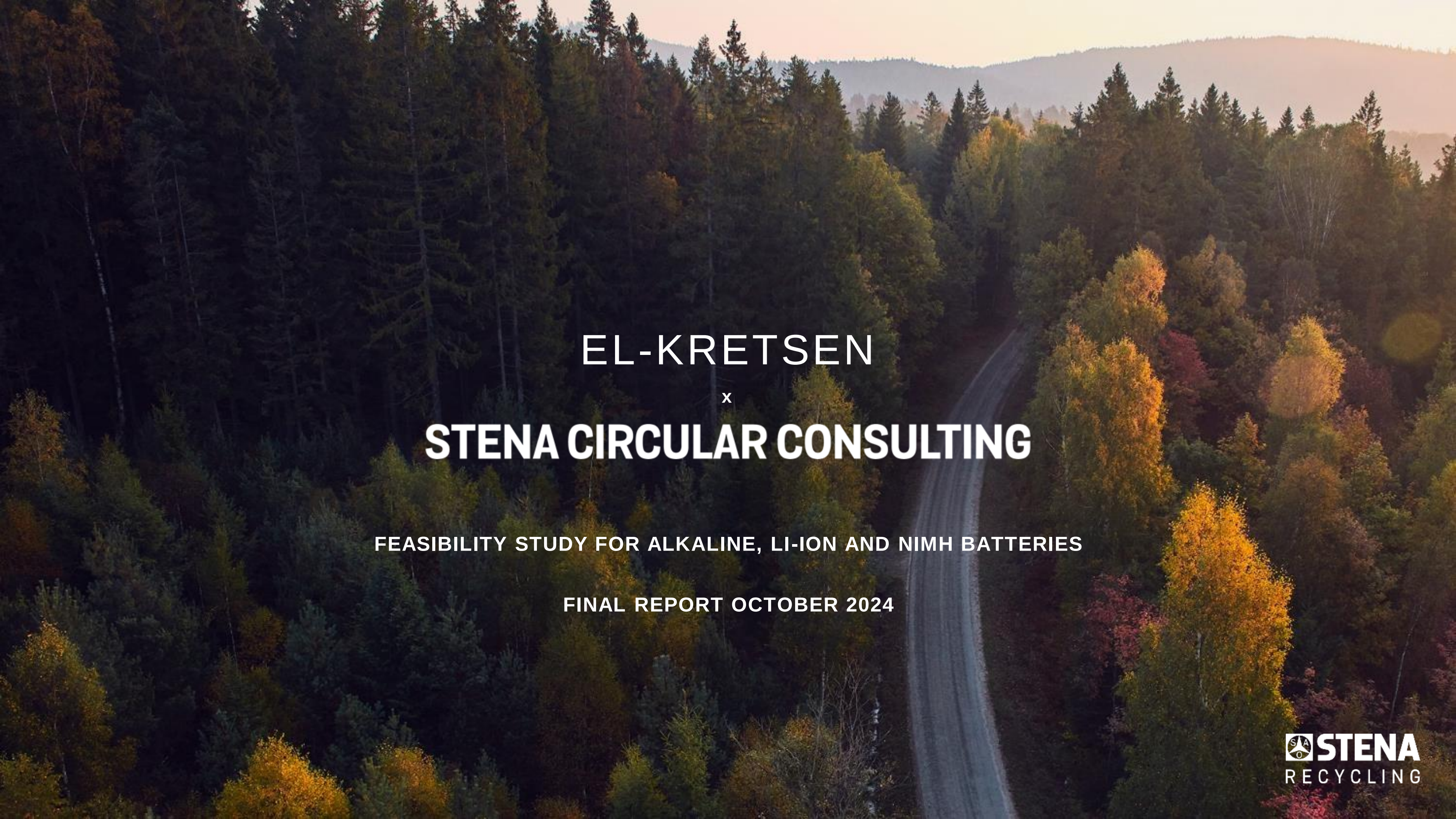

EL-KRETSEN

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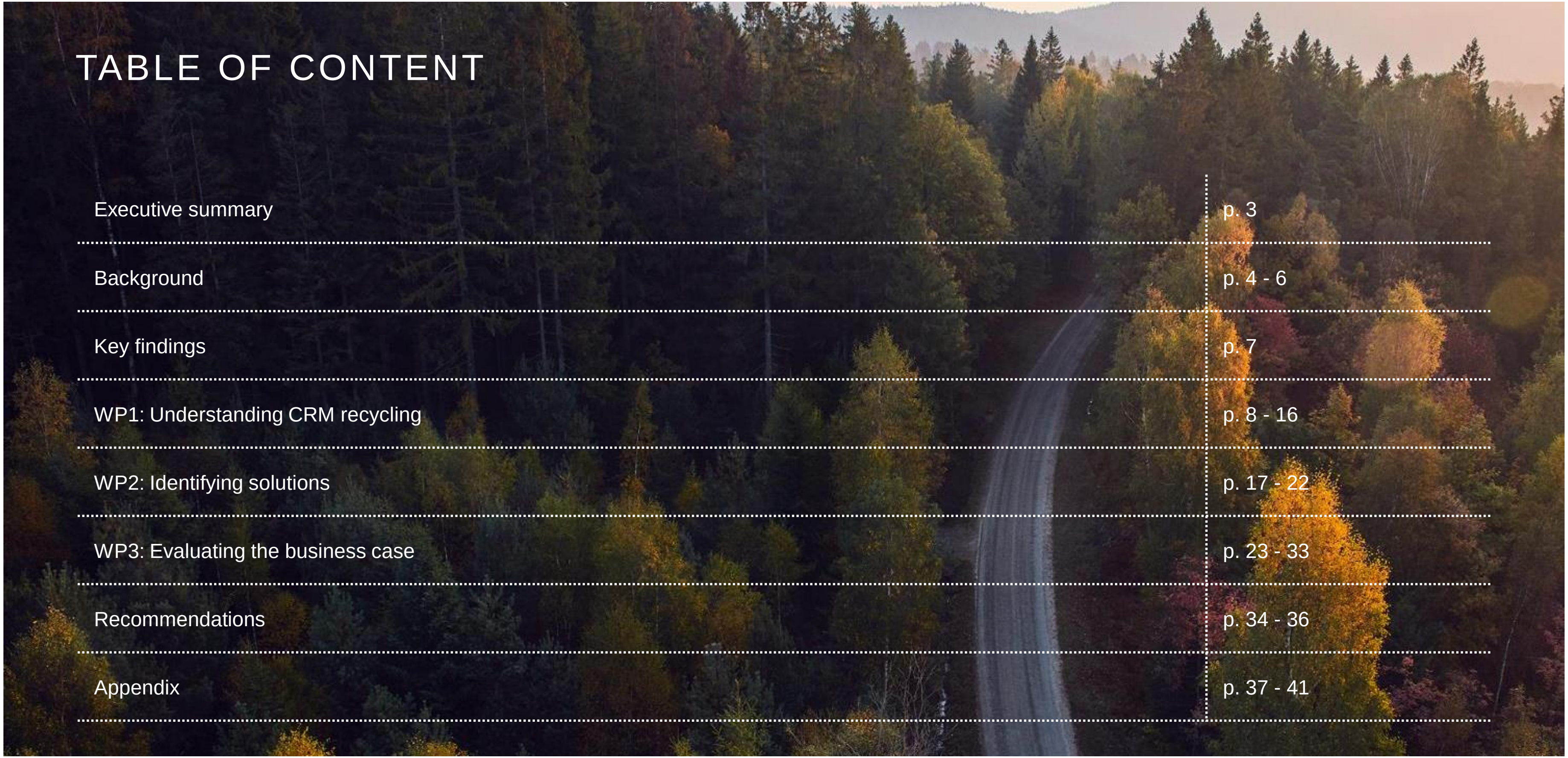
STENA CIRCULAR CONSULTING

FEASIBILITY STUDY FOR ALKALINE, LI-ION AND NIMH BATTERIES

FINAL REPORT OCTOBER 2024

STENA
RECYCLING



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EXECUTIVE SUMMARY

Background

- Many CRMs in portable batteries are lost in the current recycling system, leading to recently adopted EU legislation to mandate improvements
- In response, El-Kretsen, in collaboration with Stena Circular Consulting, has conducted a study to assess the feasibility of enhancing CRM recovery from Li-ion, alkaline, and NiMH portable batteries. It answers three questions:
    1. What are the prerequisites for closed-loop recycling of battery materials?
    2. What are the relevant solutions for sorting and discharging batteries?
    3. Is there a business case for implementation?

