BATTERIES EUROPE

EUROPEAN **TECHNOLOGY** AND **INNOVATION** PLATFORM

Batteries Europe ETIP

WG2: Raw Materials and Recycling

Roadmap

Deliverable Responsible

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A second updated version of this document will be issued by the end of 2021 and will include the latest policy documents on Battery Regulation; CRM data will be revised according to the latest list available[1].

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[1] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

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Abbreviations

3TGs	Tin, Tantalum, Tungsten, Gold
ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
AI	Artificial Intelligence
ASM	American Society for Metals
BEV	Battery Electric Vehicle
BGS	British Geological Survey
CAM	Cathode Active Material
CBM	Circular Business Model
CIRAF	Cobalt Institute Responsible Assessment Framework
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CRM	Critical Raw Material
CSA	Coordination and Support Action
CVD	Chemical Vapor Deposition
DDG	Due Diligence Guidance
DLT	Decentralized Ledger Technology
DRC	Democratic republic of Congo
EoL	End-of-Life
EIP	European Innovation Partnership
EIT	European Institute for Innovation and Technology
EMM	Electrolytic Manganese Metal
ELV	End-of-Life Vehicle
EPR	Enhanced Producer Responsibility
ETIP	European Technology and Innovation Platform
EV	Electric Vehicle
GBA	Global Battery Alliance
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
HEV	Hybrid Electric Vehicle
ICMM	International Council on Metals and Mining
ILCD	International Reference Life Cycle Data System
IWG	Implementation Working Group
JRC	Joint Research Centre

KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCE	Lithium Carbonate Equivalent
LCI	Life Cycle Inventory
LEL	Lower Explosion Limit
LGPS	Lithium Germanium Phosphorus Sulfide
LIB	Lithium-Ion Battery
LIPON	Lithium Phosphorus Oxynirtide
LME	London Metal Exchange
LLZO	Lithium Lanthanum Zirconium Oxide
LOI	Limiting Oxygen Index
LPS	Lithium Phosphorus Sulfide
MFA	Material Flow Analysis
MSA	Material Flow System Analysis
NCA	Lithium Nickel Manganese Aluminium Oxide
NiMH	Nickel Metal Hydride Battery
NMC	Lithium Nickel Manganese Cobalt Oxide
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
PAH	Polyaromatic Hydrocarbon
pCAM	Precursor for Cathode Active Material
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rule
PEO	Polyethylene oxide
PHEV	Plug-in Hybrid Electric Vehicle
PI	Principal Investigator
REE	Rare Earth Element
R&I	Research&Innovation
RMI	Responsible Minerals Initiative
SETAC	Society of Environmental Toxicology and Chemistry
SHBD	Social Hotspot DataBase
sLCA	Social LCA
SoH	State-of-Health
SWOT	Strenghts, Weaknesses, Opportunities, Threats
TRL	Technology Readiness Level
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WEEE	Waste Electric and Electronic Equipment
WEF	World Economy Forum
WG	Working Group

Summary and Recommendations

ETIP Batteries Europe has been established as the "one-stop shop" for the battery-related R&I eco-system and aims to accelerate the establishment of a competitive, sustainable and efficient value chain and globally competitive European battery industry through Research and Innovation to support the EU Green Deal and other EU policies.

Thematic Working Group 2 is addressing the subjects related to Raw Materials for the Lithium Ione Batteries (LIB) industry from its Sustainable Sourcing and Processing from primary sources and also from secondary sources as well as combination of both by means of Collection and Recycling of EoL batteries. Several cross-cutting issues such as Second Life and Safety have been identified as important topics to be covered.

The present Road Map for Raw materials and Recycling responds to the need for EU to be able to be competitive in Li-ion batteries business, i.e. to identify research and innovation areas where EU is strong on the Li-ion battery related raw materials and recycling and on other hand identify where there is lack of knowhow, knowledge and R&I.

Within the WG2, eight subgroups have been established to work on the following topics:

Sourcing, sustainability and traceability of both primary and secondary raw materials

- Sustainable processing of Li, Ni, Co and graphite
- Raw Material LCA and Material Flow Analysis
- Collection, reverse logistics, sorting and dismantling
- Metallurgical recycling processes, industrial integration and secondary material based precursors
- Circular economy-based business models
- Second life of batteries
- Safety in recycling

Through the analysis of the state of the art and the strengths and weaknesses of the R&I and industry sectors, several guidelines and proposals are given.

Sourcing, sustainability and traceability of raw materials:

European Union does not produce enough raw materials for LIBsat current level of consumption and especially at the expected growth of demand level by 2030 (many of the raw materials being listed as Critical Raw Materials) and thus also sourcing of raw materials outside European union is needed. Two main areas have been identified:

- Resource mapping and sourcing within EU
- Setting common sustainability criteria and tracing practices for raw materials sources outside Europe

It has been found that although much information about the mineral potential (EU and global reserves) and the sourcing of battery raw materials is being assembled by the EU Commission, there is a lack of harmonization in how is the data collected and categorized (who collects the data, in which databases and is that open access data base). Also, EU is missing a consensus on a uniform sustainable mining standards and regulatory standards including all the Environment, Health, Safety, Social, and Worker right aspects.

Sustainable extraction and processing of battery grade raw materials:

To be in the front of technological development of metallurgical production, innovations in processes and unit processes are required. These should aim at improved recoveries, increased amount of recovered battery elements, improved product purity and quality, improved impurity removal, and improved battery metals recovery from both primary and secondary raw materials, fed to the metallurgical processes.

Any battery raw materials that are produced from European sources or processed in Europe must be able to demonstrate superior quality and environmental criteria, with competitive cost. Simultaneous cost, quality and environmental control require R&D efforts in processing technologies, sustainability certification as well as new business models. Collaboration and understanding between primary and secondary processing in R&D is of importance in order to develop truly optimized, flexible and smart battery metals and other raw material processing and recovery, utilizing the existing and new technologies and infrastructure.

Raw Material LCA and material Flow Analysis:

This topic contains Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) datasets particularly on LCA of raw materials and recycling. Material Flow Analysis (MFA) is also relevant topic in this context. Social LCA is an assessment tool that can be included in a full sustainability assessment focusing on the three pillars that are people, planet and profit. In a full sustainability assessment, communicating of results is a key issue as many indicators can be used.

Actions in the following fields have been proposed:

- Mining: Regionalized LCA for mining such as water footprint and Harmonized energy source declaration of material producing companies all along the supply value chain from exploration to final products
- Raw materials: Reliable Raw materials LCI data, open access of LCI of raw materials, Battery passport including Ecolabel of batteries
- Material Flow Analysis: Harmonized MFA for raw materials for batteries, inclusion of extraction/processing capacity in MFA model
- Recycling: Reliable recycling LCI, comparison between primary and secondary materials
- Social LCA and sustainability assessment: understand the full sustainability

Collection, reverse logistics, sorting and dismantling

Collection, handling, sorting and dismantling end-of-life Li-ion batteries are the first and necessary steps in getting batteries back into the battery value chain through extending the product life and in the end proper recycling.

Current inefficient ways of handling Li-ion end-of-life battery streams, as well as the foreseeable growth in volumes available on the European market in following years brings the necessity need of of harmonising the battery related logistics and supply chain across the EU. This seems to be particularly important taking into account the risks related to handling batteries, especially the high-energy ones from EV or energy storage applications.

New technologies and devices for battery SoH assessment are needed. Handling of used batteries is much safer when they are discharged, therefore it is necessary to develop new discharge technologies which do not waste batteries' residual energy but recover it. To maximally increase 2^{nd} life stream and recycling efficiency of Li-ion battery scrap it is necessary to develop ambigious sorting technologies. To avoid inefficient separation, it is necessary to introduce standardized labelling systems for all Li-ion batteries.

Metallurgical recycling processes, industrial integration and secondary material based precursors:

There is a clear need to develop holistic material and energy efficient recycling processes that can recover more battery materials with reduced levels or footprint of CO_2. The objective should be to improve the recovery of Co, Ni and Cu as well as efficient recovery of Li, graphite, Mn, Al, F, and P, maximising the value of the recovered materials. Closed-loop recycling and vertical integration back to battery materials production should be attempted, although some less valuable fractions could be downcycled to other uses. The holistic aim is to keep materials as long as possible in the economic cycle. A further long-term objective is to keep the materials at highest possible value at all process steps, which could lead to direct recycling and upgrading of the active materials, e.g. as alloys or mixed oxides.

More environmentally friendly processes should be developed. This comprises minimizing the energy, water and chemical consumption, use of renewable energy and green chemicals as well as recycling of the chemicals, and minimizing the (worker and environmental) exposure to hazardous materials. Close to zero-waste recycling should be targeted in the long term. Anticipatory approach (ex-ante) of the life cycle of specifically the recycling processes is of outmost importance should be developed along with the metallurgical process development.

Circular economy based business models:

According to the EU *Action plan for the circular economy* (revised version from March 2020) and subsequent initiatives, circular economy allows to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimizing the generation of waste. Amongst the multi-dimensional issues that drive the transition to a more circular economy, Circular Business Models (CBM) play a crucial role to deliver positive economic, environmental and social impacts.

CBM consist in proposing a holistic view of product design, manufacturing, use, and end-of-life management that tries to optimize all economic, environmental and social outcomes. In this roadmap, it will cover the whole battery value chain from raw materials, eco-design, production and remanufacturing, distribution, consumption including use, reuse, repurpose, collection, and recycling.

The whole battery value chain from raw materials to EV including 2nd use should be uniformly covered in the regulative policies. Particular emphasis should be put on the accountability and transparency of the use of natural resources, traceability of battery products (identification of chemistries, technological features) and data sharing between different actors in the different use phases. New regulations are needed to clarify the business environment, e.g. the Extended Producer Responsibility (EPR) in different use phases. Moreover, unified criteria and standard methods should be developed to address the battery State-of-Health (SoH) and End-of-Life (EoL).

Second life and circular economy:

A key objective of the Circular Economy is to keep the added value in products for as long as possible in order to reduce or eliminate waste. Second Life is interpreted as any operation by which products or components that are not waste are used for a different purpose (re-purpose) for which they were originally conceived and placed on the market for the 1st time.

Most batteries from e-mobility in the future will return not because they need to be repaired, or they are damaged or defective, but just because they are underperforming to function in an electric car, or the consumer wants to buy a new car model. Instead of sending these batteries into 'retirement' they might still be used in a less demanding application (second life).

In this sense, industrial batteries from e-vehicles (mobile application) could be transformed into other applications after use in the first applications. For this to happen, safety of these operations, traceability & monitoring of these batteries and proper diagnosis of these batteries needs to be guaranteed. It is evident that there is a variety of safety issues related to the second use.

Safety:

The e-mobility market is currently in full expansion. This is leading to a transformation of the automobile sector as a whole: from the point of product development up till recycling: the entire value chain is influenced.

When looking closer to safety related aspect, it is obvious that these new technologies trigger new risks, of which basic knowledge, control measures, education and regulation is still being developed. The energy intensity, but also the chemical composition of the battery itself poses risks in all the stages of recycling from collection to metallurgical recycling processing. With regards to field of safety in the full recycling value chain, the focus is set in the following aspects:

- Identification of hazards and assess related risks: knowledge building
- Risk control measures: hierarchy of control
- Shaping a learning eco-system: feedback and continuous learning

1. Scope and Objectives

The objective of Batteries Europe is to develop a whole competitive and sustainable battery value chain in Europe through Research and Innovation aiming to support the industrial value chain.

Raw materials are a very crucial part of the European Li-ion battery value chain as Europe has been identified to be lacking own production of these materials and is relying very much on their imports, some of which has already been defined to be critical raw materials in European Union.

As the e-mobility is booming now, European car manufacturers are still dependent on imported Li-ion batteries, although there are already investments going on to build battery manufacturing capacity in Europe, which will support independence of the European Car industry in the close future. However, the investments on raw materials sourcing in Europe are still developing much slower (as the mining industry normally is a slow mover, partly because of the investment risks, partly because of slow permission procedures etc.) and it will take time for the already planned investments to become operative.

With the rapidly increasing electrical vehicle fleet in Europe also the amount of batteries in European cars will increase rapidly forming a fast growing stock in use of raw materials, which are later (even after more than 10 years) available for recycling (after the possible second life use). Currently, the Li battery recycling industry in Europe is mainly concentrating on the Li batteries coming to end-of-life (EoL) from electronics and portable instruments, which have a large challenge in collection and reverse logistics, and also the chemistry of these batteries is varying a lot. However, the materials in these batteries are already now valuable to be recycled and recovered, to support the growing Li ion battery manufacturing in Europe. At the same time, the recycling industry is preparing for the future challenges to be ready when large amounts of EV batteries are available to be recycled.

In the SET Plan WG 7 Implementation plan, there were originally some topics to be covered by R&I related to recycling, however, the raw material part of the value chain was supported by only one fiche. The Batteries Europe ETIP Working Group 2 Raw Materials and Recycling has actively supported the EU to identify the most important R&I topics related to battery raw materials and recycling, by providing three additional Fiches in Autumn 2019 (*Responsible Sourcing and Traceability*, *and Sustainable Production, Sustainable processing of battery raw materials in Europe* and *Improved total recycling of batteries and battery elements, including out-of-the-specification batteries*) and by generating three new proposals for call topics (*Improved total recycling of battery materials, Sustainable Processing of Battery Raw Materials and Collection, reversed logistics, sorting and dismantling*) also in the autumn 2019. These topics were considered to be the most urgent topics for near future activities. However, to cover the whole Raw Materials and Recycling field more widely and in alignment with the most recently set EU strategies (citing again Green Deal and others), it was decided to deliver a more comprehensive Road Map for Li ion battery Raw Materials and Recycling. This document is the very first version for this road map.

2. Methodology

The focus of the Batteries Europe ETIP Working Group 2 (WG2) is on Sustainable sourcing, Secure raw materials supply and Recycling. Cross-cutting topics with other Working Groups are e.g. Second Life (WG5 and WG6) and Design for Recycling (WG4). Safety has been also raised as one of the major topics for the WG2, but also this is a cross-cutting issue.

WG2 is very well aligned with other important actors in the European battery R&I, for example with EIT Raw Materials (Olli Salmi as co-chair), Finnish *BATCircle* program (National R&I program ecosystem, PI Professor Mari Lundström, WG2 Sherpa) and EBRA (Alain Vassart as co-chair). The WG2 also has several other industrial and R&I members.

A road map for Raw materials and Recycling R&I is needed for EU to be able to be competitive in Li-ion batteries business. I.e. to identify research and innovation areas where EU is strong on the Li-ion battery related raw materials and recycling and on other hand identify where there is lack of knowhow, knowledge and R&I.

The topics for the road map were originally collected and analysed in two face to face workshop meetings SET Plan Action 7 IWG Sub-group Recycling Meeting 15 January 2019 at Aalto University, Espoo, Finland, and ETIP Batteries Europe Raw Materials and Recycling Workshop 13-14 June 2019 in Milano, Italy, organized by antecedent working groups. The two workshops gathered 85 participants representing 46 different organizations and 12 European countries as well as the EU Commission. The report of those meeting was used as starting point for roadmap by the current WG2. Furthermore, roadmap work in WG2 was divided into subtopics, and eight subgroups worked virtually and via teleconferences to build and deliver corresponding sections to the draft roadmap. WG2 also prioritized call proposals for R&I activities given in this document.

The topics of the subgroups are as follows:

- Sourcing, sustainability and traceability of raw materials; chairs Pertti Kauranen and Ilkka Kojo
- Sustainable extraction and processing of battery grade raw materials; chair Olli Salmi
- Raw Material LCA and material Flow Analysis; chairs Maeva Philippot and Carol-Lynne Pettit
- Collection, reverse logistics, sorting and dismantling; chairs Michal Zygmunt and Alain Vassart
- Metallurgical recycling processes, industrial integration and secondary material-based precursors; chair Mari Lundström
- Circular economy-based business models; chair Arnaud Witomski
- Second life; chair Willy Tomboy
- Safety; chair Isabel Vermeulen

During the working sessions the following topics were identified to be cross-cutting issues and should be discussed with the chairpersons of the other WGs:

- Safety: all
- Design for recycling: WG4
- Active materials: WG3
- Raw materials for next generation batteries: WG3/WG1

- Second life WG5 and WG6

3. Sourcing, sustainability and traceability of raw materials

3.1. Description

According to the report generated by EIP Raw Materials[2] European Union does have limited resources, and does not produce enough LIB raw materials (many of them being listed as Critical Raw Materials), and thus also sourcing of raw materials outside European union is also needed. It is believed, that in addition to technical properties of batteries manufactured in EU the competitiveness of these batteries is based on their sustainability. This means that also the raw materials have to be produced in a sustainable manner including all the dimensions of sustainability (environmental, economic and social). To ensure this, the sources of raw materials have to be identified and their production has to independently be verified to be sustainable.

The topic can be divided into two main issues:

- Resource mapping and sourcing within EU
- Setting common sustainability criteria and tracing practices for raw materials sources outside Europe

Sourcing within EU

In a WG2 workshop research topics such as resource mapping and modelling from geometallurgy to metallurgical processes were highlighted. Additionally, the need of next generation exploration techniques and resource mapping and modelling with focus on battery-related metals from primary and secondary sources– the R&I target should be securing the future EU supply for the next generation batteries.

Moreover, increased energy efficiency, use of non-fossil fuel-based energy resources and social sustainability in mining was identified to be important. This primary raw material topic was integrated into the ETIP working group and is more widely handled in the raw material report by EIP Raw Materials[1]. However, topics such as recovery of metals from mine waste such as tailings, including waste directive and sustainable production methods were identified as research topics, as well as the social acceptance related to resource extraction.

Based on the identified needs, it seems that there has been a variety of primary projects on-going in the Europe. However, few of them focus on industrial integration of battery precursor chemicals into current infrastructure, or to the entire processing from mine to the batteries - but rather on

[2] Report on Raw Materials for Battery Applications, SWD(2018) 245/2 final.

improvement of current production of the dominating metals or side stream utilization. Strategic R&I projects are needed where battery-related resource mapping, next generation mining and geometallurgical modelling are in focus.

Sourcing outside EU

Social and environmental sustainability with fair trade principles with key producer countries like DRC is of highest importance. This calls for increased transparency and traceability throughout the raw material supply chains. Enforcing policies for ethical sourcing and increased sustainability of resources will require a reliable method to trace and verify the source of origin for the used materials. To this extent, the voluntary OECD Due Diligence Guidance lays out criteria, including on reporting and auditing, that provides a solid basis. But currently, the visibility of across the different stages of the value chain remains highly restricted, without commonly shared practices. Thus, the different operators cannot be certain of the impact of their actions. Therefore, a verifiable audit trail is a necessity for providing the incentives for improvements in sourcing and sustainability. Crucially, there is a wide array of schemes out there for different regions, materials or industry sectors. That makes it highly complex for future EU battery manufacturers to reliably source the different metals and necessitates an easy mechanism to enable tracing, verifying and auditing the supply chain coherently and efficiently. Hence, a uniform sustainable mining standards including all the Environment, Health, Safety, Social, and Worker right aspects is needed.

