European Commission

ROADMAP ON RAW MATERIALS AND RECYCLING

Prepared by Working Group 2

#BatteriesEurope

Energy

Disclaimer

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- Strategic Topic 1, chaired by Dr. Päivi Kinnunen (VTT): Sustainable sourcing, extraction and refining of battery grade primary raw materials;
- Strategic Topic 2, chaired by Dr. Alain Vassart (EBRA): Safe collection, sorting and dismantling of EoL batteries and circular business models (incl. reverse logistics and second life);
- Strategic Topic 3, chaired by: Prof. Mari Lundström (Aalto University): Metallurgical recycling processes and use of secondary raw materials in the production of battery materials;
- Strategic Topic 4, chaired by Dr. Nieves Gonzales Ramon (CEFIC): Life Cycle Sustainability Assessment.

Moreover, the major contribution by Willy Tomboy (Detomserve) in the Subgroup 2 is gratefully acknowledged.

List of Acronomys

Al	Aluminium
BEPA	Batteries European Partnership Association
BGS	British Geological Survey
BMS	Battery Management System
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CRM	Critical Raw Material
Co	Cobalt
DEC	Diethylene carbonate
DMC	Dimethylene carbonate
EBRA	European Battery Recycling Association
EC	Ethylene carbonate
EIT	European Institute of Innovation & Technology
EoL	End-of-Life
EV	Electric Vehicle
F	Fluor
HF	Hydrogen Fluoride
IWG	Implementation Working Group
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Cost(ing)
LCI	Life Cycle Inventory

List of Acronomys

LCSA	Life Cycle Sustainability Assessment
LFP	Lithium Iron Phosphate
Li	Lithium
LIB	Lithium-Ion Battery
LiPF6	Lithium Hexafluoro Phosphate
Mn	Manganese
MFA	Material Flow Analysis
Ni	Nickel
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide
NiMH	Nickel Metal Hydride Battery
P	Phosphorus
pCAM	Precursor Cathode Active Material
PEF	Product Environment Footprint
R&I	Research & Innovation
REE	Rare Earth Elements
SDG	Sustainable Development Goal
SG	Subgroup
SoC	State-of-Charge
SoH	State-of-Health
SRA	Strategic Research Agenda
ST	Strategic Topic
SX	Solvent Extraction
TF	Task Force

List of Acronomys

UNEP	UN Environment Programme
USGS	US Geological Survey
V	Vanadium
WG	Working Group
WEEE	Waste Electric and Electronic Equipment

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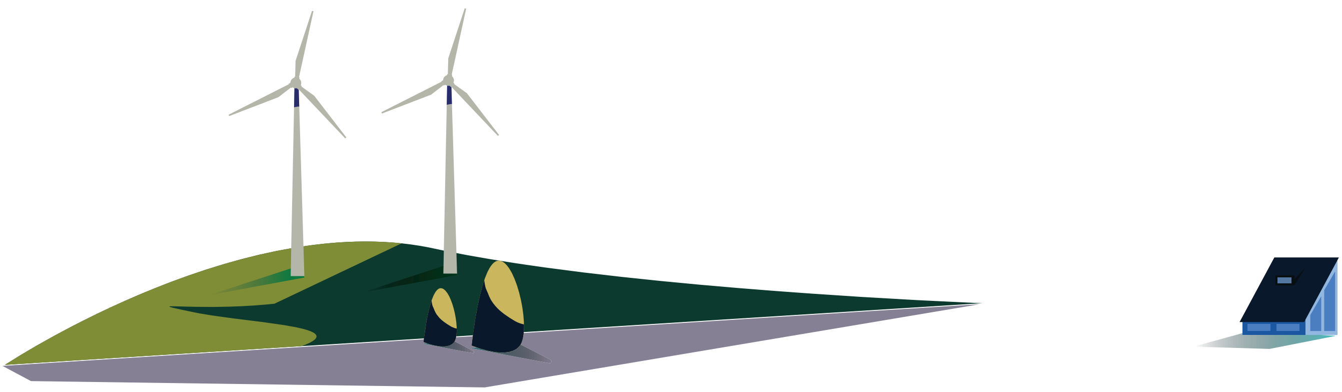
Executive Summary

The objective of Batteries Europe is to develop a competitive and sustainable battery value chain in Europe through Research and Innovation aiming to support the industrial value chain. Currently, Europe is dependent on imported raw materials and battery cells. Large scale projects are underway for the battery cell production, but the raw material sector is lagging behind in building the capacity to supply the required raw materials, some of which are classified as Critical Raw Materials (CRMs). As it is foreseen that Europe will remain dependent on imported raw materials, harmonized sustainability standards are needed. To have a level playing field, similar standards should be applied to raw materials, intermediate products and components sourced both within and outside the EU. Extension of the battery use phase and efficient collection and recycling of the End-of-Life (EoL) batteries are needed for a truly sustainable battery ecosystem.

A better understanding of the battery raw material base in the Member States can be created by harmonising the evaluation and reporting practices as well as by coordinated exploration activities to address the most promising deposits. Technological solutions to trace certified materials throughout the value chain should be piloted and implemented. Further R&I activities are needed to develop modular processing concepts for easy scale-up and to de-risk investments in the raw materials sector. Recovery and recycling of reagents and water within the processes should be improved.

Collection of EoL portable batteries should be improved and full take-back of industrial and EV batteries guaranteed. Standard transport solutions are needed for the safe reverse logistics of batteries, especially the large EV and industrial batteries. Digital solutions, data sharing and more