Key findings

- Only Li-ion batteries (LiBs), of the three battery types, show potential for future closed-loop recycling of battery materials. The conditions for closed-loop recycling can be improved by shifting from mainly pyrometallurgical treatment to hydrometallurgical treatment
- This shift necessitates improved sorting and deactivation of waste LiBs; which is technically possible through available technologies. Relevant sorting and discharging solutions include X-ray and manual sorting, followed by pyrolysis to deactivate (and discharge) waste LiBs
- Improving CRM recovery from LiBs is projected to increase the cost of recycling as the additional material value captured fails to offset the increased process cost. The value of lithium, the main material for which improvements are needed to reach the legislative targets for material recovery in 2027, only covers ~ 5-10 % of the added cost of recycling based on current market prices

Next steps

El-Kretsen is recommended to:

- Increase CRM recovery from portable LiBs, especially Li, Co, and Ni, through setting material recovery targets, co-developing sorting solutions, and establishing long-term partnerships with recyclers
- Strengthen conditions for recyclers to achieve material recovery targets by enabling economies of scale and reducing investment risks
- For alkaline batteries, require separate Mn recovery for alloy production to prevent current material losses

BACKGROUND

THE CRITICAL RAW MATERIALS PRESENT IN PORTABLE BATTERIES ARE LARGELY LOST AT END-OF-LIFE

	W% recycling	Recycled material	Recycled CRMs	Lost CRMs
 **Lithium Ion**	**~ 65%**	Aluminum, copper, iron, nickel	**Cobalt** (non-battery grade)	**Lithium, manganese, graphite**
 **Nickel-metal-hydride (NiMH)**	**~80%**	Nickel, iron, cobalt, zinc	**Cobalt** (non-battery grade)	**Manganese, REEs, graphite**
 **Alkaline**	**~ 65%**	Iron, zinc	**None**	**Manganese*, graphite**

SOURCE: El-Kretsen (Batterier | El-Kretsen); Stena Recycling (2023)

*Recycled in certain cases (non-battery grade), but not common at large

BACKGROUND

RECENTLY ADOPTED LEGISLATION IS NOW INCREASING THE PRESSURE TO RECYCLE THESE MATERIALS

New Battery Regulation: EU-wide regulation, in force from 2024

Collection Targets on Portable Batteries

- ≥ 45% (current)
- ≥ 63% by 2027
- ≥ 73% by 2030

Recycling Efficiency Targets, by 2025

Li	≥ 65%
Other	≥ 50%

Material Recycling Targets, by 2027

Li	≥ 50%
Co	≥ 90%
Ni	≥ 90%
Cu	≥ 90%

High pressure to improve collection and enhance recycling, especially for LiBs

CRM act: EU-wide regulation, in force from 2024

Definition of strategic and critical raw materials*

Li, REEs, Co, Mn, Ni, NG**

Domestic capability targets for strategic raw materials

≥ 25% of the EU's annual consumption from recycling

General national obligations for circularity

- Collection and recycling of CRM rich waste
- Recycling into secondary CRMs, i.e. high-purity materials

Increased focus on improving the recycling of critical raw materials, including to battery-grade materials

SOURCE: European Commission, COM(2023) 160 final; Regulation (EU) 2023/1542

*Non-exhaustive

**Natural graphite

BACKGROUND

EL-KRETSEN WOULD LIKE TO UNDERSTAND THE FEASIBILITY OF RECYCLING MORE CRITICAL RAW MATERIALS FROM PORTABLE BATTERIES

To help El-Kretsen understand the feasibility of achieving the recycling of critical raw materials from portable batteries, Stena Circular Consulting has conducted a pre-study to answer three key questions:

1. What are the **prerequisites** for achieving closed-loop **recycling of battery materials** through existing or alternative EoL metallurgical processes?
2. What are the relevant solutions for **sorting and discharging batteries** according to the requirements of battery manufacturers?
3. Is there a **business case** for implementing the identified solutions?

SOURCE: SCC

KEY FINDINGS

THE STUDY SHOWS THAT MORE CRMS CAN BE RECYCLED FROM PORTABLE LIBS, BUT IT WILL LEAD TO AN OVERALL COST INCREASE

1

Portable LiBs is the only battery type that shows potential for closed-loop recycling, but it requires significant improvement in pre-treatment and a shift of metal recovery process

- **Existing metallurgical treatment methods** mostly consist of pyrometallurgical treatment at high temperatures, a shift towards other methods better aimed at preserving material resources is required for closed-loop recycling
- **For NiMH and alkaline batteries,** this shift is unlikely due to the lack of legislative or financial incentives
- **For LiBs, a shift towards hydrometallurgical treatment is promising,** but mechanical recycling and improved accuracy in sorting are needed

2

Technological solutions are available to enhance sorting and deactivate waste LiBs and facilitate an enhanced recycling process

- **X-ray combined with manual sorting** is a promising solution for sorting batteries on type (li-ion, alkaline, NiMH, etc.) and internal chemistry of LiBs (NMC, LCO, LFP)
- **Pyrolysis** is the most common methodology **used to deactivate** batteries in the EU
- **Other promising options are combined deactivation and shredding** under inert or cryogenic conditions, though these technologies are less mature

3

The material value alone cannot cover the increased costs of enhanced recycling, necessitating El-Kretsen to actively support recyclers in recovering CRMs

- **The expected mass of waste LiBs is estimated to exceed the current European pre-treatment capacity,** once collection and recycling efficiency targets are tightened in line with new legislation
- **Cost associated with the enhanced recycling targets** will initially exceed the additional material value captured, indicating an increased recycling cost for El-Kretsen
- **El-Kretsen can help increase** the recovery of CRMs by setting material recovery targets, co-developing solutions for improved sorting, and fostering long-term partnerships

SOURCE: SCC

WP1: UNDERSTANDING CRM RECYCLING

PORTABLE LIBS IS THE ONLY BATTERY TYPE WITH POTENTIAL FOR CLOSED-LOOP RECYCLING IN THE MID-TERM (~ 5 YRS)

A shift to mechanical and hydrometallurgical treatment would improve the conditions for closed-loop recycling of CRMs

- **High-temperature pyrometallurgical treatment is a dominant** cost-effective method for recycling portable batteries, recovering valuable metals and minimizing hazardous materials, but leads to the loss of many CRMs
- **A shift to mechanical recycling and hydrometallurgical treatment** would improve CRM extraction, and material purity; and thereby better support closed-loop recycling of CRMs

This shift is only considered viable for portable LiBs in the mid term

- **For NiMH and alkaline batteries,** this shift is unlikely due to the lack of legislative or financial incentives, coupled with inadequate infrastructure
- **For LiBs, a shift towards hydrometallurgical treatment is promising**; driven by policy efforts to increase material recovery rates and with existing infrastructure partially supporting the transition

To facilitate this shift, portable LiBs need to be sorted with high precision and deactivated

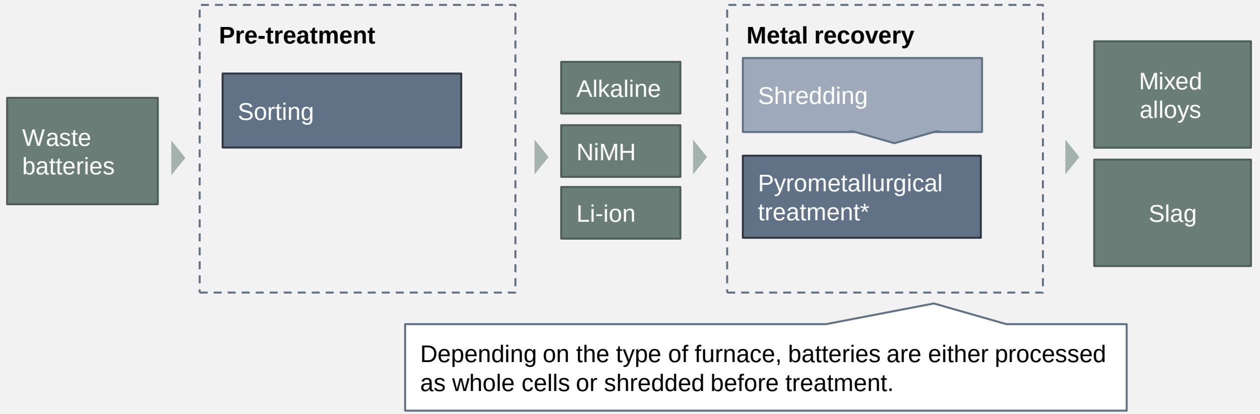
- **Precise sorting is essential** for creating the right black mass composition and removing hazardous materials (e.g., cadmium and lead), and a homogenous composition is necessary to ensure sufficient material recovery and purity
- **Deactivation is critical for safety**, as it prevents short-circuiting and thermal runaway during mechanical processing, allowing for safe shredding and further recycling

TAKEAWAY **The conditions for closed-loop recycling of CRMs in LiBs can be improved by increasing accuracy in sorting and deactivating batteries, both essential for the subsequent mechanical and hydrometallurgical processing steps.**

SOURCE: SCC

CURRENTLY, PYROMETALLURGICAL TREATMENT IS THE MAIN PROCESS FOR RECYCLING PORTABLE BATTERIES IN EUROPE

Illustration: Simplified overview of the main recycling pathway for portable batteries collected in Sweden



Waste batteries

Pre-treatment

Sorting

Alkaline

NiMH

Li-ion

Metal recovery

Shredding

Pyrometallurgical treatment*

Mixed alloys

Slag

Depending on the type of furnace, batteries are either processed as whole cells or shredded before treatment.