3.2. State of the Art

Much information about the mineral potential (EU and global reserves) and the sourcing of battery raw materials is being assembled by the EU Commission through the current H2020 projects, and the recent updates to the criticality assessments for metals, such as lithium, cobalt, nickel, etc. This information will be summarized in the new Fact Sheets (*in preparation/under review*) for many strategic materials. Recent reports provide overviews of the supply/demand situations for certain metals[3],[4] (e.g. Alves Dias et al., 2018), and also consider potential future scenarios for EV-battery sector.

With regards to the responsible sourcing of raw materials, the EU Commission notes that[5]*: 'battery manufacturing absorbs around 40% of global lithium production and around 50% of cobalt production; however, the environmental and social standards associated with this extraction are not always*

[3] Alves Dias et al., Cobalt: demand-supply balances in the transition to electric mobility, JRC112285, 2018; https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112285/jrc112285_cobalt.pdf

[4] Olivetti et al., Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Joule 1 (2017) 229-243, http://dx.doi.org/10.1016/j.joule.2017.08.019

[5] C. Santos, J.R Martin and P.Handley, EBA250 Event 25 Sept 2019

satisfactory. The (voluntary) OECD Due Diligence Guidance (DDG)[6] *for Responsible Supply Chains of Minerals from Conflict Affected and High-Risk Areas is applicable to all minerals. Voluntary initiatives based on the OECD DDG are being proposed, such as the Cobalt Institute Responsible Assessment Framework (CIRAF)*[7]*, and the London Metal Exchange proposed rules for all LME listed brands. And other options are being considered which include mandatory/voluntary due diligence schemes based on the OECD DDG.' (). There are many other initiatives such as environmental criteria applicable to mining developed by the Global Reporting Initiative (GRI), the RMI, and the Copper Mark, as well as separate regulation already in place such as in the EU Conflicts Minerals Regulation*[8] *(focuses on tin, tantalum, tungsten and gold (3TGs)).* At international level, the mineral supply, governance and sustainability are covered by fora like International Resources Panel. Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, The World Resources Forum and International Council on Metals and Mining (ICMM) [9]. Due to the multitude of standards and organization working on the topic, EU is missing a consensus on a uniform sustainable mining standards including all the Environment, Health, Safety, Social, and Worker right aspects.

Tools such as Life Cycle Assessment (LCA) are used to examine the environmental impacts of production and use of battery materials such as Lithium, Cobalt, Nickel, Manganese, Copper, and Aluminum. Most metal LCA studies consider mining to refining (cradle to gate), and some encompass the full life cycle through to recycling at end-of-life (cradle to grave). The metals industry developed harmonized LCA guidance (PE International *et al.,* 2015), and the global LCA metals datasets are available within several mainstream LCA databases, including the EC's new Product Environmental Footprint (PEF)[10] database.

In addition, the industry is still lacking a methodology for verifying the environmental impacts of different operational activities with certificates or labels. Despite the advancements in LCA for evaluating the overall impact of different choices, we are lacking tools for signalling these results to the consumers and engaging them as a part of the change. The different operators have inadequate tools for demonstrating their environmental footprint and performance against the industry average. Neither do the consumers have ways to verify the impact of their consumption choices, make informed decisions when selecting between alternative products, or give reinforcing signals to the manufacturers by making selections in favor of, e.g., more ethical or more sustainable options. Without a functioning methodology behind informing and guiding the selections by the consumers, we are failing to utilize the mechanisms of market demand for incentivizing the operators toward better choices in operational activities.

The function of these potential certificate or labelling systems rely on the verifiable traceability of material resources. The potential of new solutions and decentralized ledger technologies (DLT), such as blockchain, has been widely acknowledged[11]. In result, different initiatives have been put forward, but their operational functionality and long-term success remains to be proven. Examples span to an array

[6] http://www.oecd.org/corporate/mne/mining.htm
[7] https://www.cobaltinstitute.org/ciraf.html
[8] https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/
[9] Ali et al., Mineral supply for sustainable development requires resource governance, Nature 543 (2017) 367–372); doi:10.1038/nature21359
[10] https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm#pef
[11] OECD. (2019). Is there a role for blockchain in responsible supply chains? http://www.oecd.org/daf/inv/mne/is-there-a-role-for-blockchain-in-responsible-supply-chains.htm

of different contexts and industries, ranging from material sourcing for electric vehicle batteries[12] to traceable and sustainable fishing in the Philippines[13]. In all contexts, there are two key aspects to resolve: enabling the users – including vulnerable groups and informal supply chain actors - to contribute to the system and attaining the scalability for the DLT solutions, particularly in blockchains. For these purposes, solutions that combine on-chain and off-chain transactions[14] seem as a potential, yet practically unexplored avenue in the mining context. In the context of EU research and innovation support, scoping and putting in place a uniform template/guidance on how the block-chain like technologies should be used at scale to maximise their impact and involve all supply chain actors is a clear gap[15] that would enable EU industry benefit from the opportunity.

3.3. What is needed in EU to be competitive

What the growing EU battery industry is missing is a reliable, harmonized and easy way to source metals in the currently complex and intertwined global extraction supply chains for various metals. Using new digital technologies as well as including independent and continuous data verifications should make compliance with international social and labor charters possible[16]. Focus should be kept on such wider tracing aspects, which are at the heart of making growing battery manufacturing ethical and acceptable, on top of pure environmental considerations. Unified sustainability criteria should be set for both industrial scale and artisanal small-scale mining, e.g. within the EIT RawMaterials sponsored CERA[17] and supplementary projects.

There is a current need for better, updated and more disaggregate/process specific LCA data, especially on the battery precursor chemicals (e.g. metal sulphates, etc.) used to prepare the active cathode materials, as well as for the anode materials (e.g. graphite). PEF Category Rules should be extended from battery level to active electrode materials.

In this regard, an EU-wide regulation for batteries placed on the EU market could help establish a reliable framework.

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[12] Responsible Sourcing Blockchain Network with RCS Global, IBM, Ford, Volkswagen Group, and Volvo for tracing cobalt and potentially other battery metals (tungsten, tantalum, tin and gold); https://www.rcsglobal.com/volvo-cars-joins-responsible-sourcing-blockchain-network-launched-rcs-global-ibm-ford-volkswagen-group/

[13] Tracey application (by WWF, UnionBank & Streamr) allows the fishers to document data on the location of the catch, the size and quality of the fish, and the price they are selling it for; https://www.tx.company/wwf

[14] Monoplasma: A simple way to broadcast money to millions of people; https://medium.com/streamrblog/monoplasma-revenue-share-dapps-off-chain-6cb7ee8b42fa

[15] OECD. (2019). Is there a role for blockchain in responsible supply chains? http://www.oecd.org/daf/inv/mne/is-there-a-role-for-blockchain-in-responsible-supply-chains.htm

[16] Blockchain for Traceability in Minerals and Metals Supply Chains: Opportunities and Challenges, RSC Global 2017; https://www.icmm.com/website/publications/pdfs/responsible-sourcing/171220_rcs-global_-icmm_blockchain_final.pdf

[17] https://eitrawmaterials.eu/project/cera/

3.4. R&I and Coordination and Support actions (CSA) activities needed to reach the visioned next level

Based on urgency, the following R&I and CSA topics are proposed:

Short term (0-5 years)

- Harmonized approach for estimating the resource/reserve basis in Member States, through application of consistent (pan-EU) categorization system together with EIT Raw Materials.
- Develop common understanding of sustainability requirements for raw materials sourced outside of EU.
- Improving responsible sourcing and traceability across the complex global supply chains and providing harmonised and reliable frameworks for the EU battery industry to source different raw materials (minerals, metals, and chemicals), both from large scale mining operators and legal artisanal miners
- Development and evaluation of tracing and labelling technologies of the certified materials (cradle-to-gate)
- Assess and put in place a unified framework for how new digital ledger technologies can be used by companies and supply chain actors to reliable and effectively report and trace all the steps in complex battery supply chain

Medium term (5-10 years)

- Tracing and labelling of the certified materials through the whole life cycle (cradle-to-grave)

Potential impact of R&I advancements on this topic:

- Enable EU battery industry to source metals with least social and environmental impact, thus making EU battery industry the most sustainable globally
- Creating frameworks and conditions to use new digital technology to ease tracing and measuring impacts of materials sourcing
- Harmonised and accurate LCA data to enable simple and accurate comparisons of LCA impacts of different raw material steps (extraction, processing, etc) in the battery value chain
- Improve mineral sourcing conditions in non-EU Member States

4. Sustainable extraction and processing of battery grade raw materials

4.1. Description

Development of leading European technologies for efficient extraction and processing of battery grade raw materials is a key element in securing European leadership in the electric vehicle and other energy storage markets. The issue is pressing as the current level of extraction and processing of battery raw materials in Europe is marginal. The competitive edge of European metallurgical battery metals production lies on superior product quality, high material and energy efficiency, and low climate and other environmental impacts. This can be achieved by innovations in improved recovery of currently produced metals but also by recovery of metals such as manganese and rare earths, which are currently not recovered. Recovery of battery metals or compounds of higher purity or value can create competitive edge and in some cases integration of secondary raw materials or intermediates into the primary production may increase the value of previously unused fractions. In addition to higher profits from the battery market, Europe will also benefit from having developed the needed high-level expertise and skillsets.

In the short-to-medium term (5-15 years), it is expected that the Li-ion battery chemistries continue to dominate the EV market. Therefore, there is a high urgency of developing processing solutions for Li, Ni, Co, Mn and graphite. Lithium processing is highly demanding in energy and in water consumption. Energy efficient processing, closed water cycles with reduced need for chemical use are key targets. Downstream, it is important to secure a sufficient supply of especially lithium hydroxide (LiOH) for the European market. Also the capacity to re-process recycled Li from spent batteries integrated in primary lithium processing bears high potential for value added in Europe.

Nickel and cobalt need to be recovered from low-grade ores and secondary sources, which are currently uneconomical to be treated. The development of new technologies for these challenging material streams will significantly widen the metal base in Europe. The product purity will need to be increased to meet the needs of battery applications and integrated with European battery chemical, precursor cathode material (pCAM), cathode active material (CAM) and battery production. In particular R&D&I actions are needed to ramp up the limited capacity for cathode chemical (Ni_2SO_4 and Co_2SO_4) and pCAM production in Europe. Finally, existing primary production is in need of being adapted to more specialized battery raw materials and pCAM production.

To meet the requirements of the future LiB needs in Europe, both synthetic and natural graphite will be required. In both cases, there is a good chance to cover EU anode material demand from within Europe if certain challenges can be overcome. This will however require significant investment in R&I and infrastructure as well as streamlined permitting in order to exploit all opportunities to the maximum and in particular to make these usable/accessible for LiB in terms of performance, cost and lowered CO_2 footprint.

4.2. State of the Art

Battery grade raw materials from primary sources are produced dominantly in well developed processes, which have been tailored for virgin raw materials. This section takes a look at individual elements required to design successful battery chemistries.

Nickel occurs as oxides, sulphides and silicates, which require a variety of techniques to extract nickel. Over half of the global cobalt production comes from nickel ores. Traditionally, sulphide concentrates are smelted to produce matte, which is hydrometallurgically refined to produce high purity nickel and cobalt to the market. Processing methods include pressure and atmospheric sulfuric acid or chloride leaching, chemical purification and electrowinning or chemical precipitation. Nickel pig iron production has been used as a cheaper alternative for nickel use in stainless steel, but the quality is not suitable for battery applications.

Cobalt is largely obtained as a by-product from nickel and copper production, with a smaller amount from primary cobalt mining. A range of technologies are used for cobalt production through the processing of different nickel and copper ores, including both pyrometallurgical and hydro-metallurgical techniques. The primary cobalt materials from global sources include refined cobalt metal, cobalt concentrate, and cobalt complex intermediates. The refined cobalt metal can be used directly or can be converted into other cobalt compounds (e.g. cobalt salts and oxides) for use in various battery applications. The cobalt represents a high value resource, and it is economically viable to recover cobalt and cobalt compounds within End-of-Life (EoL) materials with good (high) recycling rates. The secondary materials recovered at EoL include cobalt-containing metal alloys and complex intermediates. These can be reprocessed into cobalt chemical precursors for production of new battery materials.[18]

Both cobalt and nickel are essential elements in battery cathode chemicals and pCAM. Unit processes for battery chemicals such as nickel and cobalt sulphates, as well as for pCAM exist but they are not developed to a degree that would allow for energy and cost-efficient production in Europe. Typical for pCAM processing, each customer producing CAM have their own production line with very strict specifications, which makes it difficult to use single process lines for multiple different products. The complexity of pCAM processing requires high degree of process control that guarantees strict product quality standards. Still today, pCAM is produced in batch processes. Moving from batch to continuous processing would improve energy efficiency, flexibility and productivity of pCAM production.

For batteries, Lithium comes in two forms: lithium hydroxide (LiOH) and lithium carbonate (Li_2CO_3). While Li_2CO_3 is used currently by battery manufacturers e.g in the US, China, South Korea and Japan, the dominant compound for next generation battery factories now being constructed in Europe is LiOH. The challenge with LiOH, however, is its lower stability compared with Li_2CO_3, and extended shelf time will lead to undesired changes in the crystalline structure. This means that LiOH should be produced near the CAM production site, which increases the attractiveness of LiOH processed and produced in Europe. Most European Lithium mine projects today in Portugal, Spain, Austria, Finland and Serbia work on hardrock deposits, for which there are a number of existing flowsheets. The common target of hardrock Lithium mineral processing is to keep the ore granularity coarse in order to save energy and water. A key challenge is how to sort the coarse ore concentrate and new sorting methods such as optical sorting, dense media separation and flotation are in uses. New processing methods such as dry comminution would lead to further water and energy savings, combined with novel sorting technologies. In downstream Lithium processing, one of the most energy consuming steps is the high temperature thermal treatment, typically conducted in a calciner. Reduction of CO_2 emissions from the thermal conversion e.g with the use of alternative fuels has great potential in reducing the environmental impact of Lithium processing.

For graphite, both natural and synthetic graphite production for the EV market take place almost exclusively in China with, in some cases additional surface modification taking place in Japan. Natural graphite production involves the mining as graphite deposits followed by a series of milling,

[18] (CI, 2019) Infographic by the Cobalt Institute. Cobalt the Technology Enabling Material.

spheronization, and purification steps. The main challenges are low yield in the spheronization and use of large amounts of hydrofluoric acid in the purification step. Thermal methods may also be used for purification, but this drastically increases the CO_2 footprint of production. Improving purification, milling, shaping and coating technologies that improve the performance characteristics of natural graphite is the near term challenge/opportunity.

For synthetic graphite, by-products of oil distillation are used as the starting point, followed by calcining, milling, shaping and graphitization. This produced a high quality EV anode graphite (enabling long lifetimes and fast charging) but is energy intensive and causes environmental emissions (CO_2, PAH). Opportunities to overcome all these problems exist already in Europe but need further development and investment to reach the required scale.

As part of the battery anode, silicon is predicted to become a vital part and the amount will be increased to generate a higher energy density of the battery. Production processes of silicon already exist in large scale, however, which of these processes will be dominant for battery grade silicon is still to be determined. Silicon can be produced both from metallurgical processes or from gas phase through chemical vapor deposition (CVD) processes. Facilities of both processes exist already in Europe but need to be tailored to meet the demands of the battery market. It is of great importance to keep both cost and energy use at a minimum level.

Finally, Slags from non-ferrous smelters can contain high amounts of cobalt, nickel and copper. For example, the cobalt content can typically range between 0.2-1 % in the slag. Thousands of tons of copper slags are produced annually in the copper smelters. Almost 3 million tons of fayalitic slags are produced in the EU annually. In addition, billions of tonnes of tailings exist already worldwide with the amount growing every year. It was estimated that 100 tonnes of cobalt has been stocked in the EU during last 20 years as extractive waste[19]. Slag engineering to recover additional elements will remain an important research topic for Europe.

Attempts have been made to produce EMM (Electrolytic Manganese Metal) by using fume wastes from furnaces. However, it was decide not to industrialize because of the hard competition of low cost but highly contaminant electrolytic process with selenium addition.

Issues with State-of-art:

- Energy and water intensive mineral processing of Lithium
- Instability of the LiOH raw material
- pCAM processed in batches with inflexible flowsheets
- High amount of off-specification battery metals and compounds lost in chemical and pCAM processing
- Significant Na_2SO_4 emissions to waterways from pCAM processing
- Ni or Co lost partially to slag in smelting – not recovered
- Small Ni or Co concentrations recovered as lower value products (NiS, CoS)

19 https://publications.jrc.ec.europa.eu/repository/bitstream/JRC116131/aaa_20190506-d3-jrc-science-for-policy-recovery_of_rm_from_mining_waste_and_landfills_4_07_19_online_final.pdf

- Small mines cannot afford starting refining operations – more flexible primary plants accepting several raw materials form different sources are needed
- Non-existent process integration from raw materias source up to Giga factories

4.3. What is needed in EU to be competitive

Europe should build its own sustainable battery value chains to be able to compete with the most advanced and most sustainable batteries in the world. Therefore any battery raw materials that are produced from European sources or processed in Europe must be able to demonstrate superior quality and environmental criteria, with competitive cost. Simultaneous cost, quality and environmental control require R&I efforts in processing technologies, sustainability certification as well as new business models. Collaboration and understanding between primary and secondary processing in R&I is of importance in order to develop truly optimized, flexible and smart battery metals processing and recovery, utilizing the existing and new technologies and infrastructure. This collaboration, also across the geographical borders will support the best battery metals recovery and recycling as well as value addition. Also R&I in upgrading the value of the recycled product will decrease the use of natural resources and energy consumption.

To reach the goal of the European Battery Alliance – 300 GWh/a of battery production in Europe – will require approximately 270 000 tons of battery grade graphite and 30 000 tons of Silicon for the anode, and 225 000 tons of Class 1 high purity nickel, 29 000 tons of cobalt, 84 000 tons of manganese and 59 000 tons of lithium for the cathode. Currently the level of extraction and processing of battery raw materials in Europe is marginal. For Lithium, hard rock mine projects exist in Austria, Portugal, Serbia and Finland, with a collective planned capacity of 11 000 t Lithium Carbonate Equivalent (LCE), corresponding to about 8% of the estimated 2027 world demand. For Cobalt and Nickel, the European mine production from a Finnish operation is expected to be 1900 tons of battery grade cobalt and 56 000 tons of nickel in the next few years. Europe is a large producer of primary silicon, and also produces both natural and synthetic graphite but not in the vast quantities needed

These goals require Europe to be in the frontline of technological development of metallurgical production, where innovations in processes and unit processes are required. These should aim at improved yield, better process control, flowsheet flexibility, improved product purity and quality, improved impurity removal, and improved recovery from secondary streams. These innovations are in some places complementary unit processes to existing process flow sheets, while in others like European Li or pCAM production, completely new flowsheets. This is expected to bring added value for the European battery metals production.