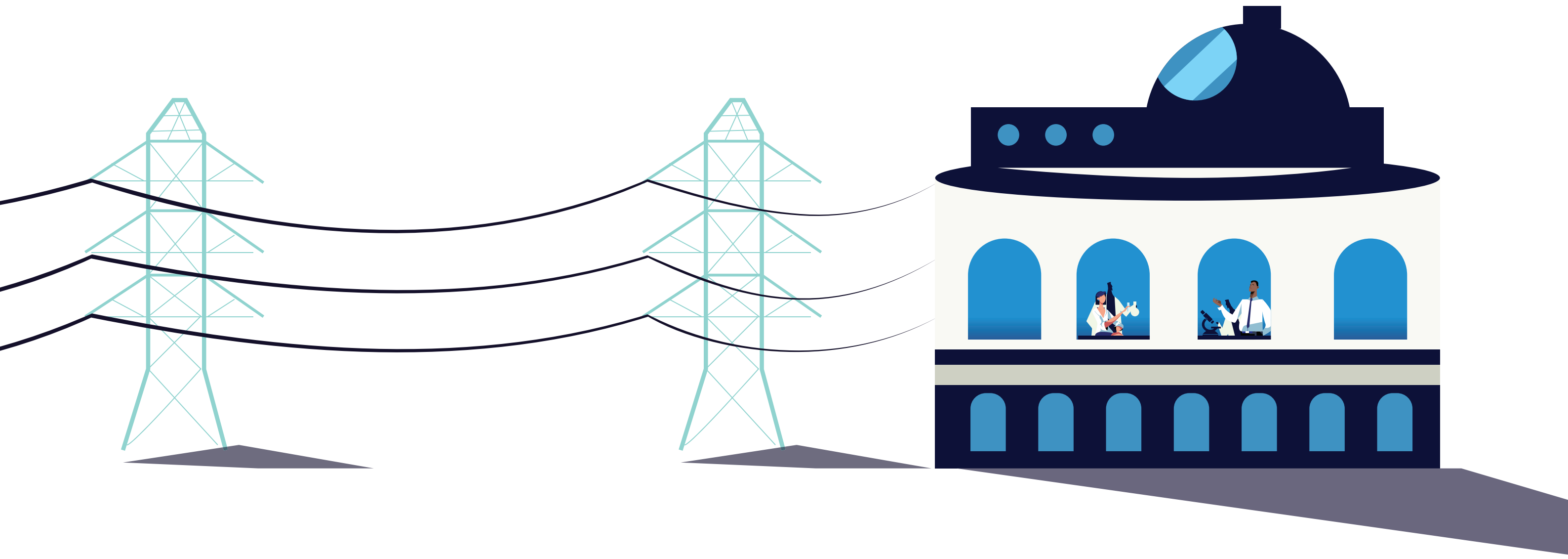


detailed labelling standards, like the proposed Battery Passport are needed to ease the sorting and recycling of the EoL batteries. Moreover, standard diagnosis protocols are needed to qualify EoL batteries for reuse, remanufacturing or repurposing for second use or to direct them to waste recycling. (Semi-)automated processes should be developed for energy recovery from and safe dismantling of the larger packs and modules.

Recycling processes should be further improved for economic recovery of the key battery materials (Ni, Cu, Co, Li) to meet the targets of the proposed Battery Regulation and extended for the valorisation of the anode materials and electrolytes. Integration of primary and secondary flows from other sectors to battery recycling processes should be studied to decrease the carbon footprint of the processes. Key performance indicators of the recycling processes should be made available for decision making.

Life Cycle Sustainability Assessment (LCSA) comprising environmental (LCA), economic (LCC) and social (S-LCA) aspects should be used for assessment of the different materials and processes. Life Cycle Inventory (LCI) dataset should be improved and made openly accessible. Aggregated and proxy data should be replaced by more specific data on regional raw material deposits as well as production and recycling process specific indicators. Finally, Material Flow Analysis (MFA) should be applied at regional, European and global level as well as product and process levels to gain deeper understanding of the flows of the key elements, especially the CRMs. MFA should be further applied to work out future scenarios and to address e.g., the availability of secondary raw materials to calculate targets for recycled content in future batteries.

The key recommendations by WG2 are summarized in the Table 1.



Number	R&I Priority
1.	Contribute to harmonizing the battery raw material resource/reserve estimation methods in the Member states (e.g. CRIRSCO compliant)[1].
2.	Pilot technical solutions to trace certified materials within the value chain.
3.	Develop (semi-)automated processes for energy recovery and dismantling of EV and industrial battery packs and modules.
4.	Contribute to development of standard SoC/SoH evaluation methods for EoL batteries and quality criteria for reuse/repurposing vs. waste recycling.
5.	Improve the recycling processes for economic recovery of key elements to meet the targets of the proposed Battery Regulation.
6.	Decrease the carbon footprint of the recycling processes by integrating secondary material streams from other sectors as raw materials to utility chemicals.
7.	Study the valorisation of the anode materials from the EoL batteries.
8.	Create reliable open access LCA/LCI data for primary and secondary raw materials, battery chemicals and active materials as well as manufacturing and recycling processes including use of different energy sources.
9.	Pilot LCSA including environmental (LCA), economic (LCC) and social (S-LCA) aspects within different parts of the battery material value chain.
10.	Piloting ex-ante LCA in the design of new materials and manufacturing processes.
	Other recommendations
11.	Contribute to establishing a common standard for sourcing of materials and components within and outside the EU.
12.	Propose digital tools for data sharing withing the value chain (e.g. Battery Passport).
13.	Provide key data of recycling processes for decision support: (LCA data, carbon footprint data, recycling efficiency, share of recycled content going to new batteries...).

1 Largely aligned with UNFC - United Nations Framework Classification for Resources.

Vision

Europe's global leadership in automotive and battery industries is built on a solid supply of transparently and sustainably extracted and processed raw materials from both European and non-European sources.

In order for Europe to become the No. 1 recycler of Li-ion battery raw materials, all the important raw materials imported into Europe in batteries or installed in batteries in Europe should be collected and processed in Europe to recover the materials without down cycling when technically, economically and environmentally beneficial.

This vision is built on four cornerstones i.e. Strategic Topics:

Strategic Topic 1: Sustainable sourcing, extraction and refining of battery grade primary raw materials

Strategic Topic 2: Safe collection, sorting and dismantling of EoL batteries and circular business models (incl. reverse logistics and second life)

Strategic Topic 3: Metallurgical recycling processes and use of secondary raw materials in the production of battery materials