🟩 Input/Output 🟦 Process step ▨ Optional process step (not applicable for LiBs)

*Pyrometallurgical treatment refers to all processes for recovery or refinement of metals at elevated temperatures. Typically, the batteries are processed in a shaft or electric furnace.

- **The current battery recycling system is designed to minimize recirculation of hazardous heavy metals (lead, mercury, cadmium)**
- **Pyrometallurgical treatment is a cost-effective method to achieve this objective**
- **The method enables high recycling efficiencies for valuable metals (e.g., Ni, Co, Zn, Fe), exceeding the previous legal requirements of 50 wt% for Li-ion, NiMH, and alkaline batteries**

SOURCE: Toro et al. (2023); Takacova et al. (2023); Tian et al. (2023); Windisch-Kern et al. (2022); Petzold (2024); Expert interviews

A DRAWBACK OF PYROMETALLURGY IS THE LOSS OF MANY CRITICAL RAW MATERIALS

Typical CRM recovery through pyrometallurgical processing

Li-ion*	**NiMH**	**Alkaline**
Recycled ✓ Cobalt (alloying element) (3-15w%)	**Recycled** ✓ Cobalt (alloying element) (4.2w%)	**Recycled** None
Lost or downcycled X Manganese (0 – 3w%) X Lithium (2 w%) X Natural graphite (25 w%)	**Lost or downcycled** X Rare earth elements (REEs) (3.8 w%) X Manganese (2.3 w%)	**Lost or downcycled** – Manganese (38 w%) X Natural graphite (4w%)

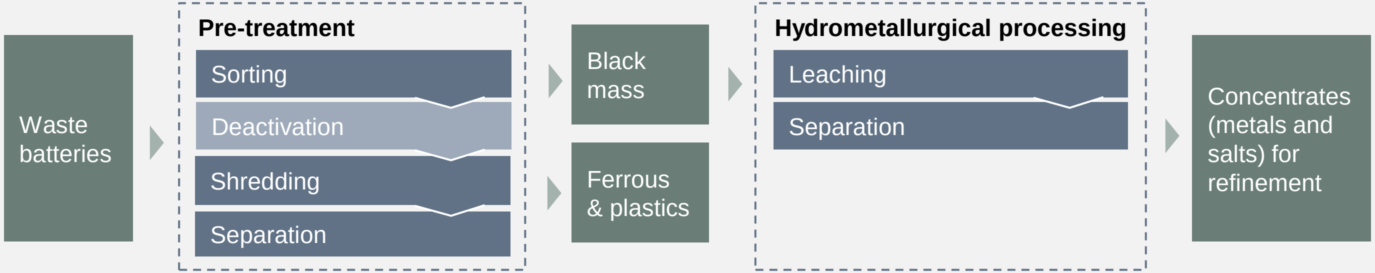
- **Cobalt is the main critical raw material recovered, with a recovery rate of ~ 80 %**
- **Manganese, lithium, and REEs end up in the slag, which is typically used as filler material in construction**
- **Some processors in the EU recover manganese as an alloying element, but due to its low value, this comes with higher processing costs**
- **While it’s technically possible to recover some of the lithium from the slag and filter dust, and some REEs from the slag, large-scale recycling capacity remains limited**

SOURCE: Toro et al. (2023); Takacova et al. (2023); Tian et al. (2023); Windisch-Kern et al. (2022): Salehi et al. (2023); Petzold et al. (2024); European Commission, SWD(2020) 335 final; Systemiq (2024); expert interviews

*CRM content depends on the specific chemistry of the LiB battery

A SHIFT TO MECHANICAL AND HYDROMETALLURGICAL TREATMENT WOULD IMPROVE THE CONDITIONS FOR CLOSED-LOOP RECYCLING OF CRMS

Illustration: Generic recycling pathway incl. hydrometallurgical processing (simplified)



Waste batteries

Pre-treatment

Sorting

Deactivation

Shredding

Separation

Black mass

Ferrous & plastics

Hydrometallurgical processing

Leaching

Separation

Concentrates (metals and salts) for refinement

■ Input/Output ■ Process step ■ Additional process step for LiBs

Reported leaching extraction efficiency (lab-scale)

Li-ion	**NiMH**	**Alkaline**
Mn recovery: ≤ 98 %	REEs recovery: ~ 99 %	Mn recovery: ≤ 98 % Mn recovery
Li recovery: ~ 94 – 99 %	Co recovery: ≥ 98 % Co	Graphite recovery: 0 %*
Co recovery: ~ 94 – 99 %	Mn recovery: ND	
Graphite: 0 %*		

- **Hydrometallurgical processing enables higher metal extraction and improved material purity; but to further improve ease of separation, the process is sometimes paired with lower temperature (100 – 500 °c) pyrometallurgical processes**
- **The efficiency of hydrometallurgical processes is influenced by various factors, with leaching extraction efficiency being particularly critical**
- **However, the overall recycling rate depends on the combined effectiveness of the entire recycling process**

Disclaimer: The reported leaching efficiency reflects only the specific process step, not the total material recovery rate. Given the greater control over input materials at the lab scale, extraction rates are likely lower at the industrial scale.

SOURCE: Toro et al. (2023; de Oliveira Demarco et al. (2019); Liu et al. (2019); Rabah et al. (2008); Accurec (2021); Velázquez-Martínez, 2019; Expert interviews

*Graphite is typically lost during thermal pre-treatment or filtered off. Recycling options are tested on a lab scale

HOWEVER, CLOSED-LOOP RECYCLING OF CRMS IN ALKALINE BATTERIES IS UNLIKELY DUE TO A LACK OF POLICY AND INDUSTRIALIZED PROCESSES

	Portable alkaline batteries
Barriers	▪ **Insufficient policy:** New legislation does not push recycling rates higher than existing standards. A potential phase-out of single-use batteries of general use (to be assessed by 2030) may significantly reduce future waste volumes. ▪ **Lack of industrialized processes:** There are no industrialized processes to recycle alkaline batteries into battery-grade materials. Lab-scale and theoretical examples show that it should be possible to recycle the materials to higher purity, however, hazardous substances (e.g., Hg, Cd, Pb) are still present in the final product to a certain extent.
Enabling conditions	▪ **Risk for supply deficit:** Supply deficits driven by the concentration of refinement capacity to China could lead to the development of processing capacity in Europe, however, the low prices (1,745 $/tonne of electrolytic manganese* compared to e.g., 10,650 $/tonne of lithium carbonate*) make market-driven investments less likely. ▪ **Potentially upcoming policies:** Battery-grade manganese and natural graphite are listed as strategic raw materials and thereby in scope for the requirements placed on EU countries to increase circulation of CRMs, but there are currently no requirements or incentives in place.
Alternative pathway	▪ **Short term:** El-Kretsen is recommended to discontinue the investigation into closed-loop recycling of alkaline batteries and instead strive towards increased recycling of manganese as an alloying element to avoid significant material losses. Recycling solutions are available today. ▪ **Long-term:** El-Kretsen should look for market developments connected to manganese, mainly concerning large legislative changes in connection to the CRM act or other events that could significantly change the demand and supply balance for battery-grade manganese.

SOURCE: Regulation (EU) 2023/1542; Tran et al. (2020); Gasper et al. (2013); S&P Global (2023); 5. Metal.com (2024); Expert interviews
*Battery-grade manganese electrolyte (99.7%) and lithium carbonate (99.5%) purity

SIMILARLY, CLOSED-LOOP RECYCLING OF CRMS IN NIMH BATTERIES IS UNLIKELY TO BECOME VIABLE DUE TO WEAK INCENTIVES

	Portable NiMH batteries
Barriers	▪ **Insufficient policy:** New legislation does not push recycling rates higher than existing standards (50 % recycling by 2027). ▪ **Lack of processing capacity:** The technology to recover mixed REEs from slag exists but processes to separate individual REEs on an industrial scale are still under development in Europe, following the prior loss of processing capacity to China. Compared to other metals, the separation process of REEs is complex due to their similar chemical properties. ▪ **Weak financial incentives**: Nickel is the main value driver of NiMH battery recycling. In an investigation of the profitability of recycling Ni, Co, and REEs from NiMH batteries, Ni was responsible for 79 % of the estimated revenue and had a higher value per unit than REEs.
Enabling conditions	▪ **Increasing value of REEs:** The demand for REEs is projected to grow by 125% from 2023 to 2035, with potential supply shortages boosting recycling incentives. However, technological changes (e.g., reduced use of REEs in electric motors) and geopolitical tensions could lead to price fluctuations and deter investments. ▪ **Potentially upcoming policies**. Several materials in NiMH batteries are listed as strategic (e.g., Ni, Mn, REEs, and Co) and in scope for the mandate placed on EU countries to increase the circulation of CRMs, but there are currently no requirements or incentives in place.
Alternative pathway	▪ **Short term:** El-Kretsen is recommended to discontinue the investigation into closed-loop recycling of NiMH batteries. The processes for extracting and separating REEs in Europe are immature and the low Mn content (~2%) along with the existing material recycling of cobalt does not justify efforts to target these materials alone. Moreover, NiMH sales volumes are declining (5%/y) and material recovery rates are well above the set targets. ▪ **Long term:** El-Kretsen is recommended to stay informed about advancements in the extraction of REEs from NiMH batteries, particularly due to their high concentration (~10wt%) and announcements of successful REE extraction from slag (e.g., by Umicore) and development of separation capacity of REEs (e.g. Solvay). If processes continue to mature and member-state efforts to enhance the circularity of critical raw materials (CRMs) under the CRM Act focus on portable batteries, future initiatives to recycle REEs may become relevant.