4.4. R&I Activities needed to reach the visioned next level

The following R&I activities are proposed:

Short term (0-5 years)

- Solutions to a sustainable Lithium value chain including:
    - Novel sorting technologies to allow for higher energy efficiency and lower CO_2 emissions
    - New comminution methods for hardrock lithium to reduce water use and improve energy efficiency
    - Alternative energy sources in thermal conversion to reduce CO_2 emissions
    - Improvement of shelf life / stability of LiOH
    - Specific physical-chemical properties for Lithium deposits, to foresee how the mineral mix could be better understood and processed.
- Development of continuous processes for pCAM to replace the currently used batch processing, including:
    - Process control solutions for different CAM recipes
    - Complete process design concepts including filtration, gas supply, mixing ratios, flow control, fluidized process solutions, and process automation
- Zero Liquid Discharge processing in battery chemical and pCAM processing, including energy cascading and waste valorisation
- Development of new recoverable reagents for battery metal leaching and extraction
- European graphite production – with vertical integration into the European battery production. Resource efficient sustainable production of both Synthetic and natural graphite (reduction of energy consumption and CO_2 emissions, optimization of yield and raw material consumption, versatility regarding products and usable primary/secondary raw materials). Including:
    - Improving the yield to spheronised product for natural graphite concentrate
    - Development of a non-HF purification technology to produce battery-grade anode material from spheronised natural graphite.
    - Developing improved coating technologies for natural graphite that will increase the performance characteristics of natural v synthetic.
    - producing Si-Graphite anodes including developing improved coating technologies for natural graphite.
    - Reduction energy consumption and volatile emissions from synthetic graphite production.
- New business models for co-processing and process integration
- New smelting and slag engineering technologies to address Ni and Co losses in smelting
- Process modelling competence combined with environmental impact evaluation (incl. LCA analysis) for individual primary processes

Medium term (5-10 years)

- An economically feasible process for Mn recovery from base metal solutions
- Substitution of petroleum based feedstock in synthetic graphite production.
- Secondary product recovery to attain a consensus flowsheet, that minimizes tailing and gangue production.
- Substitution of fossil fuels and use of smart and / or renewable energy solutions at battery raw material processing units and/or mines.

- While there is still a need for research and development on the silicon production methods, extensive development is also needed on the composite anode for the battery. The aim is to increase the silicon amount in the Si/C composite up to 20 %. However, work on stabilizing the anode with increased Si content remains. Some of the development is done already in the silicon production methods, by examining coatings and alloys of the silicon material.

5. Raw Material Life Cycle Assesment (LCA) and material Flow Analysis

5.1. Description

This topic describes Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) datasets particularly on LCA of raw materials and recycling as well as data collection and communication. Material Flow Analysis (MFA) is also relevant topic in this context for the flows and circularity of materials. Social LCA is an assessment tool that can be included in a full sustainability assessment and communicating results is a key issue as many indicators can be used.

This topic has connections to other working groups, such as WG3 on advanced materials.

5.2. State of the Art

5.2.1. Raw material LCA

Life Cycle Assessment (LCA) is a methodology used to evaluate environmental impacts of products and systems. It is standardized by ISO 14040:2006 and has widely been applied to batteries and the EC has developped PEFCR on rechargeable batteries. The environmental impacts of battery manufacturing are driven by energy production when focusing on greenhouse gas (GHG) emissions[20,21]. However, other impacts[22] such as toxicity, water footprint[23], resource depletion, show that raw material extraction and processing are key stages. There is a need for developemnts of models and data required to assess these other impact categories.

[20] Philippot M, Alvarez G, Ayerbe E, Mierlo J Van, Van Mierlo J, Messagie M. Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs. Batteries 2019;5:23. doi:10.3390/batteries5010023.

[21] Marmiroli B, Messagie M, Dotelli G, Van Mierlo J. Electricity Generation in LCA of Electric Vehicles: A Review. Appl Sci 2018;8:1384. doi:10.3390/app8081384.

[22] Peters JF, Baumann M, Zimmermann B, Braun J, Weil M. The environmental impact of Li-Ion batteries and the role of key parameters – A review. Renew Sustain Energy Rev 2017;67:491–506. doi:10.1016/j.rser.2016.08.039.

[23] Philippot M, Ayerbe E, Hoedemaekers E, Van Mierlo J. Water footprint of the manufacturing of a traction lithium ion battery pack. EVS32, 2019.

Battery raw material extraction and refining processes happen in several places on the globe, with different energy production mixes. Using renewable energy to produce raw materials allows to reduce the environemntal impacts of batteries[24] (GHG emissions, SO_x emissions, water consumption and NO_x emissions). Therefore it is necessary to have good quality LCIs of raw materials as the full supply chain influences the final results at battery level.

Tools such as LCA (and MFA) are used to examine the environmental impacts of production and use of battery materials such as lithium, cobalt, nickel, manganese, vanadium, copper, and aluminium. Most metal LCA studies consider mining to refining (cradle to gate), and some encompass the full life cycle through to recycling at end-of-life (cradle to grave). The metals industry has developed harmonized LCA guidance (PE International et al., 2015), and the global LCA metals datasets are available within several mainstream LCA databases, including the EC's new PEF database.

The metal LCA studies that are conducted by industry associations cover many company sites/facilities and a wide range of pyro- and hydro-metallurgical processing operations. This metals LCA data is aggregated or averaged by Life Cycle stage (main process), and not by unit processes for several reasons. There is a current need for better, updated and more disaggregated or process-specific LCA data, especially on the battery precursor chemicals (e.g. metal sulphates, etc.) used to prepare the active cathode materials, as well as for the anode materials (e.g. graphite).

LCA is a methodology dependent on input data. Many practioners use databases, mainly Ecoinvent and GaBi for raw material inventories used as background processes. However, those background processes may have important influence on product LCA and some raw material inventories may be outdated or characterised using proxy data. For instance, datasets available for nickel and cobalt in Ecoinvent 3.4 have 1994 as a reference year, while both metals have updated life cycle inventories more recently [25,26].

5.2.2. Metals for cathode materials

The metals industry LCA data has undergone external independent peer review, to ensure conformance with ISO standards for LCA, and data quality ratings for use in PEF and ILCD. Many inventory datasets have also been assembled for the PEF (Product Environmental Footprint) programme, which are now available in openLCA and commercial softwares.

Some questions can also be raised on lithium inventories. Until recently, lithium mostly orginated from brine processing in South America but Australia is mining lithium from spodumene and is the world largest lithium producer [27]. Several compounds can be used, carbonates or hydroxides mainly. Inventory for lithium carbonate production from spodumene in Ecoinvent 3.4 does not originate from industry and energy consumptions and emissions are estimated.

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[24] Kelly JC, Dai Q, Wang M. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitig Adapt Strateg Glob Chang 2019
[25] Gediga J, Sandilands J, Roomanay N, Boonzaier S. Life Cycle Assessment of Nickel Products. Study commissioned by the Nickel Institute. 2015
[26] Cobalt Development Institute. The Environmental Performance of Refined Cobalt. 2016
[27] U.S. Geological Survey. Mineral Commodity Summaries 2019. 2019. doi:10.3133/70202434. http://www.openlca.org/product-environmental-footprints-pefs-in-openlca/

Cathodes using Vanadium based compounds may be a good candidate for pulling ahead the built up of a LCA enhanced pilot model because the needs of Vanadium for new cathodes may be sourced from different sources. However, LCA studies for all those alternatives are being developped.

5.2.3. Anode Materials

Anode materials are predominantly graphite-based, falling into two categories: natural and synthetic. Europe is in fact rich in natural graphite deposits (mainly in Scandinavia) which are high grade, largely untapped and could in principle serve the European battery market for many decades. However, only certain types of natural graphite can be converted to anode material. Exploiting these graphite sources for active anode material within Europe is promising for a number of reasons: i) permitted graphite mines already exist, ii) extensive exploration across Sweden, Norway and Finland has defined large high grade resources, some of which in Sweden are in advanced stages of development, iii) Production of anode materials in Scandinavia can utilise renewable power sources based on hydroelectric power and wind, therefore providing a much lower CO_2 footprint than comparable treatment production from China (as well as the huge reduction in transport miles of raw materials). Key challenges however include i) streamlined permitting processing ii) surrounding infrastructure, and iii) institutional support to reach economies of scale. Synthetic graphite also offers an alternative for European production, with some key challenges to overcome: i) the existing process flow is based on petroleum coke and must be improved to increase battery grade material yields and performance, as well as reduce energy intensity, CO_2 emissions, and environmental pollutant discharges. ii) The identification and exploitation of alternative raw material sources for synthetic graphite production such as recycled anode material, by-products from anode material production and other EU available carbon sources should be explored as a priority, iii) In the longer term, biocarbon alternatives to petroleum coke could be explored to identify another type of sustainable supply. In summary, having a stable and localized graphite supply in Europe is not out of reach and will guarantee a growing economy related to steady renewable energy supply in the continent which is strategically important for the automotive industry and micro-grid use. LCA data for anode materials including the various types and production routes as well as alternative precursors are still being underrepresented and require initiatives to close this gap.

A short list of candidates for anode material must include: carbon nanotubes, carbon nanofibers, graphene, porous carbon, SiO, silicon, germanium, tin, transition metal oxides, metal sulphides, phosphides and nitrides[28].

Given their limited use compared to graphite anode materials and/or lack of technical maturity in LIB applications, a final statement on sustainability optimization potentials is not possible at this state. However, sustainability can be a criterion to select between alternative development routes, and LCA data can be built in the course of scale-up and market introduction.

5.2.4. Electrolytes

[28] Subrahmanyam Goriparti, Ermanno Miele, Francesco De Angelis, Enzo Di Fabrizio, Remo Proietti Zaccaria, Claudio Capiglia, Journal of Power Sources 257 (2014) 421-443.

Electrolytes are a key module of EV battery which plays a critical role in the global safety of the battery pack. The development of new electrolytes has a great differenciator potential and Europe may take advantage in achieving a successful roadmap toward safe solid state electrolytes. A specific LCA model for electrolyte must on one hand highlight the key differences between liquid/solid state electrolytes and on the other hand will contribute to boost the selection of the best robust solid-state electrolyte. For a strong position of Europe in the mastering of safe sustainable electrolyte.

Today the mainstream of liquid electrolytes are based on Carbonates (Ethyl-Carbonates, DimethylCarbonates, EMC,….) as solvents and LiPF6 as lithium salts. On the other hand the 3 main categories of the most promising solid-state electrolytes are: polymer (PEO) and ceramic: oxides (LLZO, LIPON) and sulfides (LPS, LGPS) .

The related LCI/LCA must evaluate the synchronization of the Electrolyte End of Life with the cathode and anode end of life in order to ensure an optimized recycling start of the battery module.

5.2.5. Chemical precursors

The battery raw materials outlined above will be transformed into certain chemical substances that are used as chemical precursor compounds to produce the active cathode component. For example, the cobalt raw materials produced from mining can be processed into chemicals such as cobalt sulphate or dihydroxide, which are transformed into lithiated cobalt oxides (LiCoO2) for the NMC or NCA chemistries used in lithium-ion batteries.

The PEF programme involved use of proxy data for battery precursor chemicals, as outlined in the PEFCR report. For example, cobalt sulphate is modelled through proxy based on LCA data for cobalt metal, and graphite in the anode is modelled through use of carbon black data as proxy, etc. The EC's PEF data underwent extensive expert peer review, and most metals data was rated good quality. However new LCA studies are required (and several are underway), to obtain new LCI datasets for specific battery precursor chemicals.

5.2.6. Nanomaterials for cathode, anode and electrolytes

Nanomaterials in batteries could be used in different components but their manufacturing may be energy demanding, which could increase the environmental impact of EVs [29].

LCA has been used to assess the environmental impacts of nanomaterials during their complete life cycles. The number of LCA studies published on manufacturing and use of nanoaterials is increasing. However, several issues and developments have been pointed by review articles. The two key shortcomings in the application of LCA to nanomaterials are 1/ the lack of LCI data and 2/the scarcity of nanomaterial-specific characterization factors for toxicity-related potential impacts. In most studies, flows of nano-substances are raerly taken into account. The exposure and effect of nanomaterial

[29] Ellingsen LAW, Hung CR, Majeau-Bettez G, Singh B, Chen Z, Whittingham MS, et al. Nanotechnology for environmentally sustainable electromobility. Nat Nanotechnol 2016;11:1039–51. doi:10.1038/nnano.2016.237.

release is not well known yet, as a result there is a need for nanomaterial-specific characterisation factors for (eco)toxicity impacts. [30]

5.2.7. Material Flow Analysis including secondary materials

Much information about the mineral potential (EU and global reserves) sourcing and the material flows of battery raw materials and secondary materials is being assembled by the EU Commission through the current H2020 projects and other studies (e.g. PROSUM, SUPRIM, BATMAN, etc.), as well as by the Geological Associations (USGS, BGS, etc.) and individual commodity associations. Available information on these materials is presented in the EC's MSA (Material Flow System Analysis) reports[31], and updated information will be summarized in the new Fact Sheets (being prepared) for many critical materials. Specific reports by the JRC[32] and others (WEF-GBA and McKinsey, 2019) provide overviews of the supply/demand situations for certain metals, and also consider potential future scenarios for the EV-battery sector.

MFA models have so far mainly analysed individual metal cycles relevant for LIBs, such as lithium, cobalt, nickel, copper, and aluminium[33]. However, these top-down models do not account for the role of LIBs in sufficient detail, and they tend to omit the linkages between the metals/battery materials. Furthermore, graphite sourcing is sometimes overlooked when considering LIB raw materials. There is a growing body of research addressing either metal demand from LIB production[34] or LIB recycling[35]using mass-balance approaches. While these studies provide useful insights into a variety of aspects, they fail to address the linkage between battery production and recycling, which is formed by the constantly evolving in-use (batteries in use) stocks. Understanding this linkage is highly relevant for forecasting material flows and thus for anticipating and addressing challenges in recycling and reuse.

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[30] Salieri B, Turner DA, Nowack B, Hischier R. Life cycle assessment of manufactured nanomaterials: Where are we? NanoImpact 2018;10:108–20. doi:10.1016/j.impact.2017.12.003

[31] https://ec.europa.eu/eurostat/documents/8105938/8465062/Study_Data_Raw_Bio_Deloitte.pdf

[32] Alves Dias P., Blagoeva D., Pavel C., Arvanitidis N., Cobalt: demand-supply balances in the transition to electric mobility, JRC112285, 2018, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112285/jrc112285_cobalt.pdf

[33]Gang Liu and Daniel B. Müller 2013, Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis, Environmental Science & Technology 47 (20), 11873-11881.

[34] Tobias Schmidt, Matthias Buchert, Liselotte Schebek, 2016. Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries, Resources, Conservation and Recycling, Volume 112, Pages 107-122, ISSN 0921-3449

[35] Kim, H., Jang, Y.C., Hwang, Y., Ko, Y. and Yun, H., 2018. End-of-life batteries management and material flow analysis in South Korea. Frontiers of Environmental Science & Engineering, 12(3), p.3

Ziemann et al. [36] Modaresi and Müller [37] and Løvik et al. [38] have used a similar approach to address material quality issues for aluminium in the vehicle system, however, they excluded batteries. There is a lack of literature that is analysing the LIBs system in a more comprehensive way, addressing linkages between materials, applications other than vehicles (e.g., LIBs used in ships and stationary applications), and the differentiation and integration of reuse and recycling.

In addition, we have a good overview of the potential reserves of key LIB materials, but little about the capacity to extract the materials from their parent ores. There seems to be a gap between the demand and supply of materials due to the limitation in exploration and mining capacities. This can be underscored and better understood by adding this aspect to a full battery material MFA model.

5.2.8. Recycling

The process for the recycling of lithium-ion batteries can be clustered according to three subsequent steps: (1) Pre-treatment (2) Material/Metal refining & extraction (3) Transformation & Chemical production. For each step, a variety of process options exist and typically a combination of technologies is used. During pre-treatment, batteries are conditioned into a form in which they are accessible for further material & metal recovery. Discharging, dismantling, mechanical pre-treatment, thermal pre-treatment and/or smelting (often a combination) are techniques currently used. The material that comes out of the pre-treatment (e.g. black mass, alloy) needs further processing to be reintroduced in the battery value chain. This happens in the subsequent step where the streams are metallurgically refined typically via hydrometallurgical unit processes; metals are extracted to solutions (acids), separated from each others and impurities are removed. Finally, the valuable battery metals are recovered from the purified hydrometallurgical solutions into products (e.g. Co salts, Ni salts, Li salts). These can be further transformed into new precursor and battery materials.

When aiming for a circular economy for Li-ion batteries, all three areas are relevant and should be considered in comparative studies. However, due to the variety in specific unit operations and final output products resulting from these three steps, it is a hard and nuanced exercise to compare one recycling process to another. Additionally, not all three steps happen necessarily by the same ‘recycling company’ – even within one step, intermediates can be passed on from one company to the other.

Many techniques described in the literature have been carried out in lab scale.[39] For all chemistries, more than 75% of the value comes from the positive electrode , which justifies why most of the

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[36] Saskia Ziemann, Daniel B. Müller, Liselotte Schebek, Marcel Weil, 2018. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach, Resources, Conservation and Recycling, Volume 133, Pages 76-85, ISSN 0921-3449.

[37] Roja Modaresi and Daniel B. Müller, 2012. The Role of Automobiles for the Future of Aluminum Recycling. Environmental Science & Technology 46 (16), 8587-8594

[38] Amund N. Løvik, Roja Modaresi, and Daniel B. Müller (2014). Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. Environmental Science & Technology, 48 (8), 4257-4265

[39] https://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf

processes focus on this part of the batteries.[40] However, other effects such as related to carbon footprint might suggest to extend focus beyond cathode metals to other components such as graphite anode materials. Anyhow, a wider variety of materials (than only positive electrode) will end up to the recycling process, and as a consequence the recycling processes need to address all of these materials.

Given the different level of technology readiness level of the recycling processes and the different types of output materials, a clear methodology should be developed if ones want to compare the environmental impact of different processes. Comparison should always be done for a same functional unit and taking into account the type and quality of the end products. There is a need for a great level of details. Also, a value chain perspective requires that less studied processes up to now, such as the collection of the batteries and steps such as the sorting, disassembly and discharge of batteries, for which very few data are available.[390]

5.2.9. Social LCA

Social impacts of industrial mining have been reviewed by Mancini et al. [41]. They listed 28 typical positive and negative social impacts of mining. Positive impacts are mainly in the field of incomes and employment: increase of population revenue, job creation, new local business opportunities and infrastructures. While negative impacts are often found at local level and include child labor, forced labor, health and safety issues, low salaries, land use, water use, … However, there is not one study assessing those raw materials with the same framework.