Strategic Topic 4: Life Cycle Sustainability Assessment

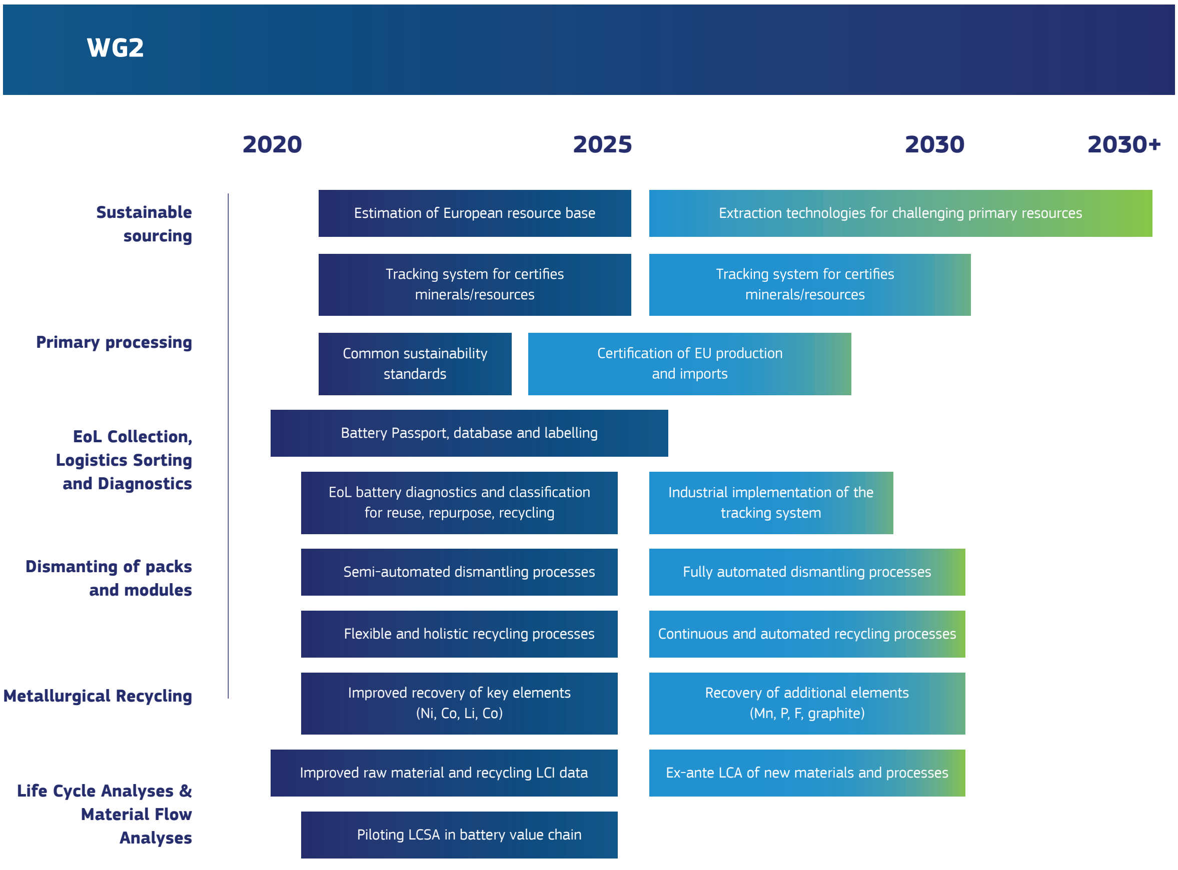


Figure A: Graphical representation of the Raw materials and recycling roadmap developed by the Batteries Europe WG2

Scope and objectives

The scope of this roadmap is to identify and elaborate topics which require R&I support for securing raw materials supply to the European battery industry based on transparently and sustainably extracted and processed materials from both European and non-European sources as well as efficient collection and recycling of EoL batteries with a main focus on EV and industrial Li-ion and NiMH batteries. The scope is divided into the four Strategic Topics given in the Vision section.

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

As e-mobility is booming now, European car manufacturers are still dependent on imported Li-ion batteries, although there are already investments to build battery cell manufacturing capacity in Europe, which will support the future independence of the European car industry. However, the investments in raw materials sourcing in Europe are developing much slower (e.g. 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.

Raw materials represent a major high impact part of battery value and carbon footprint, therefore R&I work is critical and imperative. To reach the goal of the European Battery Alliance – 300 GWh+/ year of battery production in Europe by 2025 – 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 do exist in Europe with a collective planned capacity corresponding to about 10% of the estimated global LCE demand by 2027. Although recycling based secondary materials will support the material supply in the future, there is still a gap of available materials, which has to be filled by using increasing amounts of primary, mine-based materials.

The dependency on imported materials not only poses a strategic supply risk for European battery manufacturers but also a branding issue as the sustainability and traceability of raw materials from non-European sources are very difficult to define. Building up European capacity in extraction and processing would serve the diversification of supply chains, thus, limiting supply risks; but also serves future recycling of batteries as the recycled materials can gradually be integrated into the existing primary processing facilities.

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.

With rapidly increasing electrical vehicle fleet in Europe, quantity of batteries in European cars will also increase rapidly, forming a fast-growing stock of in-use raw materials, which are a remarkable source of raw materials and available for later 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. Also, the chemistry of these batteries is varying a lot, challenging the processing and recovery of the materials. 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. The need to develop better technologies to recycle the materials contained in batteries is also important due to the upcoming Battery Regulation[1], which will introduce targets for the carbon footprint, collection rate and recycling efficiency of batteries and recovery rate of Li battery elements (Ni, Co, Li, Cu). 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, which means also a growing need for bigger scale processing units. In addition to the recycling of EoL batteries, there will be an increasing need to recycle production scrap and low value chemicals used in the battery production and recycling targeting closed-loop processes within the industry.

The objectives of this roadmap is to condense the key messages from the previous roadmap prepared in 2020[2], align it with the Batteries Europe SRA and update it according to recent developments in the European battery ecosystem and regulations[2].

[1] New proposed battery regulation, 2020.

[2] Batteries Europe Raw materials and recycling roadmap, 2021.

Methodology

This Roadmap has been elaborated in a collaborative manner by the experts involved in Working Group 2 "Raw Materials and Recycling" of Batteries Europe, taking into account valuable comments and suggestions from Batteries Europe Governing Board and Secretariat, and EC officials.

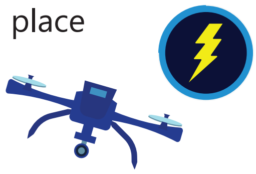
The topics of the roadmap were initially collected and analysed in two workshops in 2019 (January 2019 in Espoo, Finland and June 2019 in Milan, Italy) which gathered 85 participants representing 46 different organizations and 12 European countries as well as the EU Commission. The report of those meeting was used as starting point for the first WG2 roadmap in 2019-20202.
During the working sessions the topics of sustainability, safety and second life were identified as cross-cutting issues with other Working Groups, and special Task Forces (TF) were established to write Position Papers on these topics.
For this revised and updated Roadmap 2021, the WG2 Subgroups (SGs) were reorganized under the four Strategic Topics (STs) as mentioned in the Vision section, and were communicating and working together through online calls.

More than 100 people have participated in WG2 activities of which 40 have actively contributed to this Roadmap. WG2 is well aligned with other important actors and activities in the European Battery R&I ecosystem including the other WGs of Batteries Europe, the Finnish national battery material ecosystem BATCircle, EIT Raw Materials, EBRA and Battery 2030+.
The document was finalised after feedback given via a broad consultation of WG2 members, in addition to feedback from the Governing Board of the Batteries Europe.

1. STRATEGIC TOPIC 1: SUSTAINABLE SOURCING, EXTRACTION AND PROCESSING OF BATTERY GRADE PRIMARY RAW MATERIALS

1.1 DESCRIPTION

Efficient extraction and processing of battery grade raw materials is a key element in securing European leadership in energy storage markets, but the production volumes in Europe are marginal. The strategic R&I should focus on (Committee for Mineral Reserves International Reporting Standards) CRIRSCO[3] compliant resource mapping and sourcing within the EU and securing the future European supply for the next generation[4] of batteries. There is a high level of urgency to develop new sustainable and cost-efficient processing solutions for Li, Ni, Co, Mn, REE, V and graphite from current and emerging material streams. Specific actions are needed for more specialized battery raw materials and ramping up of the limited cathode chemical (Ni_2SO_4 and Co_2SO_4) and precursor production in Europe. The European competitive edge relies on superior product quality and value, high material, water and energy efficiency, low climate and other environmental impacts and social sustainability. Integration of secondary raw materials from recycled batteries and mining and metallurgical waste into primary production may increase the value of some unused fractions. When sourcing outside the EU, sustainability and fair-trade principles are of highest importance. Reliable methods to trace, report and verify the origin of materials and the conditions of production should be implemented. Uniform sustainable mining standards aligned with international instruments and initiatives for Artisanal and Small-Scale Mining should be put in place and the impacts monitored.