SOURCES: Regulation (EU) 2023/1542; Salehi et al. (2023); Toro et al. (2023); FDI Intelligence (2024); Otron et al,. (2024); McKinsey (2024); Expert interviews

WHEREAS CLOSED-LOOP RECYCLING OF CRMS IN LIBS SHOWS POTENTIAL THROUGH POLICY PRESSURE AND EXISTING INFRASTRUCTURE

Portable LiBs

Barriers

- **Risk for recyclers:** The inconsistent quality of the waste stream and the presence of contaminants (e.g., mercury, cadmium, led) pose risks for recyclers as failure to meet the required quality of the black mass can lead to penalties.
- **Heterogeneous composition of waste batteries:** Complicates hydrometallurgical processing which is highly selective. Variations in battery materials require process adjustments to ensure efficient material recovery, which is impractical and costly.
- **Strict purity requirements:** With no producers of rechargeable portable batteries in the EU, recycled materials must meet the standards for other batteries (e.g., EV) to enable a closed-loop system. Battery-grade materials require a purity of approximately 99.5% to 99.999%, resulting in high refinement costs.
- **Low material value:** The scale-up of Li recycling has been hindered by unfavorable economics, primarily due to its lower material value compared to e.g., Co, coupled with difficulties in recycling the material through conventional methods.

Enabling conditions

- **Policy pressure:** Increasing targets for collection, recycling efficiency, and material recovery necessitates significant improvements in the recycling process – especially for Li recovery.
- **Existing infrastructure:** The infrastructure for mechanical processing and hydrometallurgical treatment is available at an industrial scale. Capacity for recovering Li on top of Co and Ni (e.g., Accurec) and refining battery-grade Li (e.g., AMG) are underway in Europe
- **Global overcapacity of industrial and EV battery recycling infrastructure.** High competition for volume is projected to last until mid-2030. Portable waste batteries may constitute an alternative waste stream if barriers are addressed.

Targets in the New Batteries Regulation

	2025	2027	2030
Collection		63%	73%
Recycling efficiency	65%		70%
Cobalt MR*		90%	95%
Lithium MR*		50%	80%
Nickel MR*		90%	95%

Pathway

- **Identify effective solutions for sorting batteries** by type (e.g., Li-ion) and chemistry (e.g., LCO, NMC).
- **Identify processes for safely deactivating** portable LiBs to facilitate mechanical pre-treatment.

SOURCE: Regulation (EU) 2023/1542; IEA (2024); Eurometaux (2022); Linneen (2018); Choe et al. (2023); Expert interviews

*Material recovery

TO ENHANCE THE RECYCLING OF LIBS, THEY MUST UNDERGO PRE-TREATMENT INCLUDING DEACTIVATION AND SORTING

To prepare for closed-loop recycling, the LiBs must be:

- **Mechanically shredded** to break down the components
- **Refined into a black mass** with stable material content and low presence of contaminants
    - Material content: Ni ≥~10%, Co ≥ ~5%, Li ≥~3%
    - Low presence of contaminants: Al ~< 2.5 %, Cu, ~< 2.5 %, organic content ~< 0.8 %

Which in turn necessitates pre-treatment:

- **Deactivation** to facilitate safe mechanical treatment
- **Sorting on type and** chemistry to fulfill material content specifications
    - Li-ion sorted based on high, low, and no cobalt content
    - No cadmium batteries present

Sorting ensures the right composition

- The black mass composition determines its value and treatment routes (e.g., hydro- or pyrometallurgical treatment)
- Stable material content results in better material recovery in a hydrometallurgical process
- Hazardous substances such as cadmium and lead should not be present in the waste battery stream

Deactivation ensures safe processing

- LiBs, due to their high energy density, can short-circuit and trigger thermal runaway if physically damaged
- Deactivation serves the purpose of rendering the batteries safe for mechanical processing such as shredding

Disclaimer: The technical specifications for the black mass should be viewed as an indication of the requirements set for hydro-grade quality. However, the specific requirements will depend on, and likely vary between, individual processors.

SOURCE: Accurec, presentation at ICBR 2024; SCC analysis

WP2: IDENTIFYING SOLUTIONS

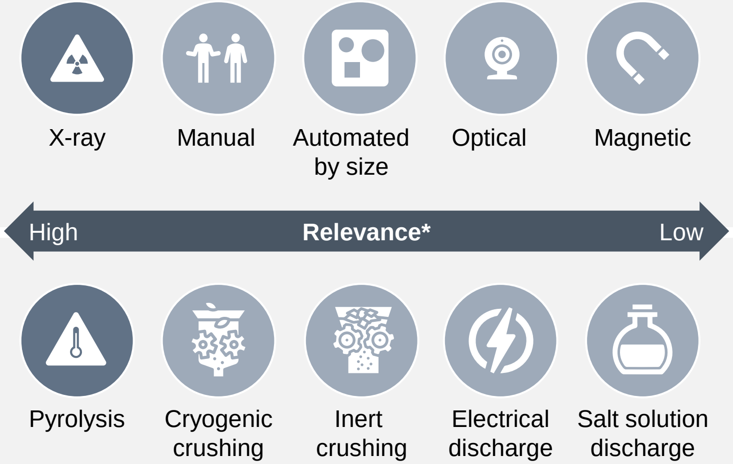
THERE ARE AVAILABLE SOLUTIONS THAT FULFILL THE REQUIREMENTS OF PRE-TREATMENT OF PORTABLE LIBS

A combination of x-ray and manual sorting is the only option which achieves sorting on type and chemistry

- X-ray scanners identify and sort batteries based on material properties, allowing differentiation based on chemistry (e.g., low cobalt, high cobalt)
- Due to its limitations in handling various sizes and shapes of batteries, combination with manual sorting is likely necessary

For deactivation, pyrolysis is currently the most likely method, but emerging technologies may become increasingly relevant

- Pyrolysis is a widely applied method for deactivation with high scalability and safety, with a lower degree of complexity than other methods
- Emerging technologies, such as shredding in inert or cryogenic environments, eliminate the need for deactivation; however, uncertainties remain regarding their operational complexity



X-ray | Manual | Automated by size | Optical | Magnetic

High — **Relevance*** — Low

Pyrolysis | Cryogenic crushing | Inert crushing | Electrical discharge | Salt solution discharge

TAKEAWAY **It is technically possible to improve pre-treatment with available solutions. El-Kretsen is recommended to set outcome-oriented rather than technology-based requirements on recyclers to encourage further development of solutions.**

SOURCE: SCC

*Based on weighted assessment of efficacy and complexity

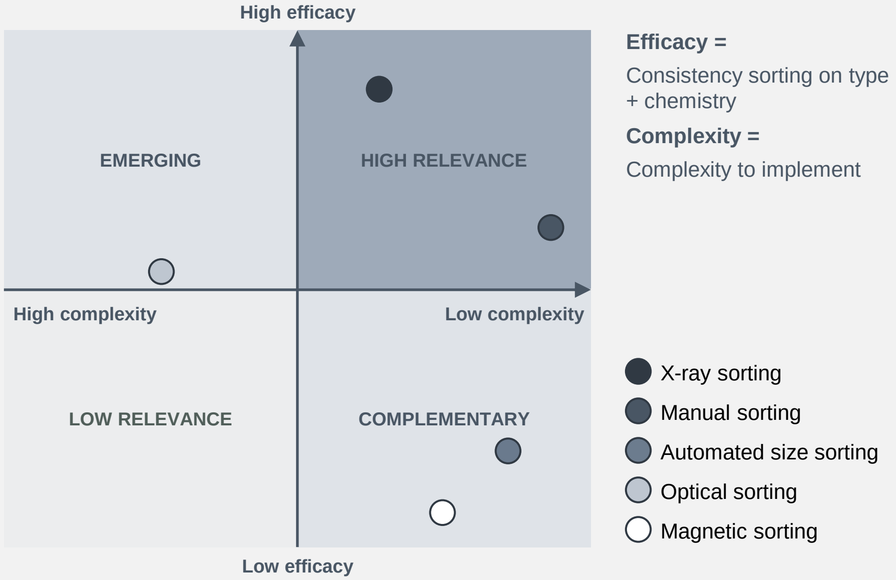
THERE IS NO SINGLE SORTING TECHNOLOGY THAT CONSISTENTLY MEETS ALL THE CRITERIA; BUT X-RAY DEMONSTRATES HIGH POTENTIAL

