. Available from: https://orama-h2020.eu/
18. Wagner M et al. Wagner, M. et al, Draft Good Practice Guidelines for the collection of SRM data, improvement potential, definition and execution of Case Studies, Deliverable 2.3, ORAMA project, 31 May 2019, available via https://orama-h2020.eu/wp-content/uploads/ORAMA_WP2_DEL2.3_20192905_v1.0.pdf. 2019.
19. Urban Mine Platform - ProSUM Project [Internet]. 2017. Available from: http://www.urbanmineplatform.eu/urbanmine/batteries/weight/detail
20. Balde CP, Kuehr R, Blumenthal K, Fondeur Gill S, Kern M, Micheli P, et al. E-waste statistics-Guidelines on classification, reporting and indicators”, United Nations University, IAS-SCYCLE, Bonn (Germany) 2015, 51 pages (ISBN Print: 978-92-808-4553-2)(with CP Balde, K. Blumenthal, S. Fondeur Gill, M. Kern, P. Micheli, E. 2015;
21. Huisman J, Leroy P, Tertre F, Ljunggren Söderman M, Chancerel P, Cassard D, et al. Prospecting Secondary

Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report. 2017.
22. European Commission. JRC - RMIS, 2019. Lithium Raw Material Profile. [Internet]. 2019. Available from: https://rmis.jrc.ec.europa.eu/?page=rm-profiles#/
23. Ardente F, Peiró LT, Mathieux F, Polverini D. Accounting for the environmental benefits of remanufactured products: Method and application. J Clean Prod. 2018;198:1545–58.
24. Murakami S, Oguchi M, Tasaki T, Daigo I, Hashimoto S. Lifespan of commodities, part I: The creation of a database and its review. J Ind Ecol. 2010;14(4):598–612.
25. European Commission. Study on the review of the list of Critical Raw Materials - Non-critical and Critical Raw Materials Factsheets; Deloitte Sustainability ; TNO ; British Geological Survey ; Bureau de Recherches Géologiques et Minières; ISBN 978-92-79-72118-2; doi:10.2873/49178. 2017; Available from: https://publications.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1/language-en
26. Ritchie M, Zhu W. Here Are the Firms Feeding China's Battery Revolution, 18 March 2018. Bloomberg [Internet]. Available from: https://www.bloomberg.com/news/articles/2018-03-18/here-are-the-firms-feeding-china-s-battery-revolution
27. Vidal B, Mancini L, Blengini G, Pavel C, Marmier A, Blagoeva D, et al. Raw materials scoreboard. 2016.
28. International trade in raw materials . ISSN 2443-8219. [Internet]. Eurostat; 2018. Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/International_trade_in_raw_materials
29. Brächer M, Hubik F, Streit M. Rising prices of raw materials pose risk to German industry. Handelsblatt [Internet]. 2018; Available from: https://global.handelsblatt.com/companies/rising-prices-raw-materials-pose-risk-german-industry-894801
30. Euromines Annual Report 2016 - Why not invest in Europe! 2016; Available from: http://www.euromines.org/publications/euromines-annual-report-2016
31. BGS. British Geological Survey. Lithium profile. Retrieved from https://www.bgs.ac.uk/downloads/start.cfm?id=3100. [Internet]. 2016. Available from: https://www.bgs.ac.uk/downloads/start.cfm?id=3100
32. World Mining Data (WMD) 2018, Iron And Ferro Alloy Metals Non-ferrous Metals Precious Metals Industrial Minerals Mineral Fuels; FEDERAL MINISTRY OF SUSTAINABILITY AND TOURISM; Stubenring 1, 1010 Vienna www.bmnt.gv.at. 2018.
33. BNEF. "Long-term Electric Vehicle Outlook 2018; Bloomberg New Energy Finance, 21 May 2018. 2018.
34. S&P. S&P Global Market Intelligence. SNL Metals & Mining database. Retrieved Jun 2018. 2018.
35. WMD. Minerals Production. Volume 34. C. Reichl, M. Schatz. Vienna, 2019. http://www.wmc.org.pl/?q=node/97 [Internet]. 2019. Available from: http://www.wmc.org.pl/?q=node/97
36. Lithium today. Lithium supply in Portugal. [Internet]. 2017. Available from: http://lithium.today/lithium-supply-by-countries/lithium-supply-portugal/
37. Argus. Lithium hydroxide demand to overtake carbonate: AABC Conference. [Internet]. 2019. Available from: https://www.argusmedia.com/en/news/1836977-lithium-hydroxide-demand-to-overtake-carbonate-aabc
38. Swain B. Recovery and recycling of lithium: A review. Sep Purif Technol. 2017;172:388–403.
39. Darton Commodities. Darton Commodities. (2016). Cobalt market review. 2016.
40. Alves Dias P, Blagoeva D, Pavel C, Arvanitidis N. Cobalt: demand-supply balances in the transition to electric mobility. Eur Comm Jt Res Cent EUR-Sci Tech Res Rep Publ Off Eur Union DOI. 2018;10:97710.
41. SMRE. Lithium and cobalt metals markets booming. Retrieved December 2017, from Strategic Metals & Rare Earths Letter. 2017.
42. Amnesty International. Industry giants fail to tackle child labour allegations in cobalt battery supply chains. 2017, November 15. Retrieved December 2019 [Internet]. 2017. Available from: https://www.amnesty.org/en/latest/news/2017/11/industry-giants-fail-to-tackle-child-labour-allegations-in-cobalt-battery-supply-chains/
43. BGS. British Geological Survey, World Mineral Production 2016. Retrieved November 2019, from http://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html [Internet]. 2017. Available from: http://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html
44. Report on Critical Raw Materials for the EU; Non-critical Raw Materials Profiles; European Union, 2017 [Internet]. 2017. Available from: https://ec.europa.eu/docsroom/documents/7422/attachments/1/translations/en/renditions/native
45. Nickel Institute. First use of nickel. [Internet]. 2018. Available from: https://www.nickelinstitute.org/about-nickel/