Drive Sustainability, Responsible Minerals Initiative (RMI) and The Dragonfly Initiative [42] compared 37 materials commonly used in automotive and electronics products. The mappings include environmental, social and governance criteria. At the level of batteries, Reuter[43] and Thies et al.[44] uses the Social Hotspot DataBase (SHDB) to assess the social impacts of batteries

The Global Reporting Initiative (GRI) Standards are used by large corporations to report their impact on sustainability issues. However, this is a voluntary framework that describes a company's own facilities,

[40] https://www.worldscientific.com/worldscibooks/10.1142/10658#t=aboutBook
[41] Mancini L, Sala S. Social impact assessment in the mining sector: Review and comparison of indicators frameworks. Resour Policy 2018. doi:10.1016/j.resourpol.2018.02.002
[42] Drive Sustainability, Responsible Minerals Initiative, The Dragonfly Initiative. MATERIAL CHANGE a study of risks and opportunities for collective action in the materials supply chains of the automotive and electronics industries. 2018.
[43] Reuter B. Assessment of sustainability issues for the selection of materials and technologies during product design: a case study of lithium-ion batteries for electric vehicles. Int J Interact Des Manuf 2016;10:217–27. doi:10.1007/s12008-016-0329-0
[44] Thies C, Kieckhäfer K, Spengler TS, Sodhi MS. Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. Procedia CIRP 2019;80:292–7. doi:10.1016/J.PROCIR.2018.12.009

and obviously is not applied to ASM which often involves unlicensed workers, health and safety issues and human rights abuses[45]. In the disclosure for mining and metal sector there is an indicator for ASM.

In the field of social impacts of mining, several initiatives exist to reduce negative social impacts such as the OECD Due Diligence Guidance for Responsible Mineral Supply Chains, the Chinese Due Diligence Guidelines for Responsible Mineral Supply Chains, US Securities and Exchange Commission, LME responsible sourcing, among others. In Europe, the Regulation (EU) 2017/821 focuses on tin, tantalum, tungsten and gold. More specifically, some materials have their own guidelines, such as the Responsible Cobalt Initiative, CIRAF (Cobalt Industry Responsible Assessment Framework)[46], and the Copper Mark.

There is a lack of information on social impacts of the sourcing, production and recycling of batteries.

The methodology for sLCA is still developing, the UNEP/SETAC guidelines on sLCA are currently being reviewed.

5.2.10.Sustainability assessment and LCA

LCA data for the recycling process are very limited and do not go into the depth of the different effects of the processes.[10] The new LCA data required for characterizing the EU battery value chain is on new technological processes being developed to produce and recover battery chemicals for recycling. It would also be useful to have an overall summary (database) for collating the various technical projects and to disseminate the findings. Modelling End of Life (EoL) in LCA is not straight forward and is subject to several methodological choices. In battery LCA studies, there are inconsistencies in methods used and attention must be drawn on that point[47].

The performance of recycling could be measured with KPIs which may be linked to the speed and efficiency of use-reuse-loss circles. Considering the active materials entry in Europe we may develop simple KPIs which could follow the KPI ratio: new entry or new manufacture/use, use/recycling, recycling/loss of recycling process. Such KPI for each active material doesn't exist and must be developed.

Most sustainability assessment results currently focus on fully developed and marketed products. The design phase of a process, when its essential characteristics are defined, is the most important phase in its life cycle, particularly with regards to future consequences as cost and environmental impacts. Decisions made at this stage, where around 70% of the final cost, requirements and environmental impacts are determined, will have far influence later. Trends are observable in technological development, but predicting where future technological changes will occur and their associated future

[45] Banza C, Nkulu L, Casas L, Haufroid V, De Putter T, Saenen ND, et al. Sustainability of artisanal mining of cobalt in DR Congo. Nat Sustain 2018;1:495–504. doi:10.1038/s41893-018-0139-4
[46] Cobalt Institute and RCS Global, Cobalt Industry Responsible Assessment Framework, primer for stakeholders
[47] Nordelöf A, Poulikidou S, Chordia M, Bitencourt de Oliveira F, Tivander J, Arvidsson R. Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries. Batteries 2019;5:51. doi:10.3390/batteries5030051.

environmental impacts is more difficult. Providing some reasonable consideration of environmental impacts as early as possible in technological development is necessary.

Life cycle assessment (LCA) can play a role in supporting this as it has a long track record as an effective multicriteria environmental assessment tool since it was introduced in the late 1960s. However, LCA is predominantly applied to existing products and is thus retrospective in nature. It has shortcomings that diminish accuracy and increase the uncertainty of assessment. Problems in all LCA phases are functional unit definition, boundary selection, allocation, spatial variation, local environmental uniqueness, and data availability/ quality. Uncertainty has been tackled with replication of LCA where assumptions are changed one at a time to compare different outcomes, exploring and reporting the sensitivity of the LCA outcomes to changes, and applying and incorporating statistical uncertainty analysis.

The application of predictive (ex ante) LCA shall be envisaged at early stages calls for extra with vigilance to the due to lack of definition of the product system when more and different uncertainties are involved. The main problems can emerge from: a) difficulties in defining the goal and scope of the LCA at such an ex ante stage; b) uncertainty of the process data which may be lacking and of poor quality, resulting in dubious potential environmental impacts ; and c) an accurate level of confidence in data interpretation. Nonetheless, attempts have been made to apply the tool to emerging technologies where requisite information for modelling is limited [48].

[48] Villares M, Işıldar A, van der Giesen C, Guinée J. Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste. Int J Life Cycle Assess 2017;22:1618–33. doi:10.1007/s11367-017-1270-6

5.3. What is needed in EU to be competitive

5.3.1. Mining

- Regionalized LCA for mining such as water footprint

The primary source of raw materials for batteries comes from mining, either hard-rock or brine related. Adding to this, mineral exploration is an important step towards the discovery of raw material sources. Widely accepted codes (CRIRSCO and/or UNECE compliant), guide the exploration and mining reports. It is within the scope of these reports that the regional LCA should begin at a regional scale. The estimate consumption of water, fuels, energy and land use impacts, such as small deforestation should be dealt with from the exploration stage, using public reports as a basis for this. There are, of course, regional differences regarding resource consumption (and of course mineral deposit type), and this should go into account in the Regionalized LCA. A simple example can be given in hard-rock Lithium exploration and mining in locations such as Portugal and Finland. Water consumption will be a much more sensible issue in Southern European countries. So, in order to assess environmental impacts, specific reporting topics (CRIRSCO and/or UNECE compliant), regarding water and energy consumption, should be demanded by national authorities in both exploration and mining phases.

- Harmonized energy source declaration of material producing companies from exploration to final products

This topic relates to the declaration of energy origin as declared from energy producers and distributors. Raw material producers should be able to report on energy consumption (quantity and mix) per sites. This reporting could therefore be used in LCA studies of raw materials and ecolabelling of batteries. An energy source estimation should be made by operators (from exploration to production) considering the energy source origin, and there is a need for harmonised guidance for these companies to describe the energy sources. This guidance should consider verification (checks) and reporting (transparency).

5.3.2. Raw materials

- Reliable raw materials LCI data

Data availability and quality are some of the big challenges that face LCA. Gathering good quality inventories of raw materials and have them accessible is needed to have reliable LCA studies. The life cycle inventories of raw materials, including chemicals and precursors need to be reliable and non-aggregated. The inventories for different geological sources and manufacturing processes (lithium processing from brines or spodumene for instance) with different energy sources are needed to assess preciously and with a high degree of reliability.

- Open access LCI of raw materials

When reliable LCI of all the raw materials, chemicals and precursors are gathered, they need to be easily accessible. Publicly available LCI are a key to trustful LCA. The electronic formats of these used to make these datasets available is subject to questions as converting formats is not straight forward and can lead to loss of information.

- Ecolabel of batteries (sustainability requirements)

Simple to understand Ecolabels have to be conceived with simple KPIs which address the Societal and Environmental issues. Ecolabel is necessary at battery level, however raw materials information is essential for developing this ecolabel.

5.3.3. MFA

- Harmonized MFA for raw materials for batteries

Need to address the gap between the demand and supply of materials due to the limitation in exploration and mining capacities, and to allow for unhindered movement of battery raw materials within EU, from the extraction stage to the recycling stage. For example, through development of a harmonized framework for MFA that considers requirements at EU level as well as country-specific aspects, in order to provide a more efficient MFA platform for batteries.

5.3.4. Recycling

- Reliable recycling LCI

The challenge related to recycling LCI data is that ideally these data would be available at an early stage in the development process, while such lab or pilot scale-based data may not be representative of an industrially running process. The scope and boundary of the "process" should also be clearly defined.

- Examinations of primary and secondary materials (in terms of energy, costs and other impacts)

When using LCA to examine batteries manufactured from primary and secondary materials, the whole life cycle and the performance of the final product have to be considered. The challenge consists in defining an adequate scope and functional unit, as well as a methodology to take into account the varying content of secondary materials in the product, as well as the technology readiness of the recycling processes.

5.3.5. Social LCA and sustainability assessment

- Understand the full sustainability

Sustainability is based on three pillars: people, planet and profit. However, there is no unified method to assess the full sustainability of raw materials and to understand the trade-offs between the three pillars. Most studies and policies focus on climate change, which is a big challenge of course but should not make us forget other indicators of environmental impacts and also social impacts. All those impacts imply a broad range of indicators, that are not comparable to each other. As in environmental LCA, weighting and normalization is subject to discussions, but it is needed to communicate more easily the results. A battery specific tool that assess the full sustainability of batteries is needed.

- Include LCA in an early design process: Methodologies for ex-ante LCA (qualitative and semi-quantitative assessments).

The choices of materials and processes are made at design and early technology stages while related life cycle related data are currently widely missing. Extrapolation upon upscaling is urgently required to address this gap, allowing for sustainability considerations at early design and development stages. A large proportion of the environmental impacts of a technology is determined by decisions at these early stages. Therefore, effective approaches to grasp the potential environmental performance of a technology early in development are needed by the ex-ante application of LCA using a case study of the impacts of a lab-scale novel process. The LCA framework shall be applied at an early stage to any novel process and linking it to upstream and downstream flows. The environmental hotspots of the scenario can be identified, and the impacts can be compared with those of a current industrial technique.

Case studies on ex-ante LCA, applicable to emerging technologies could start from mining available data and sustainability assessment results to derive generalizable rules for early-stage assessment and upscaling. The high level of uncertainty inherent to any ex-ante assessment should be carefully managed, as well as the eventual mis-concept conclusions from the anticipatory analysis results.

5.4. R&I Activities needed to reach the visioned next level

The following R&I and CSA activities are proposed:

Short term (0-5 years)

- Open access LCI data of raw materials.
- Ecolabel of batteries (sustainability requirements).
- Include LCA in an early design process
- Harmonized energy source declaration of material producing companies from exploration to final products.
- Harmonized MFA for raw materials for batteries.
- Reliable raw materials (including chemicals and precursors) LCI, for different manufacturing processes (Li from brines or spodumene, natural or synthetic graphite for instance) with different energy sources.
- Reliable recycling LCI data.
- Understand the full sustainability (not focus only on one indicator).
- Examination of primary and secondary materials (in terms of energy, costs and other impacts).

Medium term

- Regionalized LCA for mining (as impacts are site specific) such as Water Footprint.
- LCI data and LCA of next generation, e.g. solid state, Na-ion and redox-flow batteries

6. Collection, reverse logistics, sorting and dismantling

6.1. Description

This topic describes the current state of art, challenges, as well as proposals of actions related to Li-ion batteries handling when they reach the end of their 1st and 2nd life.

Collection, handling, sorting and dismantling end-of-life Li-ion batteries are the first and necessary steps in getting batteries back into the battery value chain through extending the product life and in the end proper recycling.

Current inefficient ways of handling Li-ion end-of-life battery streams, as well as the foreseeable growth in volumes available on the European market in following years brings the necessity of development of an organized and harmonized system of battery handling across the EU. This seems to be particularly important taking into account the risks related to handling batteries, especially the high-energy ones from EV or energy storage applications.

The majority of problems described above relates to all kinds of Li-ion batteries, however particular focus is put on high-energy ones from EV or energy-storage applications due to its growing importance in European energy transition.

When it comes to collection or take back, issues such necessity of assessment of the battery's state of health and discharge before the transportation phase are mentioned along with the problem of low collection rate of particularly portable batteries across EU. In logistics, the need of standardized transportation solutions connected with fire prevention and load monitoring is addressed. The mentioned solutions should match the mandatory ADR and UN Transport Regulations as amended from time to time. In sorting, the insufficient labelling problem is described as well as the lack of efficient, automated sorting solutions. Also advanced diagnostics of end-of-life batteries is pointed out as a necessary condition to maximize the 2nd life battery stream.

Finally, regulatory aspects are also included as a necessary condition to enable efficient collection, transportation and sorting of large volumes of batteries.

Norway as one of the worlds most developed EV markets is already facing main of these challenges.

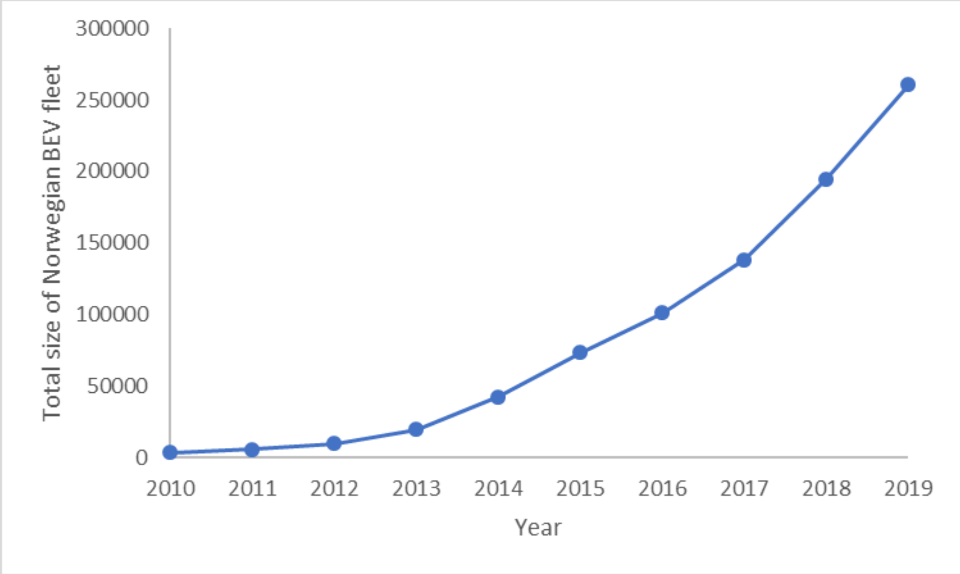

Figure 1: Development of Norwegian BEV fleet

Already in 2014, there were 42.000 full electric vehicles on Norwegian roads, with over 260.000 in 2019. This has led to challenges in handling of EV batteries such as those i) damaged in car accidents and fires ii) OEM battery re-calls and iii) end-of-life vehicles.

6.2. State of the Art

The flow throughout the value chain of Li-ion batteries across Europe is very diverse. Variety of types, sizes, shapes, connections or chemical compositions of active materials make it very difficult to be handled effectively, at maximum possible takeback rate and with minimum CO_2 footprint. The collection rate of Li-ion batteries in Europe is not satisfactory, particularly when it comes to small batteries from portable applications. Most Member States have met or exceeded the 2012 target for the collection of waste portable batteries (set at 25%), but only 14 Member States have met the 2016 target (set at 45%)[49]. However, the current collection of portable/consumer batteries is largely dominated by primary batteries like Alkaline cells. The relative collection rate for secondary portable batteries remains very low. This results in both environmental dangers and limited supply of strategic raw materials that can be extracted via recycling to support the European battery industry. With regard to high-energy batteries from EVs and energy storage, the system of organized takeback and further handling is in its very infant stage of development, both due to small volumes of EVs and ESS on the market and insufficient regulations (also due to the fact that these batteries usually have a long lifetime – 8 to 12 years before no longer able to function in the vehicle or stationary application. This is very different from e-bike batteries – 3 to 5 years, and from portable Li-ion batteries).

Upon collection/takeback of high-energy batteries, the SoH diagnostics is very rarely applied due to the lack of automated technical solutions allowing for fast and reliable verification of SoH of used batteries (however, OEM's, importers and their official dealer networks do this as they have the diagnostics tools to conduct such diagnose at the time of service, or repair, or end-of-life). This also refers to advanced

[49] https://ec.europa.eu/info/news/commission-publishes-evaluation-eu-batteries-directive-2019-apr-09-0_en

SoH diagnostics that should be applied before recycling phase, in order to effectively separate 2nd use stream from battery waste available for recycling. The discharge of batteries before logistics is rare, and if any the simple discharge methods are applied (e.g. bath in water/salt based electrolyte) which do not enable energy recovery.

In transportation, there are no standardized solutions eliminating or mitigating risks of uncontrolled fire and explosion (thermal runaway) and related emissions, or monitoring of status of batteries during this phase, that are scalable at reasonable cost (reference to UN transport & ADR regulation).

Finally, separation and sorting of used li-ion batteries nowadays is very inefficient. There are no automated solutions and effective separation requires manual approach, however even then there are significant limitations caused by lack or insufficient labelling of batteries. As a result, batteries cannot be separated effectively by their chemistries and other characteristics which would optimize further recycling processes. Due to lack of standardized protocols and automated batteries SoH diagnostics, there is still a room for increasing the share of 2nd use battery stream in the total volume of taken back battery waste.

EV batteries are large units in dimension and weight. A dismantling step is needed either (1) to refurbish the EV battery for a second life or (2) when the EoL battery is ready for recycling. There is no industrial recycling process capable of handling the EV battery as a whole. A dismantling step is always present, mostly manual for the time being. However, in order to minimize recycling costs, while guaranteeing safety during the dismantling operation, it is necessary to automatize the dismantling step. This is possible with progress made with AI and robotics. The automatic dismantling operations should become an industrial reality when the large volume of EoL BEV batteries will reach the recyclers.

6.3. What is needed in EU to be competitive

To enable steady and profound growth of Li-ion batteries recycling industry in EU, the regulatory framework should be adopted accordingly. As a result, the collection rate should increase and growing volumes would enable to create sustainable system of used battery collection, logistics and recycling. This should support innovations in the industry and supply strategic raw materials (Co, Ni, Li and others) for the developing European battery industry.

New technologies and devices for battery SoH assessment are needed. This should enable fast and automated SoH diagnosis before logistics which should reduce risk of uncontrolled fire and explosion (thermal runaway) during transportation thanks to identification of damaged & defective batteries which could then be treated in special logistic regime, which is in fact compulsory by legislation). Advance SoH verification should also take place at further stage (in recycling plant), in order to select batteries sufficient for second life applications. In order to achieve that, standardized diagnostics protocols (for EV and energy storage batteries) should be established and cut-off criteria identified to increase rate of reuse and thus reducing environmental footprint and hazards connected with reuse.
In order to enable effective movements of used Li-ion batteries from collection/takeback points to recycling facilities cost efficient storage and transportation containers and systems are needed (most OEM's have already put such systems in place by themselves or have outsourced this to expert logistics operators). Such systems should be scalable and offer sufficient load monitoring. It should be focused on fire or explosion prevention by thorough research on batteries' burning process (thermal runaway)

and identification of Limiting Oxygen Index (LOI) and Lower Explosive Limits (LEL). These should lead to development of cost-efficient storage and transportation containers with possibly neutral atmosphere that would significantly decrease the risk of fire. As a result, developed technologies would contribute to the decrease of hazards connected with transportation of end of life batteries and decrease of total cost of handling of end of life batteries. It is a matter of adhering to the transport regulation, that's the biggest problem today, with a lack of knowledge of many within that value chain.