✓ Fulfils criteria – Partly fulfils criteria ✗ Does not fulfil criteria

	Sorting on type	Sorting on chemistry	Complexity to implement
Manual sorting – Operators are positioned along a conveyor belt, manually sorting batteries by type (e.g., Li-ion, alkaline, NiMH, and NiCd)	✓ Sorts based on type consistently	– Need clear labelling to sort on chemistry	✓ Easily implementable, no advanced equipment
Automated size sorting – Tables with size slots are used to separate large from small batteries	✗ Only capable to differentiate between sizes	✗ Incapable to differentiate chemistries	✓ Easily implementable, requires other solutions as well
X-ray sorting – X-ray scanners are utilized to identify and sort batteries based on physical properties (e.g., density, shape, and size)	✓ Sorts based on type very consistently	✓ Highly capable to differentiate chemistries	– Difficult to implement, no complete solutions for all shapes and sizes
Optical sorting – Cameras and sensors are utilized to identify shapes, labels, and color variations for battery classification	– Susceptible to incorrect classification due to unclear labelling	– Incapable to differentiate chemistries unless clearly labelled	✗ Difficult to implement because of extensive data model training
Magnetic sorting – Magnets are utilized to remove batteries with iron casing	✗ Incapable of handling all types	✗ Incapable of identifying chemistry	✓ Easily implementable

SOURCE: Tomra (2021); LINEV Systems (2024); Petzold (2024); Expert interviews

IN THE SHORT TERM, A COMBINATION OF X-RAY AND MANUAL SORTING IS LIKELY REQUIRED TO ENSURE ADEQUATE ACCURACY AND CONSISTENCY



Efficacy =

Consistency sorting on type + chemistry

Complexity =

Complexity to implement

High relevance

- **X-ray sorting** stands out as the most technically capable solution, consistently differentiating between battery types and high- and low-grade Ni/Co batteries
- **Manual sorting** can identify battery types through their labels and, to some extent, determine their contents based on the operator's experience
- Combining **X-ray** with **manual sorting** is likely necessary to guarantee proper sorting and quality of LiBs

Complementary

- While **magnetic and automated size** sorting cannot effectively differentiate batteries based on type and chemistry, size sorting plays a crucial role in the initial rough sorting process, helping to reduce the volume of batteries for subsequent sorting steps

Emerging

- **Optical sorting** is limited to categorizing batteries by labels and visible traits, making it less effective as a standalone solution, while being complex and costly to implement

Disclaimer: The comparison of alternatives is relative and should not be regarded as an absolute assessment of the criteria.

SOURCE: SCC

THERE ARE SEVERAL METHODS FOR DEACTIVATION; PYROLYSIS AND CRUSHING IN CRYOGENIC OR INERT CONDITIONS SHOW MOST POTENTIAL

✓ Fulfils criteria

– Partly fulfils criteria (some risks)

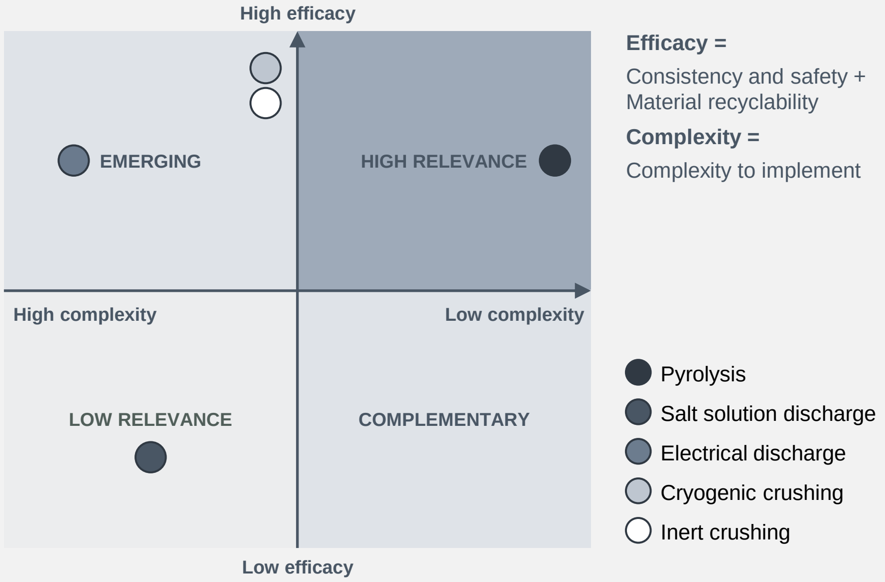
✗ Does not fulfil criteria (significant risks)

	Consistency and safety	Material recyclability	Complexity to implement
Pyrolysis – Batteries are subjected to high temperature (~ 250 - 600ºC) and organic materials are decomposed/evaporated	✓ High safety, consistent result, large handling capacity	– Some losses of plastics and binders. Facilitates Li recovery	✓ Scalable. Simple operation once installed. Need of flue gas treatment
Salt solution discharge*– Batteries are immersed in a conductive solution resulting in controlled short-circuiting	– Only applicable to non-capsulated batteries. Variability in time and concentration to fully discharge the batteries[2]	✗ Risk of corrosion and leakage of battery materials (e.g. electrolyte, Li) to the wastewater	✗ Difficult to scale due to process variability. Need of wastewater treatment
Electrical discharge with resistance – Batteries are discharged by connecting them to a resistive load, consuming the residual energy in a controlled manner	– Connections are made manually, posing safety risk to personnel. Overall consistent result	✓ None to minor impact on recyclability (deep discharging can lead to Cu precipitation)	✗ Variety in battery design makes automation challenging
Crushing in cryogenic conditions – Crushing at cool temperature (~ -185ºC) to freeze the electrolyte and render lithium inert, removing the need for discharging	✓ High safety, consistent result, large handling capacity	✓ No reported impact on material recovery. Can improve grinding as materials become brittle	– Scalable. Uncertainties regarding complexity of operations
Crushing in inert conditions – Crushing in the presence of inert gases (e.g., CO2) or vacuum, to suppress reactivity, removing the need for discharging	✓ High safety, consistent result, large handling capacity	✓ No reported impact on material recovery	– Scalable. Uncertainties regarding complexity of operations

SOURCE: Naval Research Laboratory (2023); Yu et al. (2021) Torabian et al. (2022); Dobó et al., (2023); Tian et al., (2023); Windisch-Kern et al., (2022); Expert interviews

*Acid or alkaline solutions can also be used as discharge media

SHORT-TERM, PYROLYSIS IS THE MOST LIKELY SOLUTION TO BE USED FOR DEACTIVATION DUE TO ITS LOWER COMPLEXITY



Efficacy =

Consistency and safety + Material recyclability

Complexity =

Complexity to implement

High relevance

- **Pyrolysis** is an established process for deactivating and preparing waste batteries for further treatment where several European companies, including Accurec, Redux, and SNAM, already employ this or similar thermal treatment steps

Emerging

- **Direct crushing** in **cryogenic** or **inert** conditions facilitates consistent and safe processing, however, the **implementation and operational complexities are uncertain** as they are less commonly deployed
- **Electrical discharge** is difficult to automate across the portable battery waste flow, however, it becomes a more attractive solution when dealing with a large mass of waste batteries of the same size and form

Low relevance

- **Salt solution discharge** is commonly used at the lab scale, but it has significant drawbacks in terms of efficacy and complexity at the industrial scale

Disclaimer: The comparison of alternatives is relative and not an absolute assessment of the criteria.

SOURCE: SCC

WP3: EVALUATING THE BUSINESS CASE

CRM RECOVERY FROM LIBS MUST IMPROVE TO MEET LEGISLATIVE TARGETS, BUT THE MATERIAL VALUE IS UNLIKELY TO COVER THE COSTS

Pre-treatment capacity and material recovery rates need to be improved for portable LiBs

- European capacity to pre-treat and safely shred portable batteries in preparation for hydrometallurgical treatment is low and limited to a few actors, with a dedicated pre-treatment capacity for portable batteries at 11 kt
- Upcoming legislative targets suggest collection and pre-treatment capacity needs to be expanded
- New pre-treatment and recycling capacity must fulfill higher recycling efficiency targets than current standards

Improving CRM recycling conditions will increase costs unlikely to be offset by the captured material value

- Improving the recovery rate of CRMs will add costs across the recycling value chain compared to current processes, but it is essential for fulfilling the 2027 and 2030 material recovery targets
- The main improvements needed are in lithium recovery, but its material value is unlikely to cover the cost increase
- However, recycling costs may decrease over time as economies of scale and system maturity are achieved

El-Kretsen is recommended to start preparing for the shift needed to improve material recovery of CRMs