1.2 STATE OF THE ART

Materials for Li ion batteries:

The share of clean energy technologies in the total demand of Nickel and Cobalt is expected to reach 60-70% by 2040. **Nickel and Cobalt** are often recovered as lower value sulfide products suitable for example for stainless steel, but the product specification and quality requirements are much higher for

[3] Committee for Mineral Reserves International Reporting Standards - largely aligned with UNFC.

[4] See Appendix.

battery metals. Unit processes for battery chemicals necessitate higher energy and cost efficiency and also off-specification battery metals and compounds recovery in the future. The complexity of precursor cathode active materials (pCAM) processing and strict product quality standards require a high degree of process control.

Manganese is utilised in Nickel Manganese Cobalt (NMC) and Lithium Manganese Oxide (LMO) batteries. Mn is leached with base metals and could be recovered as a by-product from the leachates.

The share of clean energy technologies in the total demand of Lithium is expected to reach almost 90% by 2040. **Lithium** can be extracted from hard rock deposits or saline brines. Most European Li mine projects work on hard rock deposits, where dry comminution, sorting and alternative fuels in thermal treatment would lead to water and energy savings and reduced CO2 emissions. More flexible primary plants which can accept raw materials from different sources are needed.

Lithium Iron Phosphate (LFP) is an alternative cathode material for low-end electric vehicles and, especially, for stationary applications. It has gained in importance as the supply of Ni-based cathode materials may face shortages. Phosphoric acid and Iron chemicals are readily available in Europe but the value chain for LFP processing is missing.

Graphite is the principal anode materials used in today's Li ion batteries. The key opportunities for natural and synthetic graphite production in Europe are linked to application of more sustainable production processes and low environmental impacts (emissions such as CO2) under the strict environmental regulatory EU framework.

Silicon is a high-capacity anode material but suffers from poor stability due to large volume expansion during charge. Today 5-10 % Si is added to graphite, and the share of Si is constantly increasing. Metallurgical processes and chemical vapor deposition for Si exist in large scale, but new integration methods and optimization are needed for battery grade Si.

Materials for other battery chemistries

There are a host of battery chemistries in various stages of development and demonstration which use a variety of raw materials. The most promising chemistries are outlined in the Batteries Europe New and Emerging Technologies Roadmap prepared by WG1. Vanadium redox flow batteries is one such battery chemistry.

Vanadium belongs to the Critical Raw Materials and there is no production and trade for vanadium ores and concentrates in the EU. For Vanadium, new technical and feasible resources and processes are needed to ensure the supply.

The EU is missing an integrated mineral exploration program to secure resources for European battery production, in addition to uniform sustainable mining standards. Life Cycle Assessment (LCA) is used to examine the environmental impacts of production and use of battery materials. The industry has developed harmonized LCA guidance, and the global LCA metals datasets are available in databases, such as Product Environment Footprint (PEF)[5]. However, the industry is lacking a methodology for verifying the environmental impacts with certificates or labelling systems allowing the verifiable traceability of material resources and CO2 emissions. A uniform guidance on the use of block-chain type technologies could be an opportunity for the EU industry.

1.3 WHAT IS NEEDED FOR EUROPE TO BE COMPETITIVE?

The growing EU battery industry is missing a reliable, harmonized and easy way to source battery materials. 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. Any battery raw materials produced, processed or used in Europe must have a superior quality and environmental footprint, with competitive cost. Technology development should aim at improved yield including minor elements, better process control, flowsheet flexibility, improved product purity and quality, improved impurity removal, reduced generation of tailings/waste and improved recovery from secondary streams. PEF Category Rules[6]should be extended from battery level to active electrode materials. EU-wide regulation for batteries placed on the EU market, such as that detailed in the proposal for Battery Regulation in December 2020[7], could help establish a reliable framework. CO2 emission should be monitored during all material process production steps. For this, standards and guidelines for the calculation of the carbon footprint from the mine to the battery are needed. Integration of primary and secondary processing is of importance to develop truly optimized, flexible and smart battery metals processing.

1.4 RESEARCH NEEDS AND RESOURCES REQUIRED

Short term (0-5 years)

- Integrated exploration plans and harmonized CRIRSCO[8] compliant estimation of the EU resource/ reserve basis including recovery of Ni, Co and V from laterites and non-conventional sources;

[6] https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

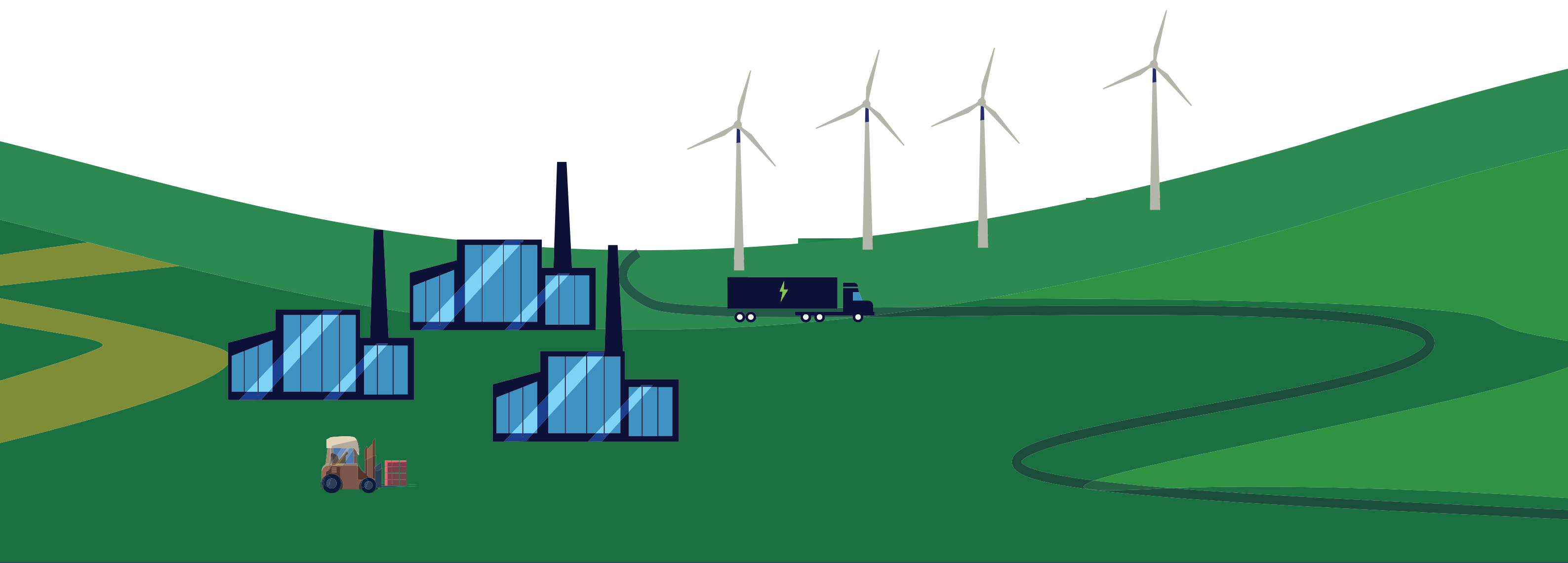
[7] COM/2020/798 final

[8] Committee for Mineral Reserves International Reporting Standards - largely aligned with UNFC.