46. Roskill. Nickel Sulphate. Outlook to 2028, 2nd Edition (summary available from https://roskill.com/market-report/nickel-sulphate/). [Internet]. 2019. Available from: https://roskill.com/market-report/nickel-sulphate/
47. BGS. British Geological Survey. World Mineral Production 2017. Retrieved June 2019, from http://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html [Internet]. 2019. Available from: http://www.bgs.ac.uk/mineralsUK/statistics/worldStatistics.html
48. Mudd GM. Nickel sulfide versus laterite: the hard sustainability challenge remains. In 2009.
49. North American Nickel. Why nickel. Retrieved Jun 2019. [Internet]. 2019. Available from: https://www.northamericannickel.com/English/investors/why-nickel/default.aspx
50. Worrell E, Reuter M. Handbook of Recycling: State-of-the-art for Practitioners, Analysts, and Scientists. Newnes; 2014.
51. Umicore. Nickel [Internet]. 2019. Available from: https://www.umicore.com/en/about/elements/nickel/
52. Eurostat. COMEXT – International Trade Database, Trade Flows Dataset. Consulted in: April 2018. 2018.
53. Deutsche Bank. Markets Research. Entering the Lithium-ion Age. 9 May 2016. 2016.
54. Syrah Resources. GRAPHITE AND ITS USES. http://www.syrahresources.com.au/graphite-and-its-uses [Internet]. 2019. Available from: http://www.syrahresources.com.au/graphite-and-its-uses
55. Kay A. What is Synthetic Graphite? [Internet]. 2018. Available from: https://investingnews.com/daily/resource-investing/critical-metals-investing/graphite-investing/what-is-synthetic-graphite-asbury-carbons-stephen-riddle-explains/
56. Ren W-F, Zhou Y, Li J-T, Huang L, Sun S-G. Si anode for next-generation lithium-ion battery. Curr Opin Electrochem. 2019;18:46–54.
57. Moradi B, Botte GG. Recycling of graphite anodes for the next generation of lithium ion batteries. J Appl Electrochem. 2016;46(2):123–48.
58. European Commission. Report on critical raw materials for the EU, report of the Ad hoc working group on defining critical raw materials. [Internet]. 2014. Available from: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm
59. Vidal-Legaz B, Blengini GA, Mathieux F, Latunussa C, Mancini L, Nita V, et al. European Commission, EIP on Raw Materials, Raw Materials Scoreboard 2018 - ISBN 978-92-79-89746-7. 2018.
60. Pavel CC, Tzimas E. Raw materials in the European defence industry. Eur Comm DG Jt Res Cent Petten Neth. 2016;
61. National Research Council. Minerals, critical minerals, and the US economy. National Academies Press; 2008.
62. BGS RL. An Updated Supply Risk Index for Chemical Elements or Element Groups Which Are of Economic Value. Br Geol Surv Nottm U K. 2012;
63. DOD U. Strategic and critical materials: 2013 report on stockpile requirements. 2013;
64. Graedel TE, Harper E, Nassar NT, Nuss P, Reck BK. Criticality of metals and metalloids. Proc Natl Acad Sci. 2015;112(14):4257–62.
65. Consult I. Rohstoffsituation Bayern-keine Zukunft ohne Rohstoffe: Strategien und Handlungsoptionen (Raw materials situtation in Bavaria-no future without raw materials: strategies and opportunities of action). IW Consult GmbH Köln. 2011;17:2013.
66. Morley N, Eatherley D. Material Security: Ensuring resource availability for the UK economy. C-Tech Innovation Limited; 2008.
67. NSTC. Assessment of Critical Minerals: Screening Methodology and Initial Application (Subcommittee on Critical and Strategic Mineral Supply Chains of the Committee on Environment, Natural Resources, and Sustainability of the National Science and Technology Council). Executive Office of the President, National Science and Technology Council (NSTC). 2016.
68. Skirrow RG, Huston DL, Mernagh TP, Thorne JP, Duffer H, Senior A. Critical commodities for a high-tech world: Australia's potential to supply global demand. Geoscience Australia Canberra; 2013.
69. COM(2008) 699 final - COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL The raw materials initiative — meeting our critical needs for growth and jobs in Europe. 2008.
70. EC. Critical raw materials for the EU–Report of the Ad-hoc Working Group on Defining Critical Raw Materials. Enterprise and Industry. EC Brussels, Belgium; 2010.
71. European Commission. Tackling the Challenges in Commodity Markets and on Raw Materials. Brussels. 2011;
72. European Commission. Communication on the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative, COM(2014)297final. Brussels. 2014.
73. Blengini GA, Nuss P, Dewulf J, Nita V, Peirò LT, Vidal-Legaz B, et al. EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resour Policy.