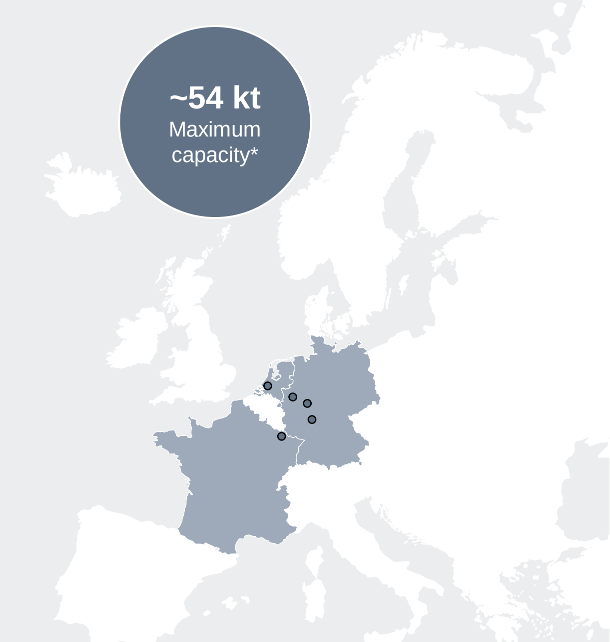
- There are several options for how a primary recycler may structure its value chain to fulfil material recovery targets, each possible option has unique risks to be considered by El-Kretsen
- El-Kretsen is recommended to use the 2025 procurement process to prepare for improved recovery of CRMs
- Preparation includes gathering data on existing material recovery, promote dedication toward improvement, and improving conditions for sorting

TAKEAWAY

Given the current lack of financial incentives for enhancing material recovery, El-Kretsen needs to play an active role in improving the recycling of CRMs from LiBs and be prepared for increased recycling cost.

SOURCE: SCC

THE CAPACITY TO PRE-TREAT AND SAFELY SHRED PORTABLE BATTERIES IN PREPARATION FOR HYDROMETALLURGICAL TREATMENT IS LIMITED



~54 kt
Maximum capacity*

European capacity to pre-treat and safely shred portable batteries in preparation for hydrometallurgical treatment is low and limited to a few actors

Overview of facilities capable of processing portable LiBs

PRE-TREATMENT AND MECHANICAL TREATMENT

- **Redux (Germany) –** Deactivation, shredding, and separation into black mass
    - Capacity ~15 kt, handling energy storage batteries and portable LiBs
- **Euro Dieuze Industrie (France) –** Deactivation, shredding in water, and separation into black mass
    - Capacity ~7 kt, handling portable alkaline, NiCd, and LiBs

PRE-TREATMENT, MECHANICAL, AND HYDROMETALLURGICAL PROCESSING

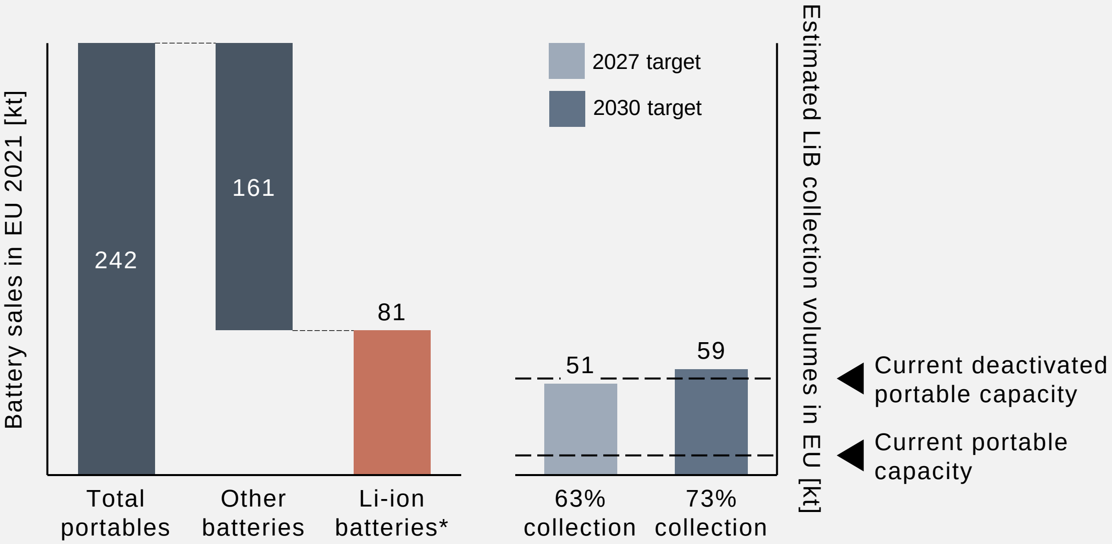
- **Accurec (Germany)** – Deactivation, shredding, and separation into salts (Li, Co, Ni)
    - Capacity ~4 kt, handling both NiCd, NiMH, and LiBs
- **Primobius (Germany) –** Deactivation**, shredding, and separation into salts (Li, Co, Ni)
    - Capacity ~18 kt, handling portable LiBs and EV batteries
- **SK TES (Netherlands)*** –** Inert crushing, separation, and separation into salts (Li, Co, Ni)
    - Capacity ~10 kt, handling mainly EV batteries

Disclaimer: The information presented is based on available information. Due to confidentiality, exact capacity and material recovery rates may vary.

SOURCE: SK TES (2024); Accurec (2024); Redux (2024); Euro Dieuze Industrie (2013); Primobius (2024); Fraunhofer ISI (2024); Expert interviews *Theoretical capacity to shred pre-treated batteries **Not stated if deactivation for portable batteries. ***Not clearly stated portable batteries are handled and/or capacity to handle portable batteries

TO KEEP UP WITH FUTURE LEGISLATIVE TARGETS, THE EU CAPACITY FOR PRE-TREATMENT OF PORTABLE LIBS NEEDS TO INCREASE...

Graph: Estimated battery sales and collection of LiBs to fulfill target for portables, EU



If member states overcome current challenges in collecting sufficient volumes of LiBs, as required by regulation, waste LiB volumes are likely to exceed (hydrometallurgical) portable treatment capacity.

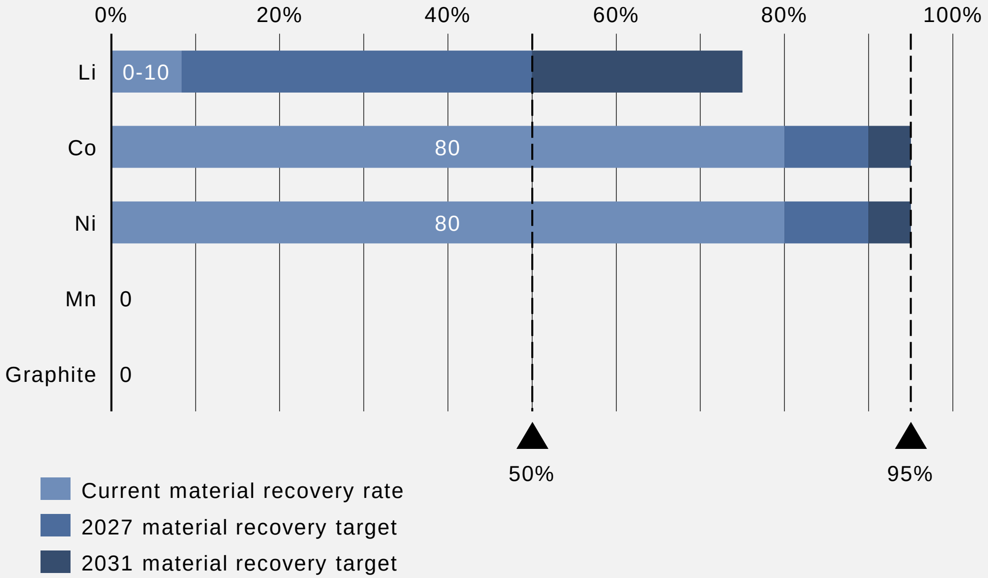
- European maximum pre-treatment capacity is currently at 54 kt, however, the largest actors (Redux, Primobius, and TES) capacity will be divided between EV, ESS, and portable batteries
- Capacity dedicated solely to portable batteries is currently at 11 kt, meaning the availability of pre-treatment for portable batteries is more uncertain once collection starts increasing

SOURCE: Regulation (EU) 2023/1542; Eurostat (2024)

*Li-ion share of sales assumed to be the same in the EU as in Sweden

… AT THE SAME TIME, MATERIAL RECOVERY NEEDS TO BE IMPROVED, ESPECIALLY FOR LITHIUM

Graph: Material recovery rates and targets for CRMs in portable LiBs, EU



The primary challenge for the recycling system will be to bridge the gap for lithium recovery as current processes are significantly below target levels, reflecting a market still in its infancy.