- Research and Innovation to support the development of a common standard for raw materials sourced within and outside of EU to reliably report, trace and label certified materials through all steps in the battery supply chain;
- Design and Demonstration of modularized processing plants to de-risk the implementation and easy scale-up;
- Development of technologies for downstream process simplification (i.e., resin in pulp, direct SX) and recycling/reduction/recovery of main reagents and water with low CO_2 footprint;
- Research to support the development of the LFP processing value chain
- Development of Si production methods for composite anode materials (Si/C composite up to 20 % Si).

Medium term (5-10 years)

- An economically feasible process for Mn recovery from base metal solutions;
- Alternative more sustainable raw materials for synthetic graphite production;
- Secondary product recovery from mining and metallurgical processing to minimize tailing and gangue production;
- Assessment of current technologies, de-risking investments, mapping of resources and potential environmental and social impacts for deep sea exploration (Ni, Vo, Mn, V) and brine use from geothermal brine (Li).

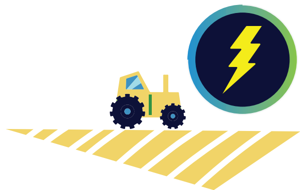


2. STRATEGIC TOPIC 2: SAFE COLLECTION, SORTING AND DISMANTLING OF END-OF-LIFE BATTERIES AND CIRCULAR BUSINESS MODELS

2.1 DESCRIPTION

The market for end-of-life (EoL) batteries is mature or slowly growing for certain chemistries (alkaline, NiCd, Lead...), and it is increasing exponentially for Li-ion (electric mobility and stationary applications). The concept of extending the lifetime of batteries is also becoming a regulatory topic and industrial reality.

The harmonisation of the logistics in the supply chain, removal of inefficiencies and enhanced circularity are some of the top priorities of the 2021 roadmap towards a safe handling of batteries, extended product life and circular business models.



2.2 STATE OF THE ART

The new proposal of a Battery Regulation foresees strong development, including increased collection rate of waste batteries, increased recycling efficiency targets up to 70%, and specific material recovery and recycled content targets for key elements (Co, Pb, Li, Ni) and the evolution of the EoL business models with new actors and an even more complex value chain.

Safe and improved collection, reverse logistics, sorting and dismantling activities will impact the market developments. Currently, the collection rate of small Li-ion batteries must be improved, as well as the takeback of high-energy batteries (EVs and industrial batteries). Standardized solutions in the logistics chain minimizing risks are missing and, upon collection/takeback of high-energy batteries, reliable and certified diagnostics (SoH, SoC) are rarely applied, despite being paramount for safe handling and extending the lifetime of the batteries. Also, traceability and knowledge of batteries volumes, BMS data, LCA/PEF information, mechanical degradation, safety and quality assurance, are not easily accessible/available, even though are key elements to decide whether reuse, remanufacturing, or repurposing are still possible, or whether batteries have to be sent for recycling. Moreover, there is no industrial recycling process capable of handling a complete EV/industrial battery, thus dismantling of high-energy batteries is always necessary for reuse or remanufacturing, repurposing and recycling. Finally, a value-chain approach and availability of information at value-chain level supporting operators in the whole EoL process (collection, sorting, testing, dismantling, recycling and marketing) is currently lacking.

2.3 WHAT IS NEEDED FOR EUROPE TO BE COMPETITIVE?

Safety is a transcendent priority for the competitiveness of the European battery value chain. Traceability, monitoring and reporting of take back of batteries, especially electric vehicles and industrial batteries, is needed to provide basic important data to all actors of the whole value-chain. Besides, the identification of incentives to develop and to establish a sustainable and competitive EU value chain is needed.

Design of batteries should address (ease of) removability for portable (WEEE) and safe cost-effective dismantling processes for industrial/EV batteries, as well as extraction of basic important data on battery chemistry and raw materials. Also, cost-efficient storage and proper transportation containers are needed to decrease the risks during transport and to avoid damage to batteries which are potentially fit for second-use applications.

Unambiguous criteria, common methodology and technical documentation are needed to establish diagnostics protocols, to calculate and report recycling efficiency, recycled content, material recovery targets but also key information to various actors of the value chain.

2.4 RESEARCH NEEDS AND RESOURCES REQUIRED

Short term (0-5 years)

- Development of (semi-)automatic dismantling processes for safe and reliable extraction of LIB packs, modules and/or cells (potentially with different geometries and architectures) from EoL products (consumer, industrial, EV, stationary);
- Development of (semi-)automatic dismantling processes for LIB packs and modules allowing the isolation of the different components (BMS, casing, cells etc.) Development of (semi-)automatic opening procedures for Li-ion cells considering safety issues;
- Support of the Battery Passport development and certification, monitoring, and reporting tools, to store digitalized information on batteries whilst supporting the

adoption of sustainable routes (min lifecycle footprint, optimal efficiency, traceability, design-for-EoL,);

- Development of new business models including co-operation between various actors of the value-chain (e.g. collectors, dismantlers, re-purposers, recyclers, manufacturers) identifying incentives for meeting the new requirements of the Battery Regulation;
- Development of efficient labelling and sorting systems for separation of LFP batteries from Ni based cathode chemistries;
- Develop new technologies and devices for reliable battery diagnose by trained and certified experts using standardised protocols enabling accurate SoC and SoH measurement and determination of mechanical degradation for safety and quality assurance;
- Development of decision-making support tools to combine the SoC/SoH diagnosis data with BMS data and the LCA/PEF information, to establish whether that battery or parts of it can still be considered as a product for reuse, remanufacturing, repurposing, or waste to be recycled accordingly;
- Develop discharge technologies which do not waste batteries' residual energy.

Medium term (5-10 years)

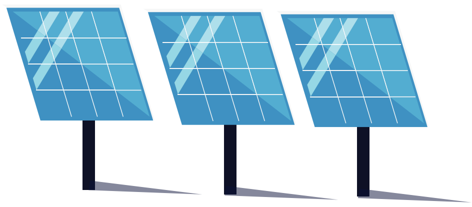
- Scaling-up of automatic extraction/opening/dismantling processes.