Handling of used batteries is much safer when they are discharged, therefore it is necessary to develop new discharge technologies which do not waste batteries' residual energy but recover it. Recovered energy can be reused in grid or in further recycling processes which would decrease recycling process' CO_2 footprint. To achieve that new, flexible solutions are needed, able to handle various kinds of batteries (especially high-energy ones). Issues such as flexible connectivity, fast, easy and automated operation, possible connection with SoH diagnostics equipment should be targeted in research activities.

To maximally increase 2nd life stream and recycling efficiency of Li-ion battery scrap it is necessary to develop sufficient sorting technologies. Such technologies should be based on automation and machine learning in order to handle growing volumes of diversified battery waste. Sorting of batteries by their composition is an important condition to optimize recycling and thus recovery of strategic battery raw materials.

To avoid inefficient separation, it is necessary to introduce standardized labelling systems for all Li-ion batteries. Labels (or international accepted serial number system, or barcoding or QR coding) should enable fastest possible automated sorting and provide necessary data for all battery handling parties, including collectors, refurbishments centres or recycling facilities. Data such as battery type, chemistry, raw materials content, weight, dimensions, voltage, capacity, manufacturer etc. should possibly be coded into the label which could be somehow connected with battery passport database which is under consideration between battery industry and EU authorities.
This would significantly support efficient SoH diagnostics and 2nd life stream separation and, perhaps most importantly, accurate separation of batteries according to their chemistries and composition before further recycling treatment.

Eventually the battery will go for recycling and a new dismantling step is necessary. In order to insure a competitive recycling chain, the dismantling step must be automatized.

6.4. R&I and CSA Activities needed to reach the visioned next level

Regulatory framework adjustment for growing volumes of Li-ion batteries and to support creation of sustainable takeback scheme. The current revision of the Batteries Directive should help in this area.

The following R&I and CSA activities are proposed:

<u>Short term (0-5 year)</u>

- Research on new technologies and devices for battery SoH assessment, including portable solutions and advanced stationary solutions, versatile, supporting multi-connectivity etc.
- Research on standardized diagnostics protocols and cut-off criteria between product (2nd life application) and waste (recycling).
- Research on battery burning process (thermal runaway), identification of Limiting Oxygen Index (LOI) and Lower Explosive Limits (LEL).
- Development of standardized and cost-efficient storage and transportation containers with visual and thermal load monitoring systems and, if necessary, inert atmosphere.
- Research on discharge technologies and devices equipped with energy recovery systems. Development of technologies for fast and efficient discharge connected with automated energy recovery, possibly integrated with SoH diagnostic equipment, with flexible connectivity and adjustable to various kinds of batteries.
- Development of standardized battery labelling system which would enable all interested parties to automatically obtain necessary data on each battery. Potential integration of labelling system with battery passport database project and with labelling systems from other regions of the world (e.g. China). Research on the scope of necessary data that should be included into labelling and battery passport projects.
- Research on batteries sorting and dismantling technologies, particularly automated sorting including machine learning.

Regarding dismantling, the automation of such steps should take the following into consideration:

- Design of batteries
  There are multiple design of an EV battery in dimensions and forms. Even for a particular vehicle model, the design can change over time in function of the revamping cycles of each model
- Modularity
  An automatic dismantling operation should be modular and adaptative to various size, model and other characteristics of the EV
- Risk and safety
  At all stage of the dismantling chain, safety should be the first priority.
- Time -dependent evolution of the chemical composition
  The chemical composition can influence sub-sorting (LCA,NMC, LFP...) but also for safety reasons
- Sorting for particular materials (thermoplastics vs. recycled plastics, high or low cobalt content, type of electrolyte, etc.)
- Assembling method (for example: glue vs. screws)

Note: the dismantling step before the final recycling is also valid for batteries specifically designed for stationary applications (not EV).

7. Metallurgical recycling processes, industrial integration and secondary material-based precursors

7.1. Description

This topic deals with metallurgical recycling of electric vehicle (BEV, PHEV and HEV) batteries and their production scrap, comprising Li-ion (LIB), NiMH and emerging new chemistries. Sorting and dismantling to cell level are covered by other sub-topics. Different mechanical, pyro- and hydrometallurgical unit processes are covered here.

The objective of the sub-topic is develop holistic recycling processes that are capable of recovering the maximum value of the battery raw materials with as low an environmental footprint as possible within the techno-economic constraints. The objective can be divided to the following sub-topics:

- Improved recovery of the base metals (Ni, Co, Cu, Fe) already recovered today.
- Recovery of additional elements that are not yet recovered (Li, graphite, REE, Mn, Al, Si, P)
- Recovery or safe disposal of the non-metallic components (F, solvents, polymers and plastics)
- Production of high purity chemicals and compounds to be reused for the production of new batteries
- Environmental and workplace safety. Generic safety aspects related to batteries will be covered by another sub-topic.
- Low greenhouse gas emissions, consumption of chemicals and waste discharge. LCA measures of battery recycling processes.
- Flexibility to handle variable input streams
- Industrial integration to existing primary and secondary processing of battery metals
- Vertical integration to battery chemicals production
- Feedback to battery manufacturers to design battery cells that would be easier to recycle

Short-term (0-5 years) challenges comprise handling of low volumes with variable feed streams and integration into the existing infrastructure. Medium (5-10 years) challenges comprise holistic handling and metal and materials recovery of the large volumes of battery waste, with more homogeneous chemistry.

7.2. State of the Art

The state-of-the-art in EV battery recycling has been recently reviewed in several reports[50,51,52]. Currently, most LIB that are recycled today are high cobalt containing (LCO) batteries from consumer

[50] Harper *et al.*, Review: Recycling lithium-ion batteries from electric vehicles, Nature 575 (2019) 75-86, https://doi.org/10.1038/s41586-019-1682-5 .
[51] Hans Eric Melin, State-of-the-art in reuse and recycling of lithium-ion batteries – A research review, Circular Energy Storage 2019, https://www.energimyndigheten.se/globalassets/forskning--innovation/overgripande/state-of-the-art-in-reuse-and-recycling-of-lithium-ion-batteries-2019.pdf

[52] Hill *et al.*, Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles, Ricardo Energy and Environment 2019, JRC117790,

electronics. NiMH batteries from HEVs are also recycled. Ni, Co and Cu are mainly recovered through state-of-the-art pyrometallurgical processes. The high value of Co drives the economics of the recycling. However, the EV batteries based on NMC and NCA chemistries are more complex, and their Co content is much lower. Moreover, the economic value of metals in LFP and LMO based batteries is even lower and may challenge the economics of recycling.

There are about 10 companies in Europe recycling LIB and NiMH[2,3]. None of them is vertically integrated into the production of battery active materials and therefore the value of the recycled materials is lower than in China or Korea where the leading companies are vertically integrated.

In the state-of-the-art pyrometallurgical process, the batteries are directly fed to a high-temperature furnace where Ni, Co, Cu and Fe form an alloy and Li, Mn and Al are lost into the slag. The alloy metals can be separated by hydrometallurgical processes. The recovery of the slag elements is technically feasible but not economic today. Graphite, solvents and plastics are burned in the process and toxic and corrosive (HF) gases have to be carefully treated. Mechanical and hydrometallurgical recycling processes are at pilot or low volume industrial scale.

Pure economics and meeting the minimum regulatory requirements have been the key driver for the recycling processes. However, the strategic value of other batteries elements beside cobalt and nickel and the environmental hazards caused by improper management of EoL LIBs should be taken into account as well.

Maximizing the amount and value of the recovered materials and compounds have played a minor role. The environmental impacts of the different recycling options have not been systematically addressed or compared. Moreover, the SHE (safety, health and environment) practices for the treatment of the flammable and toxic substances (fluorides, organic solvents, metal dust) need to be clarified and improved.

7.3. What is needed in EU to be competitive

As more and more EVs reach end-of-life (EoL), the recycling needs for LIB (and NiMH) will increase drastically. There is a clear need to develop holistic material and energy efficient recycling processes that can recover more battery materials with reduced levels of CO_2 emissions. The objective should be to improve the recovery of Co, Ni and Cu as well as efficient recovery of Li, graphite, Mn, Al, F, and P maximising the value of the recovered materials. Closed-loop recycling and vertical integration back to battery materials production should be attempted, although some less valuable fractions could be downcycled to other uses. A further long-term objective is to keep the materials at highest possible value at all process steps, which could lead to direct recycling and upgrading of the active materials, e.g. as alloys or mixed oxides.

Metallurgical tools (thermodynamic and process modelling, environmental impact evaluation) should be further developed in order to support fast scale up and piloting of the selected processes. Modelling of the metallurgical processes supported by test work in relevant scales would be needed.

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https://publications.jrc.ec.europa.eu/repository/bitstream/JRC117790/jrc117790_jrc_circular_econ_for_ev_batteries_ricardo2019_final_report_pubsy_online.pdf

More environmentally friendly processes should be developed. This comprises minimizing the energy, water and chemical consumption, use of renewable energy and green chemicals as well as recycling of the chemicals. Zero-waste recycling should be targeted in the long term. Life cycle analysis of specifically the recycling processes should be developed along with the metallurgical process development.

The health and safety related issues must be carefully addressed at all processing steps. Discharge and dismantling of the battery packs and modules is covered by another subtopics. Handling of organic solvents, metal dust and fluorides during mechanical, pyro- and hydrometallurgical processing are the key issues here. Moreover, unexpected reactions caused by impurities must be taken care of.

Pros and cons of centralized and decentralized processing options and combinations of these should be studied. The most feasible solutions may differ depending on geography and local infrastructure available.

In the short-term (0-5 years), holistic and flexible processes based on known mechanical, pyro- and hydrometallurgical unit operations and use of existing metallurgical infrastructure should be developed. Especially, intermediate fractions from the recycling processes with sufficient purity could be integrated into the primary processing of the battery metals. Production scrap and out-of-specification EV batteries will create an early material stream for recycling.

In the medium term (5-10), dedicated recycling processes can be developed for different cell chemistries and formats. However, they should still be adjustable to continuous changes in the cell chemistry. Direct recycling of active materials (as alloys or oxides) and other components should be attempted where the input streams are homogeneous enough, e.g. production scrap. Conversion of batch processes to continuous operation will also be needed for efficient treatment of the large volumes expected.

7.4. R&I Activities needed to reach the visioned next level

The following topics are proposed to reach the next level:

Short-term (0-5 years)

The short-term focus should be in LIB and NiMH chemistries and cell formats, which are in large- scale production today.

- Creation of feasible **holistic recycling processes** that can effectively exploit the vast amounts of EV battery waste reaching its EoL in the next 10 years, as well as the production scrap. The aim is to build recycling processes recovering the highest amount (high recovery of single elements/material, but also high total overall materials recovery) of resources present within these secondary raw materials – i.e. associated metals including Li, Mn, Al, P and REEs as well as Co, Cu, Ni, Fe, but also the other material fractions, such as graphite. This approach is developed as an innovative combination of optimized unit processes e.g. mechanical pre-processing, leaching, precipitation, solvent extraction, ion exchange, crystallization, electrowinning, roasting, smelting and pyrolysis. The recycling processes may also partially utilize existing metallurgical infrastructure to support feasible processing.
- Downcycling or safe disposal of the non-metallic elements like the electrolyte, separator and electrode binders.
- Further development of **metallurgical tools and modelling** of the unit operations and process flow sheets facilitating science-based techno-economic comparison of the technology alternatives.
- Developing **safety protocols** for all recycling process units, including fluoride and organic solvent treatments as well as Co-Ni containing metal dust handling.
- Reduction of **environmental impacts** of the recycling processes, comprising of energy efficiency, low CO_2 emissions, reduction of chemical use and use of green chemicals. More detailed and accurate material and process data for LCA databases will be created for more reliable comparison of alternative technology and processing options.

To realize a rapid and comprehensive response to the current challenge (to ensure full industrial operation in less than 10 years), the unit processes utilized should be based primarily on processes already in industrial use with primary/known raw materials (TRL9), while holistic battery waste recycling process concepts are targeted at TRL3-6/7 level.

Medium term (5-10 years)

The focus should still be in chemistries already in production today. However, design-for-recycling should be an integral part of the development of any new battery concept (as indicated, for example, in the Battery 2030+ roadmap[53]). Therefore, the recycling community should prepare also for the emerging technologies.

- In the longer term, development of **centralized, vertically integrated and automated close-loop** processes treating battery waste with direct operation from battery waste to high purity battery materials are foreseen. As an alternative, **de-centralized (local or mobilized)** metallurgical treatment units for flexible battery waste treatment to minimize the transportation, and safety risks in battery waste transportation, may find application in locations with lower EV coverage. Eventually, the optimal solution may comprise a combination of the centralized and de-centralized unit operations.
- **Direct recycling** of battery materials and components should be attempted to decrease the energy and chemicals need for recycling. This includes recycling of the cathode active materials as metal alloys or mixed oxides.
- The long-term objective should be **zero waste recycling** where also the non-metallic elements (electrolyte solvents and salts and polymers) are recycled back to battery use.
- New process concepts should be piloted at relevant scale facilitating further scale-up to full industrial adaption.

8. Circular economy based business models

8.1. Description

According to the EU *Action plan for the circular economy*[54] and subsequent initiatives, circular economy allows to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimizing the generation of waste. This paradigm shift from the linear economy (take, make, dispose) will be accompanied in the future with radical changes in the production, consumption and waste management patterns. Amongst the multi-dimensional issues that drive the transition to a more circular economy (science and technology, product design, policy and regulation, finance, education and training, societal acceptance, environmental responsibility…), Circular Business Models (CBM) play a crucial role to deliver positive economic, environmental and social impacts.

It has been reported that CBM are key contributing strategies to climate mitigation by making a better use of materials and products to reduce GHG emissions such as in the mobility sector[55]. Combined with higher product material efficiency (based on eco-design, low footprint production processes, remanufacturing …), better material recirculation (via second life, recycling and secondary materials valorisation…), CBM allow to achieve same and even improved benefits for users and the society with fewer resources (materials and energy) required, hence a reduced environmental footprint, thanks to a higher utilisation and intensive use and a longer lifetime of products. Besides, it was also recently

[53] Edström et al., Battery 2030+ Roadmap, 2nd Draft, https://battery2030.eu/digitalAssets/820/c_820604-l_1-k_battery-2030_roadmap-v2.1.pdf
[54] A new Circular Economy Action Plan, COM(2020) 98 final.
[55] The Circular Economy – a powerful force for climate mitigation, Material Economics (2018)

highlighted that circular battery value chain will eventually couple the transport and power sectors as new models like shared mobility, vehicle to grid and second life will develop[56]. The Battery 2030+ roadmap also underlines ambitious circular models where battery designs are prepared for maximum longevity, considering re-calibration, refurbishing, and also second-life applications.

In summary, CBM consist in proposing a holistic view of product design, manufacturing, use, and end-of-life management that tries to optimize all economic, environmental and social outcomes. In this roadmap, it will cover the whole battery value chain from raw materials, eco-design, production and remanufacturing, distribution, consumption including use, reuse, repurpose, collection, and recycling.

8.2. State of the Art

The current situation of CBMs in the batteries sector is today mostly relying on recycling activities since industrial capabilities already have been in operations for years in Europe. Furthermore, there is an existing policy framework defined by the Batteries Directive (2006/66/EC) which establishes obligations for Member States to maximize the collection of waste batteries and accumulators, and to ensure that all collected batteries undergo proper treatment and recycling.

The Batteries Directive 2006/66/EC defines targets for collection rates and for recycling efficiencies as shown in Table 1. This Directive considers three types of applications: consumer portable, industrial and automotive. All chemistries can be represented in those three categories, although the automotive ones are typically Pb-acid batteries (starter batteries in cars, included in EVs) where the collection and the recycling rates are much higher than for other batteries. EV batteries (Li-ion or NiMH) are considered as industrial batteries (BEV, PHEV, e-bike, busses, forklifts…). Recovered materials from battery recycling can be used for the battery industry (closed loop necessarily based on upcycling where materials properties are conserved to reach the same expected specifications) but also for other sectors (open loop) depending on the quality of the recycled material (typically downcycling when recovered materials properties are not high enough for closed loop).

Table 1: Collection and recycling targets according to the Batteries Directive 2006/66/EC (source: European Battery Recycling Association)

Consumer/portable	Industrial
Collection rate	
• 45% based on the average of the quantities placed on the market during the last 3 years • Mainly collected through national collection schemes (Bebat, GRS, Screlec, Etc.)	• All end-of life industrial batteries must be collected (and recycled) • Mainly collected by the manufacturers themselves having a direct contract with a recycler
Recycling target (recycling efficiency[57] *excluding energy recovery*)	
The recycling target is called the 'Recycling Efficiency' (RE) and has 3 components: a) a specific target for Pb-acid	

[56] A Vision for a Sustainable Battery Value Chain in 2030, Insight report, WEF & Global Battery Alliance (2019)
[57] Ratio between recycled outputs / input weight of batteries

b) a specific target for Cd-batteries (NiCd)
c) a RE of 50% for all the other types of batteries, including LIB, NiMH, alkaline, etc.

Concerning the current limitations, there is no requirement regarding the type of material to be recycled. Each recycler is free to choose what material is recycled as long as the RE 50% is achieved. Consequently, there is no specific target on the recovery of Critical Raw Materials (CRM). Depending on the battery chemistry, the main CRM embedded in waste batteries are antimony (mainly use for lead-acid batteries which use has declined due to new battery technologies), cobalt (specific Li-ion chemistries such as NMC) and natural graphite used for anode and some rare earth elements used for NiMH batteries[58]. As Europe is increasingly facing challenges to secure its access to a stable supply of raw materials for a large number of key sectors such as energy or mobility, recycling CRM is one of the key levers to lower their criticality in the future. To achieve this, design-for-recycling will play a decisive role to make such operations cost-efficient. Besides, other CBM strategies like batteries second life also have the potential to contribute to this challenge.

8.3. What is needed in EU to be competitive

There are clearly different business model needs for consumer portable electronics and industrial batteries for EV. Efficient collection systems, separation from WEEE and improved labeling facilitating automated sorting is needed for the portable batteries. However, the circular economy of EV batteries is much more complicated and cannot be restricted to recycling activities only, although they are very important to close the loop. Lots of R&I efforts are also needed to improve circularities on the upper side of the loop in order to be in accordance with the basic circular principles of the waste hierarchy[59,60]: *« Like accepted waste management hierarchies, where value-retention processes [i.e. direct reuse, reuse, repair, refurbishment, remanufacturing] ensure that material value and functionality are retained within the product, once functionality has degraded, it is the recycling system that ensures that material value is retained within the broader system. »*.