2017;53:12–9.
74. Dewulf J, Blengini GA, Pennington D, Nuss P, Nassar NT. Criticality on the international scene: Quo vadis? Resour Policy. 2016 Dec 1;50:169–76.
75. Schrijvers D, Hool A, Blengini GA, Chen W-Q, Dewulf J, Eggert R, et al. A review of methods and data to determine raw material criticality. Resour Conserv Recycl. 2020;155:104617.
76. European Commission. Communication on the list of critical raw materials, COM(2017) 490 final. Brussels. 2017.
77. European Commission. Annexes to the report on critical raw materials for the EU, report of the Ad hoc working group on defining critical raw materials. [Internet]. 2014. Available from: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm
78. European Commission (EC), 2018. Commission Staff Working Document - Report on Critical Raw Materials and the Circular Economy. SWD(2018) 36 final. 2018.
79. Bobba S, Mathieux F, Blengini GA. How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries. Resour Conserv Recycl. 2019;145:279–91.
80. McCullough E, Nassar NT. Assessment of critical minerals: updated application of an early-warning screening methodology. Miner. Econ. 30, 257–272. https://doi.org/10.1007/s13563-017-0119-6. 2017.
81. US Department of Interior. Federal Register: Draft List of Critical Minerals. Washington, DC. 2018.
82. Hatayama H, Tahara K. Criticality Assessment of Metals for Japan's Resource Strategy. Mater. Trans. 56, 229–235. https://doi.org/10.2320/matertrans.M2014380. 2015;
83. Fortier SM, Nassar NT, Lederer GW, Brainard J, Gambogi J, McCullough EA. Draft critical mineral list—Summary of methodology and background information—U.S. Geological Survey technical input document in response to Secretarial Order No. 3359, Open-File Report. https://doi.org/10.3133/ofr20181021. 2018.
84. Eucobat. Eucobat Position Paper – Collection Target for Portable Batteries - December 2018. 2018.
85. RIMS - Raw Materials in the Battery Value Chain - https://rmis.jrc.ec.europa.eu/apps/bvc/#/ - Retrieved March 2020 [Internet]. Available from: https://rmis.jrc.ec.europa.eu/apps/bvc/#/
86. RECHARGE. Batteries Report 2018. Available at: https://www.rechargebatteries.org/the-recharge-batteries-report-2018-is-online/. 2018.
87. EUROBAT. e-mobility - Battery R&D Roadmap 2030 - Battery Technology for Vehicle Applications. EUROBAT; 2015 p. 36.
88. EUROBAT. A review of battery technologies for automotive applications. Association of European Automotive and Industrial Battery Manufacturers (EUROBAT). Available at https://www.acea.be/publications/article/a-review-of-battery-technologies-for-automotive-applications. 2014.
89. Directive 2006/66/EC of the European Parliament and of the Council on Batteries and Accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC. OJ L266/1 26 September 2006; 2006.
90. European Commission. Commission Regulation (EU) No 493/2012 of 11 June 2012 laying down, pursuant to Directive 2006/66/EC of the European Parliament and of the Council, detailed rules regarding the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators Text with EEA relevance. 2012.
91. Melin H. The Lithium-Ion Battery End-of-Life Market—A Baseline Study. In 2018. p. 1–11.
92. Lithium Process Chemistry [Internet]. Amsterdam: Elsevier; 2015. 293–300 p. Available from: http://www.sciencedirect.com/science/article/pii/B9780128014172180016
93. Podias A, Pfrang A, Di Persio F, Kriston A, Bobba S, Mathieux F, et al. Sustainability Assessment of Second Use Applications of Automotive Batteries: Ageing of Li-Ion Battery Cells in Automotive and Grid-Scale Applications. World Electr Veh J. 2018;9(2).
94. Bobba S, Mathieux F, Ardente F, Blengini G, Cusenza M, Podias A, et al. Life Cycle Assessment of repurposed electric vehicles batteries : an adapted method based on modelling of energy flows . Submitted to the Journal of Energy Storage in January 2018.
95. Neubauer JS, Wood E, Pesaran A %J SIJ of M and M. A second life for electric vehicle batteries: answering questions on battery degradation and value. 2015;8(2):544–53.
96. Morris C. Daimler uses smart EV battery packs in German electricity balancing market. [Internet]. 2018. Available from: https://chargedevs.com/newswire/daimler-uses-smart-ev-battery-packs-in-german-electricity-balancing-market/
97. Bosch. Bosch, 2016. Bosch Energy Storage Solutions [Internet]. 2018. Available from: https://boschenergystoragesolutions.com/en/blog/-/blog/4335273/batteries-of-electric-cars-for-a-robust-