3. STRATEGIC TOPIC 3: METALLURGICAL RECYCLING PROCESSES AND USE OF SECONDARY RAW MATERIALS IN THE PRODUCTION OF BATTERY MATERIALS

3.1 DESCRIPTION

This topic deals with metallurgical recycling of portable, electric vehicle and industrial batteries and their production scrap, comprising Li-ion (LIB), NiMH, and emerging new chemistries. Different mechanical, pyro- and hydrometallurgical unit processes are covered here.

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.



3.2 STATE OF THE ART

In the state-of-the-art pyrometallurgicWal battery recycling processes, the batteries are directly fed to a high-temperature furnace where Ni, Co, Cu and Fe form an alloy to be treated hydrometallurgically whereas Li, Mn and Al end up in the slag. Graphite, solvents and plastics are burned in the process and toxic and corrosive (HF) gases need to be treated. Mechanical and hydrometallurgical recycling processes for Ni and Co containing (e.g. NMC) batteries will allow recovery of greater volumes of battery grade elements, but they are currently at pilot or low volume industrial scale. Higher efficiency in recycling processes is targeted. LFP batteries need dedicated recycling processes, which is economically challenging due to the low value of the LFP cathode elements.

3.3 WHAT IS NEEDED FOR EUROPE TO BE COMPETITIVE?

There is a clear need to develop holistic material and energy efficient recycling processes but also unit processes that can recover greater volumes of battery materials with lowered carbon footprint. The objective should be to improve the recovery of Ni, Co, Li and Cu but also improve recovery of graphite, Mn, Al, F, P as well as electrolyte salts and solvents. Direct recycling of active materials (such as alloys or oxides) and other components should also be investigated as well as battery metals recovery from slag (smelting process). This all should also be systematically addressed and compared in terms of economics and environmental impacts. Metallurgical tools (thermodynamic and process modelling, environmental impact evaluation) should be further developed in order to support fast scale up and piloting. Also, the health and safety related issues must be carefully addressed at all processing steps.

Pros and cons of centralized and decentralized processing options and combinations of these should be studied as well as integration of intermediate fractions from the recycling processes into the primary processing. Conversion of batch processes to continuous operation will also be needed for efficient treatment of the large volumes of EoL Li-ion batteries expected from 2030 onward. Improved co-operation are needed between recyclers and battery manufacturing to support vertical integration i.e. use of battery grade chemicals from recycling operations. An efficient and structural integration of secondary raw materials into battery production is to be addressed.

Along the development of new battery chemistries, a strong focus on their recyclability (design-for-recycling) should be taken in an early stage.

3.4 RESEARCH NEEDS AND RESOURCES REQUIRED

In all R&I topics the following should be addressed: developing safety protocols for recycling, economic and environmental evaluation.

Short term (0-5 years)

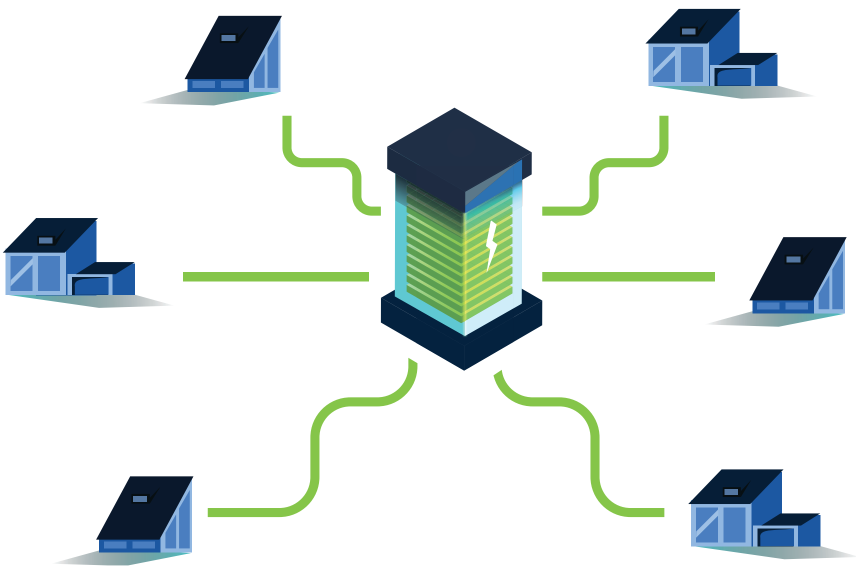
- Key data of recycling processes for decision support: New innovative recycling unit processes as well as holistic recycling processes need to be researched, experimentally investigated and also process modelled in early development stage to get quantitative measures of the process performance (recycling efficiency, mass- and energy balance, LCA data, carbon footprint data share of recycled content going to new batteries…);
- Development of metallurgical tools and modelling of unit operations;
- Research to investigate the viability of integration of secondary/primary materials streams from other sectors to recycling processes (as raw materials or utility chemicals);
- Recycling process design enabling

the recovery and valorisation of anode materials (graphite, Si, Ti);

- Electrolyte valorisation through the development of sustainable and safe processes for recovery of Li-salts and the organic solvents (EC, DEC, DMC);
- Research dedicated to cost-efficient LFP recycling processes;
- Research to investigate direct recycling of battery materials and components;
- Design for recycling for new chemistries and improvements for existing.

Medium term (5-10 years)

- Towards zero waste recycling, where also non-metallic elements (electrolyte, solvent, salts and polymers) are also recycled back to use;
- Centralized, vertically integrated and automated close-loop processes. As alternatively, de-centralized (local or mobilized) metallurgical treatment units;
- New process concepts developed in the short term should be piloted for facilitating scale up in the medium term.



4. STRATEGIC TOPIC 4: LIFE CYCLE SUSTAINABILITY ASSESSMENT

4.1 DESCRIPTION

Deploying Life Cycle Sustainability Assessment (LCSA) methods is essential to ensure that the EU battery industry is the most sustainable globally. LCSA is needed to identify the targets for improvement, not only covering environmental issues, with Life Cycle Assessment (LCA), but also economic (Life Cycle Costing (LCC)) and social issues (Social Life Cycle Assessment (S-LCA)). The LCSA analysis should give new sustainability metrics for the whole battery value chain and new indicators to capture the importance of sustainable sourcing of metals, including recycling. The quality of raw material data in life cycle inventory (LCI) databases must be improved in order to improve the accuracy of the assessments. Furthermore, those methods should be combined with material flow analysis (MFA) in order to improve its relevance in respect to circularity.

4.2 STATE OF THE ART

LCA is a key component of LCSA. LCI (life cycle inventory) datasets are available within several databases as EC's new Product Environmental Footprint (PEF)[8] database. Ecoinvent[9] and GaBi3[10] are frequently used for raw material inventories. Ultimately, given the different technology readiness levels and the variety of output materials, a clear and consistent LCA approach should be developed for levelled comparison of the environmental impact of different recycling processes.