The whole battery value chain from raw materials to EV including 2nd use should be uniformly covered in the regulative policies. Particular emphasis should be put on the accountability and transparency of the use of natural resources, traceability of battery products (identification of chemistries, technological

[58] European Commission, Report on Critical Raw Materials in the Circular Economy (2018)
[59] According to the European Commission's Waste Framework Directive (Directive 2008/98/EC, Article 4), the waste hierarchy is applied as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal.
[60] "*A complementary perspective is that all products will eventually reach a point at which they no longer qualify for arranging direct reuse, repair, refurbishment or remanufacturing – either because of the associated cost, or because their implicit quality and utility potential has been degraded. At that point, there is still an essential need for efficient and effective recycling systems to recover the value of the materials contained within the product, and to recirculate those materials back into circular materials economy*."
Redefining value- The manufacturing revolution, UN Environment International Resource Panel report (2018).

features) and data sharing between different actors in the different use phases. Nowadays, second life of batteries is not included in the Battery Directive 2006/66/EC. Therefore, new regulations are needed to clarify the business environment, e.g. the Extended Producer Responsibility (EPR) in different use phases. Moreover, unified criteria and standard methods should be developed to address the battery State-of-Health (SoH) and End-of-Life (EoL). New types of cooperation between the actors are needed to create value added ecosystems and the use of new digital boundary resources (such as application programming interfaces, tags and smart contracts that take advantage of these) and platforms among actors in the industry value chains could be promoted to support this. Finally, criteria for the exports of second hand EVs and 2nd use products to non-EU countries should be set in order to avoid illegal exports and improper handling of the EoL batteries in countries with substandard Environment, Health and Safety (EHS) legislation. The new regulative environment should encourage business models that improve resource efficiency, lower environmental footprint, and sustainable use of raw materials. The policies should create incentives for actions that follow a common standard for sustainable mining in the EU.

There is a clear need for harmonized regulation of definitions, ownership and responsibilities of different actors, especially related to the possible 2nd life applications and valorization of secondary raw materials in order to develop new business models. For example, end of first and second life should be defined and whether the batteries fall under waste regulation at a certain point of the life cycle should be clarified. Moreover, the reporting of collection and recycling rates should be harmonized. More accurate methods should be developed for the state-of-health and safety assessment to provide solid ground for battery rating for the 2nd use and guarantee safe handling during collection and storage. More reliable forecasts should be made in order to address the future availability of EoL batteries and their materials from 1st and 2nd use phases. This would help timely investments in the remanufacturing and recycling operations. It was further proposed that less valuable materials which could become scarce and valuable in the future should be stored. Scenarios analyses should be used to identify such materials and economic incentives developed to promote the storage.

8.4. R&I and CSA Activities needed to reach the visioned next level

The following R&I activities[61] have been classified according to four grand objectives that are following the circular batteries value chain. For each objective, several R&I topics are listed with a level of prioritization in terms of urgency to start, i.e. at [SHORT 0-5 years / MEDIUM / 5-10 years] term:

- ***<u>Objective 1</u>: Securing a sustainable (environmentally, economically and socially) supply of minerals, base metals (Cu, Ni, V..), and in particular Critical Raw Materials (Co, graphite) but also other materials (Li, Mn, electrolytes, fluorinated compounds or polymers…)***
    - ***Efficient primary mining*** *[SHORT]: resource/water/energy efficient mining, mineral processing and metallurgy, including for more complex and lower grades ores and minerals, enabling a safe, low environmental and sanitary impact and economically viable exploitation of primary raw materials in Europe*

[61] This roadmap is based on the Strategic Research & Innovation Agenda for a circular economy of raw materials developed in the H2020 CSA project CICERONE : http://cicerone-h2020.eu/

- *Resource assessment* [SHORT]: *holistic knowledge of global resources, social and environmental conditions of extraction, toxicity, geostrategic and economic factors regarding each of the critical, toxic and technological materials*
- *Mapping of secondary sources* [SHORT]: *scalable solutions for exploring, inventorying and sharing the information about material streams and potential sources for extracting secondary raw materials over European territories, including urban and landfill mining as well as industrial residues*
- *Valorization of secondary feedstock* [MEDIUM]: *design and production processes supporting an increased supply of materials from the optimal mix of primary and secondary sources, to address batteries (closed loop) or other applications*

* *Objective 2: Designing low lifecycle footprint material solutions (from raw materials supply to product-service applications, and including manufacturing processes)*
    - *Eco-design* [SHORT]: *strategies for designing batteries with a minimum lifecycle footprint, relying on the optimal combination of resource efficiency, use of secondary or substitute materials, design-for-usage, traceability and design-for-recycling, etc.*
    - *Eco-processes* [SHORT]: *industrial manufacturing solutions enabling minimum resource consumption in the production process, such as water-based production processes and quality standards supporting versatile sourcing*
    - *Standards & eco-labels* [SHORT]: *normalization and certification based on scientific evidence and thresholds, promoting a massive shift from linear to circular material consumption*
    - *Digital platforms* [MEDIUM]: *development of easy-to-access database to aggregate, disseminate and share knowledge on resources, experience, best practice (e.g. policies, instruments, tools, services, case studies etc.)*

* *Objective 3: Enabling maximum value usage of products in the economy*
    - *RE-strategies* [MEDIUM]: *systemic organizational solutions maximizing the material usage value, including batteries reuse[62], repair[63], refurbishment[64] and remanufacturing[65]*

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[62] *The using again of a product, objective or substance that is not waste for the same purpose for which it was conceived, possibly after repair or refurbishment.*
[63] *Fixing of a specified fault in an object that is a waste or a product and/ or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose.*
[64] *Refers to the modification of an object that is a waste or a product that takes place within maintenance or intermediate maintenance operations to increase or restore performance and/ or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended. The restoration of functionality, but not value, enables a partial new service life for the product.*
[65] *Refers to a standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products. Firms that provide remanufacturing services to restore used goods to original working condition are considered producers of remanufactured goods.*
Sources :

- *Ageing management* [MEDIUM]: understanding best product maintenance and operation strategies, based on material health monitoring, characterization of material degradation and ageing modelling to enhance service delivered per time period
- ***Monitor KPI such as services/efforts*** [MEDIUM]***:*** *assessment of outcome use of active battery materials in term of kWh outputs compared with efforts to make the active materials available from extraction to end-of-life (number cycles, kWh stored/delivered…)*

- ***Objective 4**: Implementing a responsible end-of-life of batteries, from waste collection and sorting to recycling and valorization*
  - ***Collection*** *[MEDIUM]: waste circuits ensuring an efficient aggregation of valuable material flows, especially with regards to energy technologies, transport and WEEE*
  - ***Dismantling and sorting*** *[MEDIUM]: safe and efficient processes for depolluting and disassembling complex products, aiming at concentrating material rates and enable highly selective recycling*
  - ***Material separation*** *[SHORT]: cost-efficient, robust and low-environmental impact extractive processes, delivering secondary feedstocks, including for multi-material recovery*

9. Second life

9.1. Description

What is Second Life. Second Life s interpreted as any operation by which products or components that are not waste are used for a different purpose (re-purpose) for which they were conceived and placed on the market for the 1st time.

Circular Economy. A key objective of the Circular Economy is to keep the added value in products for as long as possible in order to reduce or eliminate waste. A further objective is also to keep resources within the economy when a product has reached the end of its service life, so that they can be productively used again and again and hence create further value. The priorities of Europa evolve into the direction of (descending order):

- extension of the product's service life
- avoid waste generation
- re-use and second life
- recycling

The widespread deployment of emerging technologies is causing an unprecedented increase (i.e. from 10-fold to 100- fold) in the use of corresponding critical materials which are under high supply risks. Consequently, there is a great urgency to implement the circular economy in mitigating the criticality of

Redefining value-The manufacturing revolution, UN Environement International Resource Panel (2018)
Basel Convention - Glossary of Terms, United Nations Environment Programme (2017)

those scarce materials. Novel Critical Material Circular Economy Framework has to respond to such urgent needs:

- Firstly, the linkage of critical material is explored through a hierarchical analysis on the in-use stage along its life cycle, which helps to distinguish the option sets of End of Life oriented and Manufacturing-oriented strategies in achieving Circular Economy goals.
- Secondly, a quantitative dynamic analysis of the stocks and flows of critical materials along its life cycle is needed. In some case study, the criticality of Cobalt and Lithium embodied in a battery were assessed revealed the substantial growth of those materials to support such transition and the inadequacy of EoL-oriented strategies in material criticality mitigation. By contrast, the Manufacturing- oriented strategies are much preferred and effective due to its various benefits in reducing the demand of virgin material and waste disposal.

The efficiency of EoL-oriented strategies relies heavily on available recoverable waste (which is not the case for critical materials with emerging unprecedented material demand). Most critical materials are used in emerging technologies with limited in-use stock. Thus, the end-of-life resource becomes so limited that the capacity of such recoverable resource in substituting virgin material is not evident in the next few decades. Thus, to reduce the material demand for the same application is essential for material criticality mitigation. Material recycling and EoL-oriented options can reduce waste disposal. However, the impact on the demand reduction is quite limited due to the small volume of available recovered resource. In contrast, the implementation of Manufacturing-oriented strategies, as waste prevention option, offers a two-fold benefit:

- It reduces the critical material demand through efficient material use, product lifetime extension, and product reuse and remanufacturing;
- It helps also to reduce the waste disposal by reduced waste generation through less material input and longer material use; and supports better material circulation.

Thus, when a comparison is done with recycling conducted by consumers and waste managers, material circularity can be better be improved through product reuse and parts remanufacturing managed by manufacturers. The manufacturing can play a great role in reducing material criticality and circularity, especially in emerging applications.

Industry practice. Car OEM's support the principles of the circular economy and sustainable material management. This is certainly the case with industrial batteries for electro-mobility as these batteries are very high-tech components, rather expensive, containing valued materials, having a very long lifetime even after use in an electric vehicle. OEM's extend the product life of their industrial batteries, try to use these batteries as a valuable product as long as possible, in order to avoid that these batteries become waste and are being disposed of too soon in the life cycle (close loop approach).

Before taking the decision to send the battery to recycling, the battery of an electric car is subject to a diagnose. The main purpose of the diagnose is to prevent that such battery or components of such battery would be categorized as waste when that battery or components of that battery can still have a prolonged service life. This diagnose is a waste-prevention measure.

The dealer or workshop does a first diagnose. They need to have clear instructions and training from the OEM to judge whether the battery is suited for repair, re-use or second life. These instructions include the conditions when the batteries have to be shipped as waste.

Most batteries from e-mobility in the future will return not because they need to be repaired, or they are damaged or defective, but just because they are underperforming to function in an electric car. Instead of sending these batteries into 'retirement' they might still be used in a less demanding application (second life).

Legal clarification needed. There is a need of clarification of the definition of "second life", because a number of operations are possible, particularly:

- Repair, or remanufacture, or re-assemble different batteries with original new or used components, is producing "second -hand" batteries (échanges standard – exchange units - Austausch), but they are not "second life" batteries. From a legal perspective in the EU, a battery original manufacturer cannot oppose that a third party re-assembles a battery with original components (he may only refuse to maintain the warranty in this case).

- Rebuilding a battery for another purpose (**second life or re-purposing**) with changes in the design, in the components structure or in the battery management system, is producing a new battery, and requires re-qualification for transport. In this case, the new producer's legal liability (living up to the requirements of the Batteries Directive, the Regulation on Recycling Efficiency, and Extended Producer Responsibilities – EPR, transfer of ownership) is fully applicable, including the UN transport qualification, as this new producer is placing a new battery on the market in the EU for the first time.

Issues of Second Life. However, rebuilding a used battery into a second-life purpose is not a straightforward process; typically requiring considerable material and labor resources before being deployed. For instance, recovered cells should be grouped together according to their state-of-health (SoH), state-of-charge (SoC) and capacity, since assembling cells with various capacities increases the risk of over-voltage and over-current with the battery.

Second-life applications also require new electronic components which require manufacture and installation into the second-life system. An example would be electronic power converters needed to use e-mobility Li-ion batteries for a second-life in stationary energy storage applications.

Another issue is with reliability, where used batteries should have a remaining lifetime of at least four years for them to be candidates for second life, a characteristic which is not always guaranteed.

Entering a new application also puts new demands on safety, ensuring safe operations with a new cycling profile. It can also be highlighted that entering a battery into second life and subsequent lives can reduce the likelihood and ability to successfully recover the battery for eventual recycling.

Any regulatory approach to stimulate secondary use of batteries should recognize the complexity in ensuring environmental benefits, efficient resource and material use, recycling and collection after the second life and maintaining safe and reliable operations.

The pace of improvement in battery chemistry is such that between the time of a battery being manufactured and its reaching end-of-life after intended application some years later, battery chemistries will almost certainly have been refined and optimized. As a consequence, a new battery built for the same application is likely to require less resources than the first. Today's Li-ion battery chemistries, for example, contain 3 to 4 times less cobalt than those of even just several years ago (e.g. shifting from NMC 111 to NMC 811).

This evolution could potentially mean that the materials contained within an end-of-life battery have more value if they can be recycled and recovered, than if they are used again in a second-life application. This has to be evaluated environmentally and economically.

It could further be highlighted that when entering a battery into a second life, could reduce the likelihood and ability to recover the battery for potential recycling.

From a reverse logistics perspective, second life brings also possible challenges. This could potentially lead to decrease battery collection rates and result in leakage of batteries from the EU.

9.2. State of the Art

Takeback. So far not many Lithium-ion industrial batteries from e-vehicles are coming back (the first batteries that came back are mostly NiMH batteries from HEV), but that might quickly change due to the massive uptake of hybrid, plug-in hybrid, and electric vehicles. Recycling capacity might become an issue, and the extraction of some materials (Li – Cu – Co ..) might become crucial and strategic.

Existing agreements. Car OEM's have signed agreements in EU Member States with EPR-organisms and with recyclers to fulfil their obligations under the Batteries Directive, ELV Directive, and other battery regulatory requirements. As car OEM's or their importers are responsible from the moment the battery is placed on the market (they are considered the producer of the battery) until the battery is recycled, it is for them quite important to be able to trace the battery throughout its lifetime.

Traceability might become an issue in the future (when huge volumes will start to come back).

Existing expertise. In many countries, we find already companies specialized in the complete dismantling of batteries, the diagnose of suitable components, and the remanufacturing or re-purposing for same or other applications. In many cases, this is done with support, knowledge of the car OEM or importer. The way these activities are being conducted (only dismantling, or dismantling and remanufacturing, storage, selling) is different from company to company. This depends on the business model followed and the economics of it. Safety requirements are playing an important role here.

The diagnose of batteries. Car OEM's and importers with their dealer networks have the required diagnostic tools and the experts to conduct the diagnose for repair. Whether they will decide, based on the conducted diagnose, if the battery or components of the battery are still suitable to be used for another purpose or whether the battery or components of the battery are no longer suited for re-use and need to be recycled (and thus become waste) is not sure. The proper diagnose to determine whether a battery or components of a battery is still a product (article) or whether this has become a waste is an important step in the value chain as it has implications for storage, transport, labelling, permits). This is an area that needs investigating.

9.3. What is needed in EU to be competitive

- The **market** for re-use, remanufacturing, re-purposing, is an existing market. What will happen is that a new product line will be added: industrial batteries from e-vehicles (mobile application) that will be transformed into a storage battery (stationary application). It is market-driven.

- **Safety** of these operations needs to be guaranteed.
- **Traceability & monitoring** of these batteries needs to be guaranteed.
- Proper **diagnosis** of these batteries needs to be guaranteed.
- **Legislative requirements** & obligations need to follow this trend (adaptation of the Batteries Directive is a must: clear definitions to avoid interpretations at national or even regional level making it for industry very complicated).
- The stacks and modules should be easy to dis-assemble and the BMS should enable 2nd use.
- The 1st use **BMS data** should be made available for the qualified remanufacturers in order to ease the SoH estimation and address possible safety issues.
- There should be a **qualification process** for the dismantlers/remanufacturers in order to guarantee the safety of the operation and the new products.
- **Reverse logistics** should be developed in order to get End-of-Life 2nd use batteries to recycling, also the batteries exported outside Europe.

9.4. R&I Activities needed to reach the visioned next level

The following R&I and CSA activities are proposed:

Short term (0-5 years)

- Adaptation of the **Batteries Directive** & related regulatory requirements are fundamental for industrial operators to be able to work within the context of the law. This is crucial for second life activities. (CSA)
- Regulations to guarantee the **safety** in all parts of the operations and products. (CSA)
- Need to support operators engaging in the collection, sorting, diagnoses, and re-manufacturing of batteries for **second life** purposes. (R&I + CSA)
- **Market deployment** (from laboratory scale to real life activities) should be supported: small scale operations with monitoring of performances.
- Development of multipurpose **BMS** concepts. (R&I)
- **LCA** of the battery life cycle with and without 2nd use. (R&I)
- Ex-ante LCA methodology to Enhance Technological Development (R&I and CSA)

Medium term (5-10 years)

- Large scale application development (> 100 MWh). (R&I)

10. Safety in recycling

10.1. Description

The e-mobility market is currently in full expansion. This is leading to a transformation of the automobile sector as a whole: from the point of product development up till recycling: the entire value chain is influenced[66].

[66] Ensuring safety for all stakeholders throughout the life cycle of electric cars; Tomboy W. and Lenaerts C.; IARC 2020, Geneva – March 12 2020.

When looking closer to safety related aspect, it is obvious that these new technologies trigger new risks, of which basic knowledge, control measures, education and regulation is still being developed. It is the intention of this sub-workgroup to surface commonalities and highest risks in the field of safety with regard to the full recycling value chain. Starting with these common topics we will identify routes to gather more in-depth knowledge to support to full value chain in tackling them. This means that it is intended to understand the underlying mechanisms, triggers and ways to avoid these "unsafe" situations.
This knowledge can indeed further be used in the shaping of the value chain, education of stakeholders and putting in place the supporting regulation.