electricity-grid-bosch-cooperates-with-bmw-and-vattenfall
98. Morris C. Nissan and Eaton introduce home energy storage system with second-life EV batteries. [Internet]. 2018. Available from: https://chargedevs.com/newswire/nissan-and-eaton-introduce-home-energy-storage-system-with-second-life-ev-batteries/
99. Hyunday. Hyundai Motor Group and Wärtsilä Forge New Partnership [Internet]. 2018. Available from: https://www.hyundai.news/eu/technology/hyundai-motor-group-and-waertsilae-forge-new-partnership/
100. Ardente F, Mathieux F. Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. J Clean Prod. 2014;83:126–41.
101. Olivetti EA, Ceder G, Gaustad GG, Fu X. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule. 2017;1(2):229–43.
102. Pehlken A, Albach S, Vogt T. Is there a resource constraint related to lithium ion batteries in cars? Int J Life Cycle Assess. 2017;22(1):40–53.
103. Reuter B, Riedl J, Hamacher T, Lienkamp M, Bradshaw AM. Future Resource Availability for the Production of Lithium-Ion Vehicle Batteries. 2014; Available from: https://mediatum.ub.tum.de/doc/1226680/1226680.pdf
104. Schmidt T, Buchert M, Schebek L. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resour Conserv Recycl. 2016;112:107–22.
105. Sun X, Hao H, Zhao F, Liu Z. Tracing global lithium flow: A trade-linked material flow analysis. Resour Conserv Recycl. 2017;124:50–61.
106. Ziemann S, Müller DB, Schebek L, Weil M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach. Resour Conserv Recycl. 2018;133:76–85.
107. Weyhe R, Yang X. Investigation about Lithium-Ion Battery Market Evolution and future Potential of Secondary Raw Material from Recycling. Also available at: https://accurec.de/battery-market. 2015; Available from: https://accurec.de/battery-market
108. Advanced Materials for energy storage in Li-ion batteries. European Innovation Summit 2017November 28th 2017 – European Parliament. Umicore, 2017. Available at https://emiri.eu/uploads/content_files/47/value__attachment/Umicore%20presentation%20at%20EIS%20event%20-%20v05%20281117.pdf [Internet]. Available from: https://emiri.eu/uploads/content_files/47/value__attachment/Umicore%20presentation%20at%20EIS%20event%20-%20v05%20281117.pdf
109. Lebedeva N, Di Persio F, Boon-Brett L. Lithium ion battery value chain and related opportunities for Europe. EUR 28534 EN, Publications Office of the European Union, Luxembourg,. doi:10.2760/6060, JRC105010. 2016.
110. Meeus M. Overview of battery cell technologies. In 2018.
111. Berckmans G, Messagie M, Smekens J, Omar N, Vanhaverbeke L, Van Mierlo J. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies. 2017;10(9):1314.
112. Zubi G, Dufo-López R, Carvalho M, Pasaoglu G. The lithium-ion battery: State of the art and future perspectives. Renew Sustain Energy Rev. 2018;89:292–308.
113. European Commission. Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation. Brussels,: EUROPEAN COMMISSION; 2015 p. 17. Report No.: C(2015) 6317 final.
114. Gao L, Porter AL, Wang J, Fang S, Zhang X, Ma T, et al. Technology life cycle analysis method based on patent documents. Technol Forecast Soc Change. 2013;80(3):398–407.
115. Stahl H, Baron Y, Hay D, Hermann A, Mehlhart G, Baroni L, et al. Study in support of evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators. Final Rep. 2018;
116. Pillot C. The worldwide rechargeable battery market and main trends 2017-2025, June 2018, Avicenne Energy. 2018.
117. Cairn Energy Research Advisors. Sam Jaffe, Consumer Electronics Battery Energy Capacity by Region and Global Revenue, Forecast: 2013-2020 [Internet]. batterypoweronline.com; 2015. Available from: http://www.batterypoweronline.com/images/Cairn.pdf
118. Baes K, Kolk M, Carlot F, Merhaba A, Ito Y. Arthur D. Little. Future of batteries. Winner takes all? 2018.
119. Ferg E, Schuldt F, Schmidt J. The challenges of a Li-ion starter lighting and ignition battery: A review from cradle to grave. J Power Sources. 2019;423:380–403.
120. Ceraolo M, Huria T, Pede G, Vellucci F. Lithium-ion starting-lighting-ignition batteries: Examining the feasibility. In IEEE; 2011. p. 1–6.