- Lithium recycling ranges from 0–10% and rates closer to 0% for portable batteries, although some recyclers claim to achieve 50% recovery, recovery has been limited by high processing costs and low material value
- Cobalt and nickel are recycled at scale from portable batteries, but improvements are needed to meet future targets, moreover, it is unlikely that 95 % recovery can be achieved through high-temperature pyrometallurgical processing (>1000°c)
- Manganese and graphite recovery as separate fractions is unlikely due to lack of policy pressure

SOURCE: European Commission, Impact Assessment Report of the Battery Directive (2020); Regulation (EU) 2023/1542; SCC

ENHANCED MATERIAL RECOVERY IS LIKELY TO ADD COSTS ACROSS THE RECYCLING VALUE CHAIN COMPARED TO THE CURRENT MAIN PROCESS

	A Collection	B Pre-treatment	C Mechanical recycling	D Metal recovery	E Refinement
Current main process	Logistics*	Sorting, 98 % accuracy		High temperature pyrometallurgical treatment	
Enhanced material recovery process	Logistics*	Sorting >98 % accuracy ▨ Deactivation	Shredding Separation	▨ Low-temperature pyrometallurgical treatment Hydrometallurgical treatment	Extraction / precipitation Crystallization Separation Drying
Cost impact	**Low**	**Medium**	**High**	**Uncertain**	**Out of Scope**
Reason for cost impact	• Cost changes independent of the recycling process	• Higher precision sorting • Deactivation capacity	• Mechanical recycling, additional process step	• Generally higher CAPEX but lower OPEX compared to baseline • Overall cost will depend on several factors incl. composition and purity of input material • Cost is likely to increase with higher Li recovery, as it’s a complex element to separate	

□ Mandatory process step ▨ Potential process step (dependent on process design)

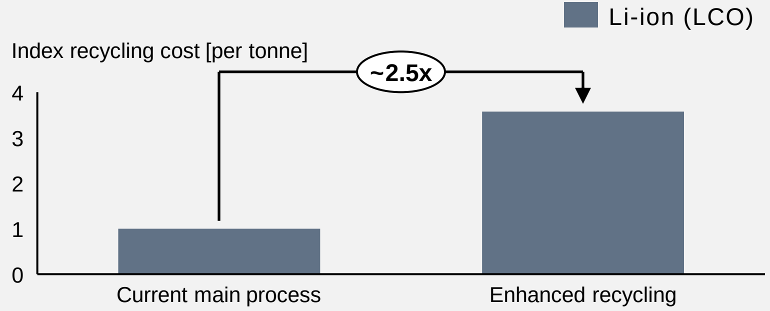
SOURCE: Expert interviews; SCC

*Includes awareness raising campaigns, collection points, and transport – assumed not to be impacted by the choice of recycling process.

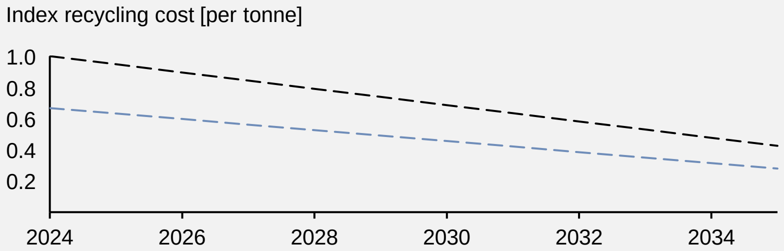
STENA RECYCLING

FOR HIGH-COBALT LIBS, COST ESTIMATES INDICATE A POTENTIAL INCREASE OF 2.5 TIMES THE CURRENT LEVELS

Graph: Recycling cost for portable LiBs (LCO)



Graph: Projected recycling cost development for LiBs



The cost of recycling and metal recovery is expected to rise if lithium is to be separated and the overall material recovery enhanced.

- LiBs are generally more expensive to recycle than other battery types – but chemistry types with high cobalt content (LCO) have historically been less costly to recycle due to efficient, industrialized processes for cobalt recovery
- However, the cost of recycling LCO batteries is expected to rise significantly if material recovery is further enhanced; recycling LCO batteries with 50 % Li recovery is estimated to increase the cost by 2.5x compared to the assumed current process with 0 % Li recovery
- In the long term, the recycling cost is expected to decline. However, the overall cost for LiB recycling and recovery may not necessarily decrease, as it depends on several factors including
    - Raw material prices
    - Cost of additional processing steps (e.g., sorting) and logistics
    - Quality of the input material
    - Economies of scale

SOURCE: El-Kretsen; European Commission, Impact Assessment Report of the Battery Directive (2020); Expert interviews; SCC

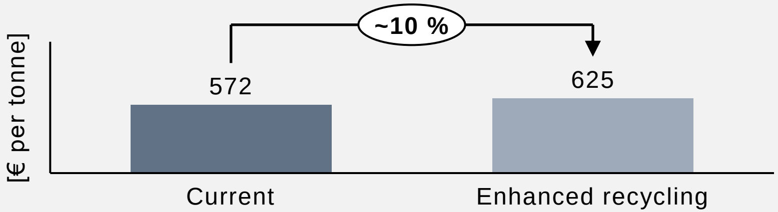
WP3: EVALUATING THE BUSINESS CASE

FOR THE OVERALL WASTE STREAM, WITH THE CURRENT BATTERY TYPE DISTRIBUTION, THIS TRANSLATES TO A COST INCREASE OF ROUGHLY 10%

The total average recycling cost for portable batteries would increase slightly if all LiBs were processed into black mass

- The relatively low share of LiBs (~6% in 2022) in the total portable battery waste stream means that enhancing the recycling process does not significantly impact the average cost

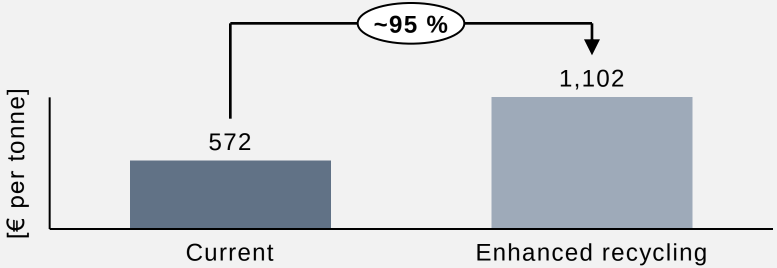
Graph: Forecasted recycling cost development with a 6% share of LiBs* (40% NMC, 60% LCO) and enhanced recycling of LCO batteries



However, as the share of LiBs in the total portable battery waste stream increases, the cost increase could become significant

- The new collection targets outlined in the battery regulation would result in a significantly higher share of LiBs in the battery waste stream, ~34% at the beginning of 2028
- This could increase the average cost of recycling portable batteries by approximately 95% compared to current levels

Graph: Forecasted recycling cost development with 34% share of LiBs* (40% NMC, 60% LCO) and enhanced recycling of LCO batteries



Disclaimer: The data does not consider any changes in cost for recycling NMC LiBs or other portable batteries, as NMC batteries typically undergo some of the process steps included in the enhanced process today (e.g., shredding). However, treatment routes and material recovery rates vary between individual recyclers.

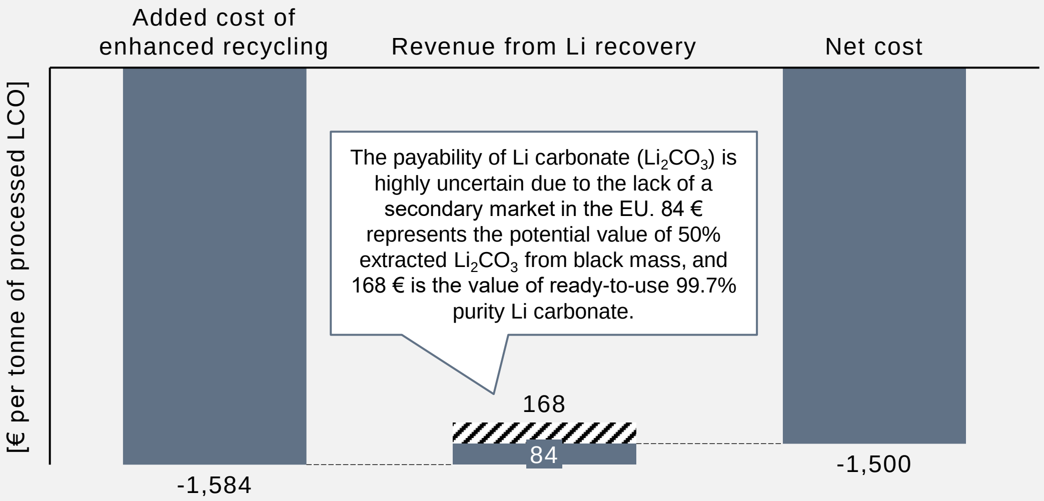
SOURCE: European Commission, Impact Assessment Report of the Battery Directive (2020); El-Kretsen; SCC

*Varying data on the share of each battery chemistry (NMC and LCO)

THE ADDITIONAL MATERIAL VALUE CAPTURED IS UNLIKELY TO COVER THE RISE IN COSTS, UNDERLINING THE NEED FOR INTERVENTION

An enhanced recycling process would mainly improve lithium recovery, but its material value alone is not enough to cover the increased processing cost

Graph: Estimated enhanced recycling costs and revenue based on current costs and material prices



The payability of Li carbonate (Li_2CO_3) is highly uncertain due to the lack of a secondary market in the EU. 84 € represents the potential value of 50% extracted Li_2CO_3 from black mass, and 168 € is the value of ready-to-use 99.7% purity Li carbonate.