Concerning **Material Flow Analysis**, information about the mineral potential (EU and global reserves and production) are available from Geological Associations (USGS[11], BGS[12], etc.) and the supply/demand situations (including future projections) are described by JRC[13] and others. First models of material flows

[8] https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

[9] https://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

[10] GaBi Databases

[11] GUS Geological Survey

[12] British Geological Survey

[13] CRMs for Strategic Technologies and Sectors in the EU, JRC, 2020. British Geological Survey

[14]ProSUM Project

[15] SUPRIM: Sustainable Management of Primary Raw Materials through a better approach in Life Cycle Sustainability

of battery raw materials and secondary materials are being developed through specific studies and H2020 projects (e.g. PROSUM[14], SUPRIM[15]). Only a few MFA models (considering recycling) beyond EV applications are available, e.g. for stationary applications.

Life Cycle Sustainability Assessment needs to combine all the above methods with Social Life Cycle Assessment (S-LCA). Guidelines for S-LCA of Products and Organizations 2020 has been recently published by UNEP[16]. In addition there are several Initiatives, which have carried out sustainability mappings for materials, see more details in the WG2 2020 Roadmap.

4.3 WHAT IS NEEDED FOR EUROPE TO BE COMPETITIVE?

The European battery value chain has the ambition to implement the highest sustainability standards, hence will need to systematically implement life cycle thinking through LCA in its business practices. Reliable, representative and non-aggregated LCI data (for raw materials from different geological sources, chemicals, precursors and processed materials, components and assemblies considering manufacturing processes with different energy sources, as well as recycling processes) are needed. LCI availability and accessibility will have to be ensured not only for current industrial practices but also for materials and processes with low technology readiness levels. Life cycle-based data will be used to lead life cycle impact assessment studies to improve practices, also at early stages of development process, and to identify robust environmental criteria to be complied with (e.g. for ecolabels). LCA should begin at a regional scale with the estimate consumption of water, fuels, energy and land use impacts from the exploration stage, using public reports as a basis. Differences regarding resource consumption, mineral deposit type should be taken into account in the regionalized LCA approach.

The European battery value chain will also need to further develop its capacity on MFA to be able to trace current and future battery raw materials flows and stocks, to ensure sustainable origin and to identify dissipations. MFA studies will not only need to be constantly updated for all battery raw materials, including emerging ones, but also to establish links between materials and other applications, to capture synergies and competitions between sectors. MFA will also need to be dynamic and forward-looking, considering realistic or extreme scenarios, and addressing the gap between the demand and

[16] Guidelines for social life cycle assessment of products, UNEP - UN Environment Programme.

supply of materials, and related risks. Therefore, harmonized MFA datasets will be needed for battery raw materials, at European, country, life cycle stage and even process specific levels, in articulation with global MFA datasets. MFA will also be a powerful tool for the EU to map batteries and materials available for collection, effectively collected and recycled, hence helping to measure circularity performances, and contributes to the new EU battery regulation. MFA will also be necessary to better address in a prospective manner open loop and close-loop recycling and related effects.

The batteries made in Europe need to be sustainable not only from environmental but also from economic, social and governance perspective. Therefore, the R&D actions in the area of LCSA are recommended. In order to understand the full sustainability and the trade-offs between the three pillars of sustainability it is essential to capture more information on social impacts of the sourcing, production and recycling of batteries. LCSA metrics will have to be related to the UN Sustainable development goals (SDGs). We need to include LC based methods in an early design process developing methodologies for ex-ante (qualitative and semi-quantitative assessments) analysis. An LCSA framework shall be applied at an early stage to any novel process. Sustainability hotspots can be identified, and the impacts can be compared with those of current industrial practices allowing to anticipate improvements and drive transitions.

4.4 RESEARCH NEEDS AND RESOURCES REQUIRED

Short term (0-5 years)

- Open access and reliable LCI data of primary and secondary raw materials (chemicals and precursors) and of manufacturing and recycling processes considering different energy sources and Methods to construct interoperable LCI datasets along the value chain;
- Deployment of LCA studies as the approach in an early stage of a process design;
- Pilot studies concerning full multi-criteria sustainability assessment implemented in individual companies along the value chain;
- Identification of shared sustainability requirements for batteries (e.g. ecolabel).

Medium term (5-10 years)

- LCI data and LCA of next generation batteries, e.g. solid state, Na-ion and redox-flow batteries;
- Blueprint for an EU framework to undertake sourcing in countries or regions with small scale materials mining to enable those communities to benefit from battery value chains;
- Mapping of high social Hotspots, countries and sectors related;
- Sustainability assessment policies and studies fully implemented in companies' strategies.

5. Prioritisations & Key Recommendations

Batteries produced and used in Europe should meet the highest sustainability standards and proposal Battery Regulation1 offers the needed framework. Sustainability standards should cover the whole value chain from mining to recycling and should be based on science-based harmonized sustainability criteria. The same sustainability criteria should be applied to all processed or raw materials as well as batteries and modules sourced both within and outside of the EU. Furthermore, the EU should develop all-European value chain including recycling to minimize any risks in sourcing critical raw materials. Health and safety issues should be given high priority at all stages of the value chain.

In order to get an improved understanding of the feasibility of the sourcing of European **primary raw materials**, harmonized methods should be developed and applied to the estimation of the EU resources and reserves. Moreover, integrated exploration plans should be developed to improve the accuracy of these estimates and to identify the most economically and environmentally viable deposits. A common sustainability standard should be implemented for raw materials sourced both within and outside EU, and technical solutions to trace the flow of the certified materials should be piloted. Flexible and modular processing units accepting raw materials from diverse sources should be developed to facilitate easy scale-up. Recovery and reuse of reagents and water in the raw materials processing units should be improved. With regard to Li ion battery anode materials, silicon raw material processing should be optimized for Si/C composites and more sustainable raw materials identified for synthetic graphite production.

Collection of portable batteries should be improved and full **take back** of industrial and EV batteries guaranteed. Standardized containers should be used for safe **reverse logistics** of EoL batteries, even damaged ones. Standard State-of-

Health (SoH) diagnosis protocols should be developed and used for **sorting** and classification of EoL batteries for reuse/ repurposing or waste recycling. (Semi-) automatic discharge and **dismantling** processes should be developed for safe and cost-efficient energy recovery and dismantling of EV and industrial battery packs and modules and for the opening of the cells. Digital tools and platforms like the Battery Passport should be used for data sharing (e.g. chemistry, BMS use history) between different actors in the value chain, and new business models should be developed for efficient co-operation between these actors.