121. ITRI Ltd. Lead-Acid Batteries, Impact on future tin use. Available at: https://www.internationaltin.org/reports/itri-tin-in-lead-acid-batteries/. 2017.
122. EASE/EERA. European energy Storage Technology Development Roadmap Towards 2030 - Update. Available at: https://www.eera-set.eu/wp-content/uploads/2017.01.16_Update-of-the-EASE-EERA-ES-Technology-Development-Roadmap_for-public-consultation.pdf. 2017.
123. EUROBAT. Battery Energy Storage in the EU - Barriers, Opportunities, Services & Benefits. Available at: https://www.eurobat.org/news-publications/publications/108-battery-energy-storage-in-the-eu-barriers-opportunities-services-benefits. 2016.
124. IRENA, 2019. Behind-the-meter batteries. innovation landscape brief. International Renewable Energy Agency, Abu Dhabi.SBN 978-92-9260-140-9. 2019.
125. Kessels K, Mantels B, Hussy C, Bons M, Comaty F, Goes M, et al. Support to R&D strategy for battery based energy storage, Costs and benefits for deployment scenarios of battery systems (D7). Batstorm Proj POWNL16059 9th Sept. 2016;
126. Kempener R, Borden E. Battery storage for renewables: Market status and technology outlook. Int Renew Energy Agency Abu Dhabi. 2015;32.
127. U.S. Department of Energy (DoE) Global Energy Storage Database", DoE, downloaded April 2016. [Internet]. 2016. Available from: http://www.energystorageexchange.org/
128. EPBA. European Portable Battery Association (EPBA). The collection of waste portable batteries in Europe in view of the achievability of the collection targets set by Batteries Directive 2006/66/EC. Update December 2016. Available at: https://www.epbaeurope.net/wp-content/uploads/2017/03/OF_Reportontheportablebatterycollectionrates-UpdateDec-16-SummaryofChanges_final_13500.pdf. 2016.
129. RECHARGE. On the Road to Sustainability and Low Carbon Society. 2013.
130. Mobius and EUCOBAT. How battery life cycle influences the collection rate of battery collection schemes. Available at: https://www.eucobat.eu/sites/default/files/2019-01/Eucobat%20-%20Mobius%202017%20Battery%20Lifespan.pdf. 2017.
131. Delta-EE. European Market Monitor On Energy Storage (EMMES). see at: http://www.energy-log.in/90-of-european-energy-storage-installations-were-based-on-lithium-ion-batteries/. 2018.
132. Hogg D, Elliott T, Corbin M, Hilton M, Tsiarta C, Hudson J, et al. Study on Waste Statistics - A comprehensive review of gaps and weaknesses and key priority areas for improvement in the EU waste statistics. Eunomia Research & Consulting Ltd. Available at: https://ec.europa.eu/environment/waste/pdf/Eunomia_study_on_waste_statistics.pdf. 2017;
133. Ambrose H, Gershenson D, Gershenson A, Kammen D. Driving rural energy access: a second-life application for electric-vehicle batteries. Environ Res Lett. 2014;9(9):094004.
134. Ahmadi L, Fowler M, Young SB, Fraser RA, Gaffney B, Walker SB. Energy efficiency of Li-ion battery packs re-used in stationary power applications. Sustain Energy Technol Assess. 2014;8:9–17.
135. Casals LC, García BA, Aguesse F, Iturrondobeitia A. Second life of electric vehicle batteries: relation between materials degradation and environmental impact. Int J Life Cycle Assess. 2017;22(1):82–93.
136. Daimler. Daimler Sustainability report 2018. Available at https://www.daimler.com/sustainability/archive-sustainability-reports.html. 2018.
137. Dubarry M, Devie A, McKenzie K. Durability and reliability of electric vehicle batteries under electric utility grid operations: Bidirectional charging impact analysis. J Power Sources. 2017;358:39–49.
138. Jongerden M, Haverkort B. Battery Aging and the Kinetic Battery Model. CTIT Tech Rep. 2016;(TR-CTIT-2016-11).
139. Chiodo E, Lauria D, Andrenacci N, Pede G. Probabilistic battery design based upon accelerated life tests. Intell Ind Syst. 2016;2(3):243–52.
140. Chris Meehan, 2020. How long do lithium ion batteries last? Available at https://www.solar-estimate.org/news/how-long-do-lithium-ion-batteries-last.
141. Hesse HC, Schimpe M, Kucevic D, Jossen A. Lithium-ion battery storage for the grid—A review of stationary battery storage system design tailored for applications in modern power grids. Energies. 2017;10(12):2107.
142. Velázquez-Martínez O, Valio J, Santasalo-Aarnio A, Reuter M, Serna-Guerrero R. A critical review of lithium-ion battery recycling processes from a circular economy perspective. Batteries. 2019;5(4):68.
143. EIT InnoEnergy invests €5.8m into Northvolt's "mission critical" battery recycling plant - 16 December 2019 [Internet]. Available from:

https://www.innoenergy.com/news-events/eit-innoenergy-invests-58m-into-northvolt-s-mission-critical-battery-recycling-plant/
144. Bobba S, Podias A, Di Persio F, Messagie M, Tecchio P, Cusenza MA, et al. Sustainability Assessment of Second Life Applications of Automotive Batteries (SASLAB). JRC Explor Res 2016-2017 Final Rep. 2018;
145. Azevedo M, Campagno N, Hagenbruch T, Hoffmann K, Lala A, Ramsbottom O. McKinsey&Company. Lithium and Cobalt - a tale of two commoditie. 2018.
146. Berman K, Carlson R, Dziuba J, Kackson J, Hamilton C, Sklar P. BMO Capital Markets - The Lithium Ion Battery and the EV Market: The Science Behind What You Can't See. 2018.
147. Müller M, Viernstein L, Truong CN, Eiting A, Hesse HC, Witzmann R, et al. Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe. J Energy Storage. 2017;9:1–11.
148. Ralon P, Taylor M, Ilas A, Diaz-Bone H, Kairies K. Electricity storage and renewables: costs and markets to 2030. Int Renew Energy Agency Abu Dhabi UAE. 2017;
149. Battery 2030+ [Internet]. Available from: https://battery2030.eu/
150. Edström, K., Dominko, R., Maximillian Fichtner, Perraud, S., Tarascon, J.-M., Vegge, T., Winter, M., Christian Punckt, Asinari, P., Castelli, I.E., Chistensen, R., Clark, S., Grimaud, A., Hermansson, K., Heuer, A., Lorrmann, H., Løvvik, O.M., Vegge, T., Wenzel, W., Bayle-Guillemaud, P., Behm, R.J., Berg, E., Grimaud, A., Hahlin, M., Hartmann, S., Latz, A., Lyonnard, S., Vegge, T., Wenzel, W., Amici, J., Berecibar, M., Bodoardo, S., Dominko, R., Kallo, J., Paillard, E.-E., Raccurt, O., Heiries, V., Guillet, N., Tarascon, J.-M., Laethem, D. Van, Ayerbe, E., Diehm, R., Hofmann, J., Lorrmann, H., Miguel, O., Placke, T., Sheridan, E., Barboux, P., Chanson, C., Jacques, P., Lorrman, H., Meeus, M., Trapp, V., Weil, M.,. BATTERY 2030+ Roadmap. Research need and future actions (D2.1 - second draft). 2020.
151. European Commission. a major opportunity for a sustainable society. European Commission (EC) Directorate-General for Research and Innovation. 2017.
152. Chukwuka C, Folly KA. Batteries and super-capacitors. In: IEEE Power and Energy Society Conference and Exposition in Africa: Intelligent Grid Integration of Renewable Energy Resources (PowerAfrica). IEEE; 2012. p. 1–6.
153. Recharge Association, 2018. PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications. 2018.
154. Ellingsen L, Hung C. Research for TRAN Committee-Battery-powered electric vehicles: market development and lifecycle emissions. Study Rep DG Intern Policies Policy Deparment Struct Cohes Policies Transp Tour Eur Parliam Eur Union Doi. 2018;10:944056.
155. Rohr S, Müller S, Baumann M, Kerler M, Ebert F, Kaden D, et al. Quantifying uncertainties in reusing lithium-ion batteries from electric vehicles. Procedia Manuf. 2017;8:603–10.
156. Alonso Raposo, M., Ciuffo, B., Ardente, F., Aurambout, J.P., Baldini, G., Braun, R., Christidis, P., Christodoulou, A., Duboz, A., Felici, S., Ferragut Martinez Vara de Rey, J., Georgakaki, A., Gkoumas, K., Grosso, M., Iglesias Portela, M., Julea, A.M., Krause, J., Martens, B., Mathieux, F., Menzel, G., Mondello, S., Navajas Cawood, E., Pekar, F., Raileanu, I., Scholz, H., Tamba, M., Tsakalidis, A., van Balen, M., Vandecasteele, I., 2019. The future of road transport - Implications of automated, connected, low-carbon and shared mobility. doi:10.2760/9247.
157. Cano ZP, Banham D, Ye S, Hintennach A, Lu J, Fowler M, et al. Batteries and fuel cells for emerging electric vehicle markets. Nat Energy. 2018;3(4):279–89.
158. Willson, Q., 2018. Why it Makes Sense to Buy a Used EV [Internet]. Available from: http://www.routemonkey.com/drivers/everything-ev/why-it-makes-sense-to-buy-a-used-ev
159. Timmers H. Driving Towards Decarbonisation of Transport: Safety, Performance, Second Life and Recycling of Automotive Batteries for e-Vehicles-Recycling. In 2016. p. 22–3.
160. Oko Institute. Assessment of the implementation of Directive 2000/53 /EC on end-of life vehicles (the ELV Directive) with emphasis on the end-of life vehicles of unknown whereabouts. Oko Institute e.V. – Institute for Applied Ecology. Darmstadt (Germany). 2016.
161. UMICORE, n.d. Battery recycling: Audi and Umicore start closed loop for cobalt and nickel 2019. [Internet]. 2019. Available from: https://www.umicore.com/en/media/press/battery-recycling-audi-and-umicore-start-closed-loop-for-cobalt-and-nickel