The approach that is proposed in this sub-workgroup is three-fold:

1. Identification of hazards and assess related risks: knowledge building

   Identify known hazards and risks in the recycling value chain and cluster them based on the underlying fundamental mechanisms leading to these. By gaining more in depth understanding of these mechanisms, it is intended to identify their share in currently noted "unsafe situations" and potential risk in the recycling value chain. Different parts of the value chain are visually represented in Figure 2. From a first questioning of potential key safety mechanisms, following were raised to be detrimental:

   - Thermal runaway
   - Electrocution
   - Metal dust (Co, Ni)

   And to a lesser extent, but also important:

   - Fluorides, solvents
   - Gas formation (mainly pyro/hydro related)

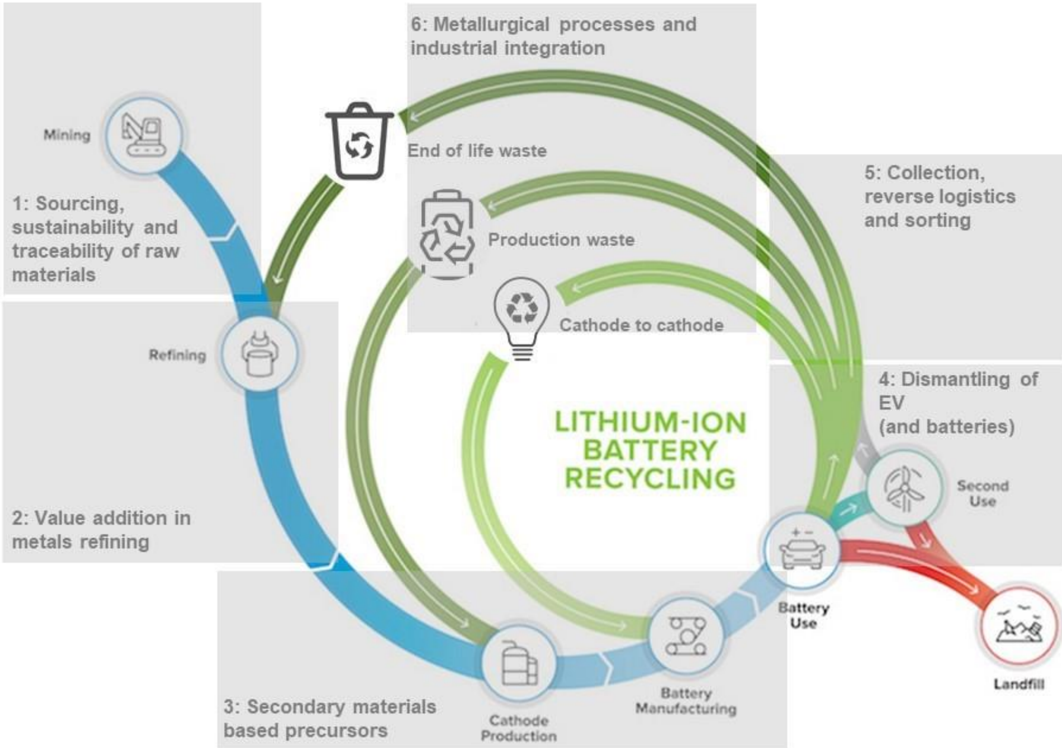

Figure 2: Visual presentation of different parts of the recycling value chain – critical for safety [Imagge by Argonne National Laboratory]

When linking separate parts of the value chain with key safety mechanisms following overview can be generated:

Safety mechanism	1	2	3	4	5	6
Thermal runaway				■	■	■
Electrocution				■	■	■
Metal dust	■	■	■			■
Fluorides, solvents				■	■	■
Gas formation						■

It is intended to gain more in depth, scientific, insights in these underlying mechanisms through the set-up of research programs. Paragraph 2 (State of the art), clearly stipulates that most attention is currently dedicated to thermal runaway (most often during use phase) and how battery design should evolve. It is of importance to steadily broaden the scope of research with regard to safety, e.g.: thermal runaway at different parts of the value chain, other safety risks (electrocution, metal dust).This knowledge can indeed further be used in the shaping of the value chain, education of stakeholders and putting in place the supporting regulation. To further cultivate this knowledge evolution towards a learning eco-system will be needed. The latter will be discussed in more detail in Point 3 (Shaping a learning eco-system).

2. Risk control measures: hierarchy of control

Identify which control measures can be taken to off-set certain mechanisms that lead to safety risks and even incidents at this point in time. Indeed, hazards are present in each industrial environment. To create a safe work environment, it is important to adequately control the risks that these hazards represent. Therefore, control measures need to be identified from a full system perspective, taking into account the hierarchy of risk control, Figure 3. Not all measures are equal, not on safety level they can attain, nor ease of implementation or enforcement. To control risks you need to do everything that is "reasonable practicable", thus by balancing out "time, scope and budget" . Moreover, commonly it is seen that the most effective safety measures for one part of the value chain have to be controlled in other parts of the value chain or that risks from previous (more unsafe) designs have a memory effect throughout the different parts of the value chain.

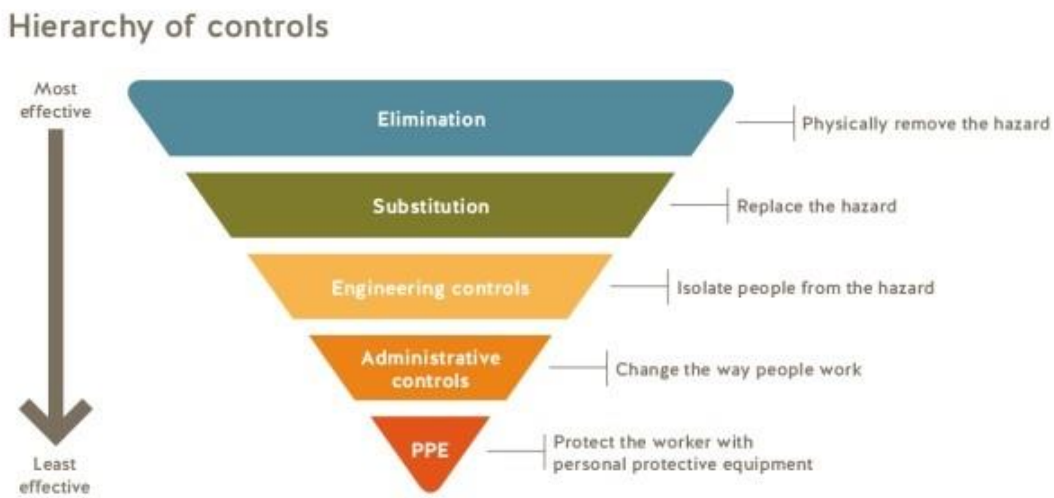

Figure 3: Hierarchy of risk control

Example of choice of packaging

Aside from the effectiveness, adequate control measures are also heavily influenced by the market in which these products are present. To make this tangible, distinction will be made between the use of LiB in:

- Small and medium size consumer products
- Electric vehicles

Indeed, the size of the LiB, and thus the amount of energy that can be stored in it will differ largely in these different market segments. Therefore, that the hazard itself (electrocution, thermal runaway) will be higher, whereas the effective risk is lowered by professionalization of the EV value chain. This means that whereas the inherent safety mechanisms are independent of the application/market, the actual control measures that have to be taken are not.

3. Shaping a learning eco-system: feedback and continuous learning

As stated in the previous paragraphs: the different parts of the recycling value chain are heavily coupled from a safety perspective. This coupling implies the need to impose control measures and feedback loops to ensure the effective implementation of identified control measures, but also to enable a vast learning and knowledge build-up. The latter can be enabled by setting up a "learning eco-system". Basically, this entails the collection of stakeholders, processes and tools that deliver, integrate and support the learning and development across the value chain. The interconnection of this collection is represented in Figure 4[67].

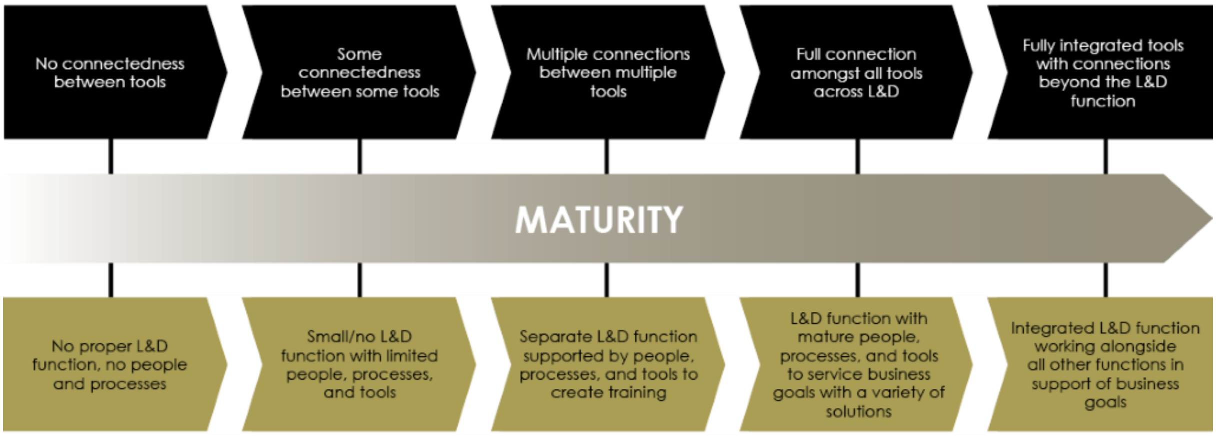

Figure 4: Maturity model that shows the technology and connectedness of the ecosystem (top) and the L&D function's people and process maturity [63]

The setting up of such an ecosystems, implies the need of learning and development (discussed in the task force education and skills) as well as regulatory measures that facilitate and support these interactions. Similarly, to the discussion that was raised in point 3, also in the set-up of this eco-system, distinction needs to be made between application in which the LiB is adopted. Mainly a distinction between two application types is made: small and medium sized consumer products and electric vehicle products.
As an example, we will detail some major focus points for both applications:

i. For the EV market an important focus point is safety at the end of life stage: how to enable the transfer of information on product design and safety towards emergency workers on scene. The availability of intel on how to remove a battery fast and safely and prevent thermal runaway of the LiB from a crashed vehicle can definitely safe lives and should be readily available at all times.
ii. For the small and medium sized consumer product market, major focus point is the dispersion (and piling) of these products in non-dedicated/educated collection points. E-bikes return to bike shops, laptops at e-commerce shops or waste collectors. A broad education of all

[67] Learning Ecosystems: What are they, and What can they do for you? Rose Benedicks, link – June 25, 2018.

stakeholders and/or increased centralization can substantially decrease the potential risks at multiple points in this value chain.

It is clear that the challenges of each part of the value chain are similar, whereas the possible measures and actions to create a learning eco-system can largely differ.

10.2. State of Art

Overview of fire-related statistics of 2018-2019 summary from Waste360[68]:
Several overview papers are putting more and more attention to the risks of fires and explosion, linked to the use of LiBs in several applications. In the overview of fire-related statistics of 2018-2019 [3], some interesting figures, from different parts of the world are detailed:

- In the US and Canada in 2019 the waste and recycling industry has experienced 338 reported facility fires in the U.S. and Canada. Additionally, we incurred 48 reported injuries and four deaths that can be directly or indirectly attributed to these fire incidents. Based on reasonable assumptions, we can extrapolate that 1,800-plus facility fires have occurred during that time
- Veolia UK recently issued a press release that stated that fires in waste vehicles have increased by 37.5 percent since 2017. To put that into perspective, Veolia has 113 lithium-ion battery drop-off sites and a very extensive waste and recycling footprint in the UK and Ireland. The press release goes on to say that the average UK resident throws away around 24.5 kilograms of electronics annually.
- According to an article in the Japan News section of The Asahi Shimbun last month, the Japan Containers and Packaging Recycling Association released data from its survey reporting that in fiscal year 2019, recycling facilities for plastic containers reported 230 incidents of smoke or fires by the end of December. This is up from 128 incidents in 2018 and less than half that number from 2013 to 2017.

So it can be stated that there is an apparent increasing trend in fire and explosion related accidents, along with the increased application of LiB in multiple products. Nevertheless, this doesn't entail that the product itself is inherently unsafe, but that both product safety as well as incorporation of safety throughout the entire value chain should be enhanced in the upcoming years.

Overview of safety related scientific papers – topical clusters:

The above mentioned statistics are focusing on fire related accidents due to storage, transport and handling of Li-ion batteries in recent years. Aside from these figures, mainly related to thermal runaway, a brief mapping on safety related scientific papers was conducted. Idea was to surface current focus of scientific community with regards to battery safety. From this first search, it could also be surfaced which regions are most active in this research field: the majority, roughly 60% of the papers came from Asia (predominantly China), 30% from US and only 10% from Europe.

[68] Fire report: Lithium-ion Batteries are a growing, global problem – Factiva Select Advanced Materials – February 07, 2020.

Following topics came out of this search:

- Mechanisms of thermal runaway
  Currently, most papers linked to battery safety are focused on thermal runaway. Most commonly focus the use phase due to short circuit or (accidental) overcharge[69,70,71,72,73,74,75]. It is indeed obvious that as the energy stored in battery per unit of weight is increasing, that battery safety is becoming more critical[76]. Over the years, focus appears to be shifting from understand the risk and magnitude of a thermal runaway[71,77], towards proposing preventive measures in the design of batteries[65,72,78].
  Nevertheless, when looking at transport, storage, 2nd life use and recycling of these batteries, it is known that the external triggers are more severe and more diversified. Questioning remains whether the proposed design changes are sufficient in guaranteeing safety in these parts of the value chain, whether other measures are required and if so: which.

- Cell/pack design to mitigate thermal runaway
  Re-design of batteries, taking into account safety considerations is aside from the mechanisms of thermal runaway, a common topic in battery safety. It is indeed that in this stage the most effective measures can be taken: elimination, substitution and engineering controls. Over the years focus also

[69] Modeling li-ion battery temperature and expansion force during the early stages of thermal runaway triggered; By: Caiz, Ting; Stefanopoulou, Anna G.; Siegel, Jason B.; Source: Journal of the Electrochemical Society, Volume: 166, Issue: 12, Pages: A2431-A2443, Journal; Online Computer File, 2019 CODEN: JESOAN, ISSN: 0013-4651, DOI: 10.1149/2.1561910jes.
[70] New exploration of the fire behaviors of large format lithium ion battery; By: Peng, Yang; Zhou, Xiaodong; Hu, Yue; Ju, Xiaoyu; Liao, Baisheng; Yang, Lizhong; Source: Journal of Thermal Analysis and Calorimetry, Pages: Ahead of Print, Journal, 2019, ISSN: 1388-6150, DOI:10.1007/s10973-019-08459-3.
[71] Safety issues caused by internal short circuits in lithium-ion batteries; By: Liu, Binghe; Jia, Yikai; Li, Juan; Yin, Sha; Yuan, Chunhao; Hu, Zihan; Wang, Lubing; Li, Yangxing; Xu, Jun ; Source: Journal of Materials Chemistry A: Materials for Energy and Sustainability, Volume: 6, Issue: 43, Pages: 21475-2148.
[72] Perspectives on mitigating safety incidents in Li-ion cells ; By: Sriramulu, Suresh; Singh, Surendra K.; Stringfellow, Richard; Ofer, David; Oh, Bookeun; Barnett, Brian ; Source: Proceedings of the Power Sources Conference, Volume: 43rd, Pages: 513-516.
[73] Safety considerations for materials design and testing of lithium-ion batteries ; By: Barnett, B.; Singh, S. K.; Stringfellow, R.; Sriramulu, S.; Thomas-Alyea, K. ; Source: Proceedings of the Power Sources Conference, Volume: 42nd, Pages: 45-48.
[74] High energy battery safety: anecdotes, issues and approaches ; By: Banner, Julie A.; Winchester, Clinton S.; Source: Journal of Power Sources, Volume: 65, Issue: 1-2, Pages: 271-274.
[75] Fire Tests on E-vehicle Battery Cells and Packs ; By : Sturk David; Hoffmann Lars; Ahlberg Tidblad Annika ; Source: Traffic injury prevention, Volume: 16 Suppl 1, Pages: S159-64.
[76] Materials for lithium-ion battery safety ; By: Liu, Kai; Liu, Yayuan; Lin, Dingchang; Pei, Allen; Cui, Yi ; Source: Science Advances, Volume: 4, Issue: 6, Pages: eaas9820/1-eaas9820/11.
[77] Internal shorts and safety of Li-ion batteries ; By: Takata, Rosalind; McCoy, Christopher; Ofer, David; Stringfellow, Richard; Barnett, Brian; Sriramulu, Suresh ; Source: Proceedings of the Power Sources Conference, Volume: 44th, Pages: 12-13.
[78] Failure analysis of short-circuited lithium-Ien battery with nickel-manganese-cobalt/graphite electrode ; By: Lee, Seung-Mi; Kim, Jea-Yeon; Byeon, Jai-Won ; Source: Journal of Nanoscience and Nanotechnology, Volume: 18, Issue: 9, Pages: 6427-6430.

in this topic focus appears to be shifting: from cell and pack control for use phase (engineering control), towards cathode and electrolyte choice (elimination and substitution) and protective measures during other parts of the value chain, like 2nd use[79,80,81,82,83,84,85]. Most references are patents, originating from China[75-80]. Meaning that focus on the safety related matter is predominantly coming from a business/industrial perspective and Asia is far more active in this field. It is indeed important that incorporate these considerations (from the entire value chain) in the design phase and that we all are aware of the measures that are taken. But we also need to design the value chain itself, so that next steps, like 2nd use and recycling, in such a way that they can handle a wide variety of designs and ensure robustness of these flowsheets.