Flexible and holistic **recycling processes** in which economic recovery of the key elements (Ni, Co, Cu, Li) supporting the targets of the proposed Battery Regulation can be achieved should be developed. Improved metallurgical tools and models should be developed to address the sustainability of the different processing options and key data should be created and made available to support decision making. In addition to the cathode materials, valorisation of the anode materials (C, Si, Ti) as well as the electrolyte salts and solvents should be targeted. Conversion of batch processes to continuous ones should be targeted to prepare for the larger volumes in the future. Different combinations of decentralized, local processing units and larger centralized units should be optimized. Direct recycling processes of the active materials as alloys or compounds should be further developed. Design for recycling or circular design principles should be applied especially for new materials and concepts. Finally, structural concepts for easy vertical integration of the secondary material streams to battery production should designed.

Improved tools should be developed for **Life Cycle Sustainability Assessment (LCSA)**, comprising environmental (LCA), economic (LCC) and social (S-LCA) aspects. The quality of the LCI datasets should be improved and they should be made available and accessible for different stakeholders (Open Access). Aggregated and proxy data should be replaced by more specific data, e.g. for raw materials from different geological sources, chemicals, precursors and processed materials, components and assemblies considering manufacturing processes with different energy sources, as well as recycling processes. Standard methods should be developed to calculate the carbon footprint of different materials and processes. (Ex-ante) LCA should be applied early in the design phase of new materials and processes. Social aspects should be included in the sustainability assessment (S-LCA) and they should reflect the UN Sustainable Development Goals. Multi Criteria Sustainability Assessment should be piloted in individual companies in different parts of the value chain.

Datasets for **Material Flow Analysis (MFA)** should be harmonized at national, European and global level including product and process specific data, and they should be constantly updated. Cross sectoral materials flows should be accounted for to address synergies or competition between the sectors. MFA should be further used for future scenarios to address possible critical issues and to estimate the sectorial contribution of recycled secondary raw materials, e.g. the recycled content in future batteries.

The key recommendations by WG2 are summarized in the Table A as provided in the Executive Summary.

5. Prioritisations & Key Recommendations

Large scale LIB cell manufacturing plants are at different phases of planning and construction around Europe to support the electrification of European vehicle manufacturing and integration of a large share of renewables into the power grid. However, Europe is largely dependent on imported raw materials and components for these manufacturing plants. Development of European value chains for the battery raw materials and efficient collection and recycling of EoL batteries are essential to decrease the supply risk related to imported materials and to guarantee the sustainability of the whole value chain from mines to recycling.

Harmonized methods are needed to report the raw material resources and reserves and joint exploration plans are needed to identify and develop the most promising deposits. The industry needs unified and transparent standards for sourcing materials and components both within and outside the EU. Modular extraction and refining processes are needed to decrease the investment risks and chemical and water recovery should be improved within the processes.

Full takeback of EV and industrial batteries and standard diagnosis protocols to classify them for reuse/remanufacturing/repurposing or waste recycling should be implemented. The battery pack and module dismantling and cell opening processes should be automated to handle the large volumes foreseen. The recycling processes should be further improved to meet the Battery Regulation targets cost-efficiently and to decrease the carbon footprint. Processes for the valorisation of the anode materials and electrolytes should be developed.

LCSA, combining environmental, economic and social aspects and MFA using the Multi Criteria Decision Analysis approach and reflecting the UN SDGs, should be piloted at different parts of the battery value chain to address the different aspects of sustainability. The LCA/LCI data should be improved and made accessible. Especially, non-aggregated data is needed for the raw material resources and process specific data is needed for the different extraction, refining and recycling processes. Design for recycling and ex-ante LCA should become an integral part of the development of new materials, processes and battery designs.

Appendix A – KPI Tables

Table 1: Li-ion batteries Generations

Generation	1	2		3		4			5
		2a	2b	3a	3b	4a	4b	4c	
Type	Current	Current	State-of-The-Art	Advanced Lion HC	Advanced Lion HC	Solid State			Beyond Li-ion
Expected Commercialisation	Commercialised	Commercialised		2020	2025	>2025			
Cathode	NMC/NCA LFP LMO	NMC111	NMC424 NMC523	NMC622 NMC811	HE NMC Li-rich NMC HVS	NMC	NMC	HE NMC	
Anode	Modifed Gaphite $Li_4Ti_5O_{12}$	Modified Graphite	Modified Graphite	NMC910 Carbon (Graphite)+Si	Silicon/Carbon (C/Si)	Silicon/Carbon (C/Si)	Li metal		Li metal
Electrolyte	Organic LiPF6salts			(5-10%)	Organic+ Additives	Solid electrolyte -Polymer (+Additives) -Inogranic -Hybrid			
Separator	Porous Polymer Membranes								

Source: Nationale Plattform Elektromobilität, Marcel Meeus, JRC.

Table 2: Total recycling battery materials

Parameter	KPI	Operating conditions	Description	System/Pack level	Unit	2023	2028	2030
Recycling	Recycling efficiency		Recycling efficiency Li-ion batteries (by average weight of waste battery)		&	50	60	60
Recycling			Metal specific targets			Cobalt: 90	Cobalt: 95	
						Nickel: 90	Nickel: 90	Nickel: 95
						Lithium: 35	Lithium: 70	Lithium: 65-85%
						Copper: 90	Copper: 95	Copper: 95
			Other battery chemistries			Pb-acid: 65	50 for all other batteries except:	
						NiCd: 75	Pb-acid: 75	
							NiCd: 75	
Recycling	Product recovery		Number of recovered products eg Cu, Al, Li, Co, etc		-	4 to 6	6 to 10	
	Recovered elements		Number of elements recovered from battery waste back to use (Mn, graphite, REEs, electrolytes, F ...)		%			80
	Reduced direct or indirect CO2 emissions							
	Quick addressing of new chemistries		Addressing the recyclability of new battery chemistries (eg. V, Mn, Na, solid state, sulphur)					

Table 3: Take back of batteries

<table>
<tr><th>Parameter</th><th>KPI</th><th>Operating conditions</th><th>Description</th><th>System/Pack level</th><th>Unit</th><th>2023</th><th>2028</th><th>2030</th></tr>
<tr><td colspan="9">Portable batteries*</td></tr>
<tr><td>Take back</td><td>Collection</td><td></td><td></td><td></td><td>%</td><td>45</td><td>55</td><td>65</td></tr>
<tr><td colspan="9">Industrial and automotive batteries</td></tr>
<tr><td>Take back</td><td>Collection</td><td></td><td></td><td></td><td>%</td><td colspan="3">No specific Take-back target, well implementation of a reporting system</td></tr>
<tr><td colspan="9">LIB Batteries</td></tr>
<tr><td>Recycling</td><td>Overall recycling efficiency</td><td></td><td></td><td></td><td></td><td></td><td>50</td><td>60</td></tr>
<tr><td rowspan="2">Recycling</td><td rowspan="2">Material recovery targets**</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>Co, Ni, Cu: 90</td><td>Co, Ni, Cu: 95</td></tr>
<tr><td>Li: 35</td><td>Li: 70</td></tr>
</table>

** 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 from the actual form(s) of the recovered material)*