Annex 1

Battery classification ProSUM/ ORAMA project

Table 3. ProSUM/ ORAMA battery classification

Nr	Application	Battery Key	Battery sub-key	Short name	Code for chemistry - application combinations
1	Portable PC	LiRechargeable	LiCoO2	LCO	LiCoO2Portable PC
2	cell phones	LiRechargeable	LiCoO2	LCO	LiCoO2cell phones
3	cameras/games	LiRechargeable	LiCoO2	LCO	LiCoO2cameras/games
4	ebikes	LiRechargeable	LiCoO2	LCO	LiCoO2ebikes
5	Industrial excl mobility	LiRechargeable	LiCoO2	LCO	LiCoO2Industrial excl mobility
6	others portable	LiRechargeable	LiFePO4	LFP	LiFePO4others portable
7	ebikes	LiRechargeable	LiFePO4	LFP	LiFePO4ebikes
8	Industrial excl mobility	LiRechargeable	LiFePO4	LFP	LiFePO4Industrial excl mobility
9	cameras/games	LiRechargeable	LiMn	LMO	LiMncameras/games
10	others portable	LiRechargeable	LiMn	LMO	LiMnothers portable
11	ebikes	LiRechargeable	LiMn	LMO	LiMnebikes
12	PHEV	LiRechargeable	LiMn	LMO	LiMnPHEV
13	BEV	LiRechargeable	LiMn	LMO	LiMnBEV
14	Industrial excl mobility	LiRechargeable	LiMn	LMO	LiMnIndustrial excl mobility
17	Portable PC	LiRechargeable	LiNMC	NMC	LiNMCPortable PC
18	tablets	LiRechargeable	LiNMC	NMC	LiNMCtablets
19	cell phones	LiRechargeable	LiNMC	NMC	LiNMCcell phones
20	cameras/games	LiRechargeable	LiNMC	NMC	LiNMCcameras/games
21	cordless tools	LiRechargeable	LiNMC	NMC	LiNMCcordless tools
22	others portable	LiRechargeable	LiNMC	NMC	LiNMCothers portable
23	ebikes	LiRechargeable	LiNMC	NMC	LiNMCebikes
24	HEV	LiRechargeable	LiNMC	NMC	LiNMCHEV
25	PHEV	LiRechargeable	LiNMC	NMC	LiNMCPHEV
26	BEV	LiRechargeable	LiNMC	NMC	LiNMCBEV
27	Industrial excl mobility	LiRechargeable	LiNMC	NMC	LiNMCIndustrial excl mobility
30	Sealedcordless tools	NiCd	NiCdSealed	NiCd	NiCdSealedcordless tools
31	Sealedothers portable	NiCd	NiCdSealed	NiCd	NiCdSealedothers portable
32	VentedIndustrial excl mobility	NiCd	NiCdVente d	NiCd	NiCdVentedIndustrial excl mobility
33	SealedPortable PC	NiMH	NiMHSeale d	NiCd	NiMHSealedPortable PC
34	Sealedcordless tools	NiMH	NiMHSeale d	NiMH	NiMHSealedcordless tools
35	Sealedothers portable	NiMH	NiMHSeale d	NiMH	NiMHSealedothers portable