- Safety in transportation
  Few papers focus on safety in post-use phases, like transportation. Most of these papers[86,87] describe the consequence of certain external conditions on safety and how to measure risks upfront. Only few describe measures that can be taken to lower risks during these actions[88]. Charge is a topic that is raised, and indeed it can be found that discharging and inertisation of end of life batteries

[79] Fire prevention and control device of lithium ion battery energy storage system and implementation method ; By: Dong, Haibin; Zhang, Shaoyu; Li, Yi; Yu, Dongxing; Xian, Xuelei; Yi, Chengyi; Sheng, Yanfeng; Han, Guang ; Assignee: Tianjin Fire Research Institute of MEM, Peop. Rep. China ; Patent Information: Sep 24, 2019, CN 110270032.
[80] A lithium-ion battery safety test data synchronization acquisition method ; By: Li, Dahe; Yang, Kai; Gao, Fei; Liu, Hao; Zhao, Luxing; Wang, Lina; Hu, Chen ; Assignee: China Electric Power Research Institute, Peop. Rep. China; State Grid Corporation of China; State Grid Shanghai Municipal Electric Power Company Patent Information: Nov 18, 2015, CN 105070968, A.
[81] Explosion-proof cap for lithium-ion batteries ; By: Lu, Qianglin; Wu, Shuquan ; Assignee: Wuhu Genyuan Technology Co., Ltd., Peop. Rep. China ; Patent Information: Oct 06, 2010, CN 101853930, A.
[82] Explosion-proof combined cap for high-rate cylinder lithium ion battery
By: Zhou, Weibing SciFinder® Page 36 Copyright © 2020 American Chemical Society (ACS). All Rights Reserved. Assignee: Peop. Rep. China Patent Information: Jul 14, 2010, CN 101777633, A.
[83] Explosion-proof cap for high-rate discharge lithium-ion cylindrical battery By: Fang, Qi; Li, Ailiang; Fang, Zhenhua; Dai, Jinfang; Wu, Hongfeng Assignee: Ningbo Yisida Lithium Cell Co., Ltd., Peop. Rep. China Patent Information: Sep 10, 2008, CN 101262050, A.
[84] A lithium ion battery electrolyte solution for preventing overcharge By: Chen, Juncai; Wang, Feng; Qin, Hu; Yuan, Xiangyun; Qian, Chunfeng; Wu, Qin Assignee: Zhangjiagang Guotai-Huarong New Chemical Materials Co., Ltd., Peop. Rep. China Patent Information: Dec 24, 2014, CN 104241685, A.
[85] Building thermally stable Li-ion batteries using a temperature-responsive cathode By: Ji, Weixiao; Wang, Feng; Liu, Daotan; Qian, Jiangfeng; Cao, Yuliang; Chen, Zhongxue; Yang, Hanxi; Ai, Xinping Source: Journal of Materials Chemistry A: Materials for Energy and Sustainability, Volume: 4, Issue: 29, Pages: 11239-11246.
[86] Guidelines for chemical transportation safety and risk management By: Bennett, Gary F. Source: Journal of Hazardous Materials, Volume: 166, Issue: 2-3, Pages: 1568.
[87] Safety of lithium batteries in transportation By: Farrington, M. D. Source: Journal of Power Sources, Volume: 96, Issue: 1, Pages: 260-265.
[88] Transportation Safety of Lithium Iron Phosphate Batteries - A Feasibility Study of Storing at Very Low States ; of Charge By: Barai, Anup; Uddin, Kotub; Chevalier, Julie; Chouchelamane, Gael H.; McGordon, Andrew; Low, John; Jennings, Paul Source: Scientific Reports, Volume: 7, Issue: 1, Pages: 1-10.

prior to transport, storage and recycling can be a detrimental step in this value chain. Nevertheless, such technologies and their upscaling are still lacking and should become focus of future research

10.3. What is needed in EU to be competitive

- Mapping of key safety mechanisms throughout the entire recycling value chain. Initial mapping is taken up in this document, but this need to be expanded towards all parts of the value chain and all key safety mechanisms.
- In depth, scientific understanding of these key safety mechanisms, including the identification of (external/internal) triggers that contribute to the evolution from a hazard into an actual risk, for the entire value chain.
- Link between how these safety mechanisms are expected to shift (or alter in risk-level) based on product-evolution (energy density, sizing, …) and design of Li-ion battery segments.
  à active link/feedback loop with battery design but also taking into account the memory effect of previous designs throughout the value chain.
- Identification of risk control measures at the critical parts of the recycling value chain – linked to the hierarchy of control (or effectiveness) and balancing of with time-scope-budget. Herefore, a tool could be to adopt a SWOT analysis for all identified risk control measures.
- Discharging and inertisation of end of life batteries prior to transport, storage and recycling. Current techniques aren't always feasible to scaling-up to the sizes this market is growing.
- Create the needed connections towards education and skills: information in one part of the value chain can be of high value to ensure safety in other parts of the value chain. Sharing of knowledge and overall knowledge management will be of high value. How to create think thanks and communities in which knowledge can be easily shared.
  ⍰ not only for universities and knowledge centre, also learning by mistakes within the industry.
- Create the needed connections towards regulation: insights in these key safety mechanisms and identification of risk control measures, need to be translated in regulatory measures to safeguard safety throughout the value chain.
  ⍰ This is the base requirement for the evolution towards a learning eco-system

10.4. R&I Activities needed to reach the visioned next level

This workgroup intends to incorporate the concept **"design for safety"**.

For the short term (period of 0-5 years) focus is put on **"design of the value chain":**
Focus on the critical parts of the value chain (for two major LiB application) and support the correct control measures and set-up of a learning eco-system by starting a more thorough knowledge building on safety related key mechanisms. Indeed, at this point most safety related research and patents are focusing on thermal runaway, during the use phase.

This should be extended towards the entire value chain, also taken into account other risks like for instance Co, Ni bearing dusts. Prioritisation between critical and non-critical parts of the value chain can be supported by statistics readily available from both LiB recycling as well as adjacent industries, like metal recycling or scrap handlers.

For the long term (period of >5 years) focus is put on **"design of batteries":**
These insights in the critical steps in the value chain of LiBs, should enable the identification of more safe design of batteries. Whereas inherently safe products must be a target to be strived for, zero harm during all phases should be obtained in this time horizon. Only by setting these actions and taking these

steps in battery designs, a fast and sustainable growth of this market in all its applications will be possible.

Appendix 1: Activity Fiches

R&I Activity Fiche 1 – Methodologies for ex-ante LCA (qualitative and semi-quantitative assessments)
WG 2 – Raw materials and recycling Participants writing this Fiche: Nieves Gonzalez Ramon
Description of R&I topic The ex-ante application of life cycle assessment on an emerging technology will bring systematic rigour to the ambiguous situation at the start of technological development. Applying the LCA framework to new batteries materials, battery manufacturing and recycling processes will allow introducing a systems approach and a long-term view. The approach supports the rational of the technology's potential and developmental challenges are better defined at an early stage. Ex-ante LCA outcomes have a signaling contribution to a technological development. Though with much conjecture involved, the approach gives a valid mock-up of a plausible future providing useful insights to be built upon. Applying ex ante LCA (exploratory scenario) to an emerging technology is of great value as a developmental design tool and can be further refined in later development stages. Current State of Art of the technology in brief Emerging technologies often only work at lab scale and their corresponding process data are also only available at such scale. The choices of materials, chemicals, resources, and processes are made at design and early technology stages while related life cycle related data are currently widely missing. Extrapolation upon upscaling is urgently required to address this gap, allowing for sustainability considerations at early design and development stages. However, the constraints are the large variability in technologies, scenarios and options to find generalizable pathways for early-stage assessments. Performing LCAs of emerging technologies is challenging since unit process data, characterization factors of new chemicals, etc cannot be fully projected to the final system. Reasoning behind need for R&I on this topic LCA impact assessment models have drastically grown as well as the tools and databases to be applied to those studies. The lack of impacts data when emerging technologies are firstly presented can bring a self-ensuring feeling that at first glance the emerging performs better than the existing technology. Recent developments have evolved to move away from this first decades LCA practice that only analyzed systems ex-post (at full market scale). New methodologies contemplate that the use of scenarios in LCA to project future of emerging technologies and to assess their largescale implementation supports early design improvements and optimization. The LCA framework shall thus be applied at an early stage to any novel process linking it to upstream and downstream flows. The environmental hotspots of the defined scenario can be identified, and the impacts can be compared with those of a current industrial practice. Methods for improved ex-ante sustainability assessment are urgently required to facilitate early-stage evaluations that usually come with limited data availability. Studies on ex-ante LCA could start from mining available data and sustainability assessment results to **derive generalizable rules for**

early-stage assessment and upscaling. The high level of uncertainty inherent to any ex-ante assessment should be carefully managed, as well as the eventual mis-concept conclusions that can derive from the anticipatory analysis results. Ex ante LCA is not a crystal ball to predict the future, but rather it explores a range of possible scenarios that define and steer the technology towards the preferred future state in which it may operate. Potential impact of R&I advancements on this topic A large proportion of the environmental impacts of a technology is determined by decisions at the early development stages. Therefore, effective approaches to grasp the potential environmental performance of a technology early in development are needed by the ex- ante application of LCA using case studies of the impacts of a lab-scale novel process. An ex-ante study is aimed at the scaling up of an emerging technology using likely scenarios (expertise learning views from similar technologies) to a full operational scale with optimal performance. This is also achieved in sequential steps by comparing the emerging technology with the evolving existing technology. Aspects that differentiate ex-ante assesments from common LCA practice are the methodological/tools used and the data needs.
TRL level that R&I action should start and end on TRL 1 to TRL 9
Expected deliverables & suggested timeline Ex-ante LCA methodology for reliable comparisons of existing technologies with emerging recycling techniques understanding and addressing the limitation of replicability, impacts data availability and quantified output results Specific characterization models and scenario building for ex-ante LCA ensuring iterative impact assessment taking into consideration the complexities and uncertainties of the emerging technologies data extrapolations. Proof of concept of main tools (IT tools, software, databases) and scenarios (prospective, anticipatory) ensuring that the emerging technology performs and avoids environmental burdens ahead of its full implementation. Timeline: 2 years
Envisaged Budget and No of projects required on this topic Number of projects 2 Budget: 6 Million Euro

R&I Activity Fiche 2 – Open access LCI of raw materials

WG 2 – Raw materials and recycling
Participants writing this Fiche: Maeva Philippot

Description of R&I topic

This topic targets the emergence of raw materials database that can provide reliable, easily available, detailed and non-aggregated Life Cycle Inventories (LCI) of raw materials (metals, precursors, chemicals) of current and future battery materials. Raw material extraction and processing are numerous for a same material and must be differentiated in such a database. This database will bring consistency, rigor and enforce comparability between Life Cycle Assessment (LCA) studies. The Open Access to these databases ensures transparency and use. Data quality description should be embedded in all the datasets, using for instance a Pedigree matrix.
The recyclable and recycled materials is a topic that also needs to be clearly defined in those databases with the emergence of battery recycling. End of Life (EoL) modelling is subject to methodological choices of the LCA study. A database of raw materials therefore need to provide LCI for different EoL modelling. As a first step, virgin raw materials need to be included in the database but there is also a need for recycled raw material inventories.
Allocation between products, co products, wastes is a key issue in LCA. For this reason, allocation have also to be treated in the database, following the ISO standard. Datasets with different allocation methods are needed.
This database is a first step to a battery sustainability tool that is needed to fairly be able to assess the sustainability of battery chemistries and their applications. Europe is well placed to be the leading source of good quality data for raw materials for batteries.

Current State of Art of the technology in brief

LCA is a data intensive tool: many data are needed for foreground processes (system under study) and background processes such as raw material extraction and transformation. Good quality data is necessary but not so easy to obtain. It is time consuming to get those data and in majority LCA studies rely on paid databases to include the background processes. In paid databases such as GaBi and Ecoinvent, many LCIs are available however for raw materials, some are outdated or based on proxies. Those LCI are often aggregated while a same raw material can be extracted from several geological sources or using several energy sources. Being able to study the effect of these changes on the environmental impacts of products is essential to identify sustainable value chains in Europe.
This is true for materials currently used in batteries but even more for future materials, including nanomaterials.
However, many inventory datasets have already been assembled for the Product Environmental Footprint (PEF) programme, which are now available in openLCA. Datasets are aggregated and some proxies are nevertheless used in the PEF programme. The advantage of open access is that it guarantees transparency.

Reasoning behind need for R&I on this topic

Data availability and quality are some of the big challenges that faces LCA experts. Background systems need to be assessed by reliable, easily available, detailed and non-aggregated datasets. The datasets could be disaggregated by geological sources, manufacturing processes and energy sources.

For some major raw materials currently used in batteries, no disaggregated and reliable LCI exist, forcing LCA studies to be based on proxies, while these raw materials may have environmental impacts that are not neglectable. This lack of good quality data may bring some doubts on the certainty of the results. The use of different proxies does not permit comparability between studies even if they assess the same battery chemistry. Potential impact of R&I advancements on this topic The project results are expected to contribute to: • Availability of good quality data for LCA of batteries and their applications • Reliability of LCA studies • Comparability of LCA studies • Identification of sustainable value chains for batteries
TRL level that R&I action should start and end on
Expected deliverables & suggested timeline Available datasets (in several electronic formats) for several group of raw materials (metals, chemicals, precursors) currently used in batteries and also for next generation batteries. This database have to be updated in order to avoid outdated LCIs and to follow development of new technologies. Suggested timeline:
Envisaged Budget and No of projects required on this topic 3 to 4 projects of 10 millions

Appendix 1: Proposed KPIs for Raw Materials and Recycling and circular economy

TOPICS:

Sustainable extraction and processing of battery grade raw material
Take back, reverse logistics, sorting and dismantling
Metallurgical recycling processes, industrial integration and secondary material-based precursors
Sourcing, sustainability and traceability of raw materials
Raw Material LCA and material Flow Analysis
Second Life of batteries

Sustainable Processing of Battery Raw Materials

KPI	Description	Value
BY 2025		
European extraction of battery metals	Number of new mines in operation for lithium, cobalt or graphite	3-5 (2027)
Battery metal processing	Number of new pilot plants, demonstration units or prototypes	TBD
Valorization of side streams	Number of sites where tailings or other side products taken into use	TBD
Improvement of existing processes	Reduction of processing steps demonstrated in add-on for old processing, e.g. leaching steps	TBD
BY 2030		
Environmental footprint	Liquid discharge from battery grade material processing	Zero
Energy efficiency	Efficiency improvement in graphite, battery chemical and pCAM (precursor cathode active materials) processing against current state of art	25 %
CO_2 emissions	Reduction of CO_2 emissions in lithium extraction and processing compared to current state of art • 25% of LCE used by European battery manufacturers produced from European own sources	50 %
European sourcing and processing	Share of battery grade lithium (carbonate, hydroxide) used by European battery manufacturers produced from European own sources	25 %

KPI	Description	Value

Take back, reversed logistics, dismantling, sorting and recycling

KPI for Take back of batteries	
Portable batteries *	Industrial and automotive batteries
Collection Actual target: 45% 55% by 2025 65% by 2030	Collection No specific Take-back target, well implementation of a reporting system
KPI for recycling of LIB Batteries	
1. Overall Recycling Efficiency • By 2023: 50% • By 2028: 60% 2. Material recovery targets (°): • By 2023: Co, Ni, Cu: 90%, Li: 35% • By 2028: Co, Ni, Cu: 95%, Li: 70%	

* Take back rate calculated based on the average of portable batteries placed on the market during the last 3 years.

(°) material recovery targets are calculated on the quantity of metal equivalent (independently form the actual form(s) of the recovered materials)

Improved total recycling of battery materials

KPI	Description	Value
2020		
Recycling efficiency *	Li ion batteries (by average weight of waste battery)	50% (60% by 2028)
Recycling efficiency	Metal specific targets	Cobalt 2023: 90%, 2028: 95% Nickel 2023: 90%, 2028: 95% Lithium 2023: 35%, 2028: 70% Copper 2023:90%, 2028: 95%
Recycling efficiency	Other batteries chemistries **	for all other batteries except: **Pb-acid:** • Recyclig efficiency: 2023: 65%, 2028: 75% • Material targets o for Pb: 2023: 93%, 2028: 95% o plastics: 10% **NiCd:** Recycling efficiency: 75% (recycling of Cd-content to the highest degree technically feasible without excessive costs)
Product recovery	The number of recovered products eg. Cu, Al, Li, Co, etc	4-6
2030 (as from 2028?)		
Recycling efficiency *	Li ion batteries (by average weight of waste battery)	60%
Recycling efficiency	Metal specific targets	Cobalt 95% Nickel 95% Lithium 75% Copper 95%
Recycling efficiency	Other batteries chemistries **	50% for all other batteries except: **Pb-acid:** • Recyclig efficiency: 2028: 75%

		• Material targets ○ for Pb: 2028: 95% ○ plastics: 10% **NiCd:** Recycling efficiency: 75% (recycling of Cd-content to the highest degree technically feasible without excessive costs)
Product recovery	The number of recovered products eg. Cu, Al, Li, Co, etc	6-10
Recovered elements	Number of elements recovered from battery waste back to use (Mn, graphite, REEs, electrolytes, F ...)	80%
Reduced direct or indirect carbon emissions		Consortia to deliver evidence
Quick addressing of new chemistries	Addressing the recyclability of new battery chemistries (eg. V, Mn, Na, solid state, sulphur)	
Monitored of inventory of each chemistry / material in market. Battery passport global battery alliance world economic forum case. **** Dynamic tool...	We know how much of material is available and which batteries: *** Solid state, *** New break through batteries	All industrial batteries

* Battery pack without external casing.

** Category representing all other type of battery chemistries (except Li-ion, NiCd and Pb-acid): Alkaline, Zn-C, Li-primary, button cells, NiMH.

*** If we consider a ca. 25% annual LiB market growth rate, the market size doubles every 3-4 years. Assuming end-of-life for a battery after 6-8 years, the maximum receivable recovery would be ca. 25% (at 100% recovery rate). Thus, multiplied with 80% rate from the line above, 20% would be max. target.

**** Active contribution of EU to this and ETIP could participate to this i.e. activate ETIP with Global Battery alliance in this topic.

Sourcing, sustainability and tracking

KPI	Description	Value
Sustainability of the value chain. *	Sustainability Standard for Mining. Number of sustainability approaches/certificates in use	1
LCI availability (for raw materials)	Update within 2 years PEF database and identify gaps by material (prioritized). Address gaps and proxy needs	

KPI	Description	Value
LCI availability from large scale mining	Environmental information available for battery raw materials	90% by production volume**
ASM data availability	Process based LCA data on battery raw material extraction and processing is made available; ensure data quality is adequate and improve it. Provide guidelines to ensure safety Collect environmental information	Apply PEF DQR; aim to move from 4 to 2 within 2 years;
LCI availability from artisanal mining	Environmental information available for battery raw materials	50% by production volume
Environmental impacts per kg of raw materials	Revisit list from the PEFCR for High Specific Energy Rechargeable Batteries for Mobile Applications	Improve accuracy of data, characterization factors and models
Data sharing	Decentralizing information on industry aggregates for mining site operations and emissions	15% of European mines have decentralized information 50% by 2025
Social impacts	Incorporate social impacts that could be based on the UNEP SETAC guidelines for sLCA. Impacts on health of miners and social indicators (human rights).	Assessment of specific materials by chemistry (CRMs, active materials)
Stock and flows, Volumes of batteries placed on market and Raw Material Index	See PROSUM project and Material System Analysis by EC (JRC). Update to the trade codes (PROC, …) to provide more consistent descriptions of raw materials, components and products	PROSUM project revisited and updated. Improvement in coding to improve the tracking systems. Balanced stocks and flows (only 20% missing flows and stocks)
Share of European raw materials	Increase the share of European primary and processed (imported) raw materials in batteries produced in Europe. Increase the Li recovery in recycling.	1 Scale up pilot for Lithium material refining and recycling
Tracing	Number of tracing technologies/concepts from mine to battery piloted/evaluated	3–5
Tracing	Share of batteries manufactured in Europe where an approved raw material tracing technology has been implemented	90% by 2030

* Sustainability standards exists already. To be defined more precisely which standards are used in Europe. Should also include CO_2 emissions. Sourcing of materials outside Europe should also include transportation. Mining sustainability and sourcing of material are separate issues.

** Shall be more specific which materials we are focusing on and explained in more details. Quality of the data more important than the quantity.

Second life of batteries, Circular Economy model

KPIs	Market data related KPIs (multi-functional use):
KPI-1–KPI-7 *	• KPI-1: Capacity and weight of EV-ITB placed on the market for the first time • KPI-2: number/weight of EV-ITB taken back (collected) and sent at EoL directly towards recycling • KPI-3: number/weight of EV-ITB taken back (collected) and sent to a contracted remanufacturer (for re-use in the same EV application) • KPI-4: number/weight of EV-ITB remanufactured and sent at EoL towards recycling • KPI-5: number/weight of EV-ITB taken back (collected) and sent to a contractor for refurbishment/re- purpose (for second life in another application) • KPI-6: number of EV-ITB re-purposed and placed on the market for the first time (after refurbishment, i.e; for a second life) • KPI-7: number of EV-ITB re-purposed and sent at EoL towards recycling (at the end of the second life)

* KPIs based on rechargeable Industrial Traction Batteries (ITB) from electric vehicles (EV), per EU Member State, and consolidated for total EU.