36	SealedHEV	NiMH	NiMHSealed	NiMH	NiMHSealedHEV
38	Sealedothers portable	Pb	PbSealed	Pb-acid	PbSealedothers portable
39	SealedSLI	Pb	PbSealed	Pb-acid	PbSealedSLI
40	Sealedebikes	Pb	PbSealed	Pb-acid	PbSealedebikes
41	Industrial excl mobility	Pb	PbVented	Pb-acid	PbVentedIndustrial excl mobility
42	Primary	Zn	Zn	Zn	Zn
43	Industrial excl mobility	Other	Other	Other	OtherIndustrial excl mobility
44	Primary	LiPrimary	LiPrimary	Li-prim.	LiPrimary
45	SLI	LiRechargeable	LiMn	LMO	LiMnSLI
46	Home Energy Storage	LiRechargeable	LiNMC	NMC	LiNMCHome Energy Storage
47	BEV	LiRechargeable	LiNCA	NCA	LiNCABEV
48	Home Energy Storage	LiRechargeable	LiNCA	NCA	LiNCAHome Energy Storage

Table 4. ProSUM/ ORAMA battery classification – clustered for various reporting choices

Nr	Code for chemistry - application combinations	A: Batt Dir.: Port./Ind. / Autom.	B: Battery Keys	C: Pb, Li, other	D: Comb. A+C	E: Batt Dir+
1	LiCoO2Portable PC	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
2	LiCoO2cell phones	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
3	LiCoO2cameras/games	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
4	LiCoO2ebikes	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
5	LiCoO2Industrial excl mobility	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
6	LiFePO4others portable	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
7	LiFePO4ebikes	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
8	LiFePO4Industrial excl mobility	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
9	LiMncameras/games	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
10	LiMnothers portable	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
11	LiMnebikes	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
12	LiMnPHEV	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
13	LiMnBEV	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
14	LiMnIndustrial excl mobility	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
17	LiNMCPortable PC	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
18	LiNMCtablets	Portable	LiRechargeable	Li	PortableLi	Industrial
19	LiNMCcell phones	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
20	LiNMCcameras/games	Portable	LiRechargeable	Li	PortableLi	Portable Rechargeable
21	LiNMCcordless tools	Portable	LiRechargeable	Li	PortableLi	Industrial

22	LiNMCothers portable	Portable	LiRechargeable	Li	PortableLi	Industrial
23	LiNMCebikes	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
24	LiNMCHEV	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
25	LiNMCPHEV	Industrial	LiRechargeable	Li	IndustrialLi	Portable Rechargeable
26	LiNMCBEV	Industrial	LiRechargeable	Li	IndustrialLi	Portable Rechargeable
27	LiNMCIndustrial excl mobility	Industrial	LiRechargeable	Li	IndustrialLi	Portable Rechargeable
30	NiCdSealedcordless tools	Portable	NiCd	Other	PortableOther	Portable Rechargeable
31	NiCdSealedothers portable	Portable	NiCd	Other	PortableOther	Portable Rechargeable
32	NiCdVentedIndustrial excl mobility	Industrial	NiCd	Other	IndustrialOther	Industrial
33	NiMHSealedPortable PC	Portable	NiMH	Other	PortableOther	Portable Rechargeable
34	NiMHSealedcordless tools	Portable	NiMH	Other	PortableOther	Portable Rechargeable
35	NiMHSealedothers portable	Portable	NiMH	Other	PortableOther	Portable Rechargeable
36	NiMHSealedHEV	Industrial	NiMH	Other	IndustrialOther	Industrial
38	PbSealedothers portable	Portable	Pb	Pb	PortablePb	Portable Rechargeable
39	PbSealedSLI	Automotive	Pb	Pb	Automotive Pb	Automotive
40	PbSealedebikes	Industrial	Pb	Pb	IndustrialPb	Industrial
41	PbVentedIndustrial excl mobility	Industrial	Pb	Pb	IndustrialPb	Industrial
42	Zn	Portable	Zn	Other	PortableOther	Portable Primary
43	OtherIndustrial excl mobility	Industrial	Other	Other	IndustrialOther	Industrial
44	LiPrimary	Portable	LiPrimary	Li	PortableLi	Portable Primary
45	LiMnSLI	Automotive	LiRechargeable	Li	Automotive Li	Industrial
46	LiNMCHome Energy Storage	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
47	LiNCABEV	Industrial	LiRechargeable	Li	IndustrialLi	Industrial
48	LiNCAHome Energy Storage	Industrial	LiRechargeable	Li	IndustrialLi	Industrial

KJ-NA-30315-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office of the European Union

doi:10.2760/069052

ISBN 978-92-76-20885-3