Numerous variables make it challenging to predict the future cost of portable battery recycling accurately

Raw material prices

- Material prices have seen a significant downturn lately with Co down 75% and Li 90% since 2022 highs
- Price fluctuations introduce risks that must be shared across the value chain

Downstream value chain

- Economies of scale are crucial for the long-term viability of portable LiB recycling, as significant investments are needed to expand capacity
- Processing costs are expected to decrease as the collection of waste LiBs increases and process knowledge improves

European refinery capacity

- Limited refinery capacity in Europe restricts payability, especially if materials need to be processed outside the region
- Expanding local capacity could lower expenses since logistic costs would be reduced

SOURCE: European Commission, Impact Assessment Report of the Battery Directive Pt. 1 and 3 (2020); Benchmark, (2023); Trading Economics, accessed 2024-10-21; Shanghai Metals Market, accessed 2024-10-21; SCC

INTERVENTIONS BY EL-KRETSEN SHOULD CONSIDER THE RISKS AND BENEFITS OF DIFFERENT STRUCTURES OF THE RECYCLING VALUE CHAIN

Primary recycler*	A **Sorting**	B **Sorting + deactivation**	C **Sorting + deactivation + mech. recycling**
Value chain structure	⬛ Sorting → 🟨 (sorting) → 🟨 Deactivation → 🟨 Mechanical processing → 🟨 Metal recovery Most of the processes are carried out by secondary recycler(s) in the EU; likely to do a second sorting step to ensure the correct quality of waste batteries	⬛ Sorting → ⬛ Deactivation → 🟨 (Sorting) → 🟨 Mechanical processing → 🟨 Metal recovery Batteries are pretreated by the primary recycler and transported for further processing in the EU	⬛ Sorting → ⬛ Deactivation → ⬛ Mechanical processing → 🟨 Metal recovery Batteries are pre-treated and mechanically processed by the primary recycler, who separates the materials and transports the black mass for processing elsewhere
Benefits for El-Kretsen	▪ **Competitive pricing,** as many primary recyclers in Sweden have sorting capacity ▪ **Value chain risks** distributed across multiple actors, reducing vulnerability	▪ **Increased availability of secondary recyclers,** leading to lower recycling costs ▪ **Reduced risk of fires** since deactivation is carried out by the primary recycler	▪ **Increased transparency,** working closely with partners to create a marketable product ▪ **Reduced financial and GHG costs** from transactional actions (e.g., transport, admin) ▪ **Reduced risk of fires**
Risks for El-Kretsen	▪ **Uncertain recycling cost** due to limited capacity among secondary recyclers ▪ **Fragmented value chain** leading to decreased transparency and traceability, increasing risk of mishandling	▪ **Uncertain recycling cost** due to unpredictable value and payability for deactivated batteries ▪ **Fragmented value chain** leading to decreased transparency and traceability, increasing risk of mishandling	▪ **Potential lock-in**, as the capabilities and waste volumes required suggest utilizing one primary recycler ▪ **Concentration of value chain risks** (e.g., production halts, improper material quality)

⬛ Primary recycler(s) (Sweden) 🟨 Secondary recycler(s)

SOURCE: SCC

*Primary recycler is responsible for the export of waste batteries or black mass

EL-KRETSEN CAN ALREADY NOW START PREPARING FOR THE SHIFT NEEDED TO MEET MATERIAL RECOVERY TARGETS BY THE END OF 2027

1

Establish the baseline

Issue a Request for Information (RFI) to enhance baseline understanding of:

- Material recovery rates of CRMs (Co, Li, Ni, Mn)
- Opportunities and cost of short-term improvements in CRM recovery

2

Promote dedication toward improvement

Set procurement criteria which:

- Encourage short-term improvements in CRM recovery (if deemed possible)
- Promote recyclers committed to 2027 targets, demonstrated by e.g., willingness to engage in long-term partnership with El-Kretsen to advance pre-treatment and pilot new solutions

3

Improve conditions for sorting

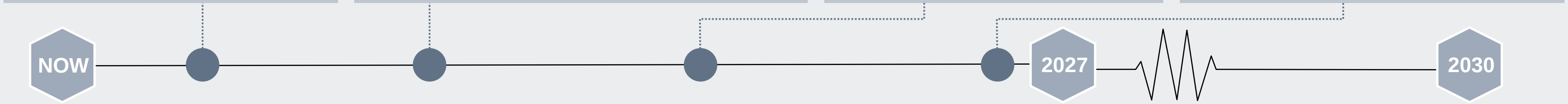
Work with producers and recyclers to find solutions in the upstream value chain that improve conditions for downstream sorting processes. Examples include pre-sorting of LiBs at the point of collection, labelling, etc.

4

Ensure fulfillment of targets

Set procurement requirements which:

- Ensure target fulfilment
- Considers the benefits and risks of different value chain structures
- Promote recyclers who present a credible plan for achieving 2030 targets



Existing material recovery (subject to variation among recyclers)

Cobalt 80 %

Lithium 0 %

Nickel 80 %

Material recovery targets

Cobalt 90 %

Lithium 50 %

Nickel 90 %

Material recovery targets

Cobalt 95 %

Lithium 80 %

Nickel 95 %

Given the current lack of financial incentives for recyclers to improve the recovery of critical raw materials (CRMs) such as lithium, significant progress by 2027 is unlikely without targeted intervention and support from El-Kretsen.

SOURCE: SCC

RECOMMENDATIONS

EL-KRETSEN IS RECOMMENDED TO IMPLEMENT ACTIONS TO IMPROVE CRM RECYCLING CONDITIONS FOR LIBS AHEAD OF 2027 TARGETS

OPPORTUNITY

Improve the material recovery rate of CRMs (especially Li, Co, Ni) from portable lithium-ion batteries, in line with 2027 targets

ACTIONS 2024 – 2025

- **Improve traceability of recycling routes and material recovery rate** at the material level, i.e., the recovery rate for Li, Co, Ni and Mn
- **Investigate the opportunity for short-term improvements.** Examples include setting procurement criteria on material recovery rate
- **Promote recyclers** dedicated to delivering on 2027 material recovery targets in the design of the procurement process

ACTIONS 2026-2027

- **Work with recyclers and producers to find solutions** in the upstream value chain that enhance the downstream sorting process
- **Set procurement requirements** to ensure 2027 targets are met, considering the benefits and risks of various value chain structures, while prioritizing recyclers with credible plans for achieving 2030 targets

FURTHER OBSERVATIONS

The conditions for recyclers to meet the 2027 and 2030 material recovery targets can be improved by addressing two key barriers

Barrier

Lack of economies of scale

Solution

Increase the mass of waste LiBs

Examples of actions:

- Improve the collection rate of portable LiBs
- Investigate Nordic collaboration opportunities for portable LiBs recycling to increase the volume of waste batteries

Barrier

High investments, uncertain returns

Solution

De-risk investments

Examples of action:

- Co-invest in pilots to reduce financial risk
- Establish long-term partnerships to improve predictability
- Create performance-based incentives to reward process improvements

SOURCE: SCC

EL-KRETSEN IS RECOMMENDED TO IMPROVE MN RECOVERY IN ALKALINE BATTERIES AND STAY INFORMED ABOUT LONG-TERM DEVELOPMENTS

		OPPORTUNITY	ACTION
 **Alkaline**	**Short term**	Increase the recycling of Mn as an alloying element to avoid significant material losses	Add specific requirements on Mn to be recovered separately in the recycling process
	Long term	The risk for supply deficit and upcoming legislation (CRM Act) could encourage the development of processing capacity in the EU and make closed-loop recycling more relevant	Stay informed about market developments and events that could significantly change the demand and supply balance for battery-grade manganese
 **Nickel-metal-hydride (NiMH)**	**Short term**	No identified short-term for improved recycling based on existing processes and developments in recycling technology of NiMH	No action required
	Long term	The projected demand increase for REEs and upcoming legislation (CRM Act) could make extraction and separation of REEs from NiMH batteries more relevant	Stay informed about market development and advances in the extraction of REEs from NiMH batteries and the development of separation capacity in the EU

Short term: 0 – 2 yrs; long term: > 5 yrs

SOURCE: SCC

APPENDIX

APPENDIX

ABBREVIATIONS

General

CE	Circular Economy
EoL	End of life
SCC	Stena Circular Consulting
CRM	Critical raw material
RFI	Request for information
ESS	Energy storage system
EV	Electric vehicle

NiMH	Nickel-metal-hydride
LiB	Lithium-ion battery
LCO	Lithium-cobalt
NMC	Nickel-manganese-cobalt
NCA	Nickel-cobalt-aluminium

Materials

Ni	Nickel
Cd	Cadmium
Li	Lithium
Co	Cobalt
REEs	Rare earth elements
Mn	Manganese
Pb	Lead

APPENDIX

PROJECT SCOPE

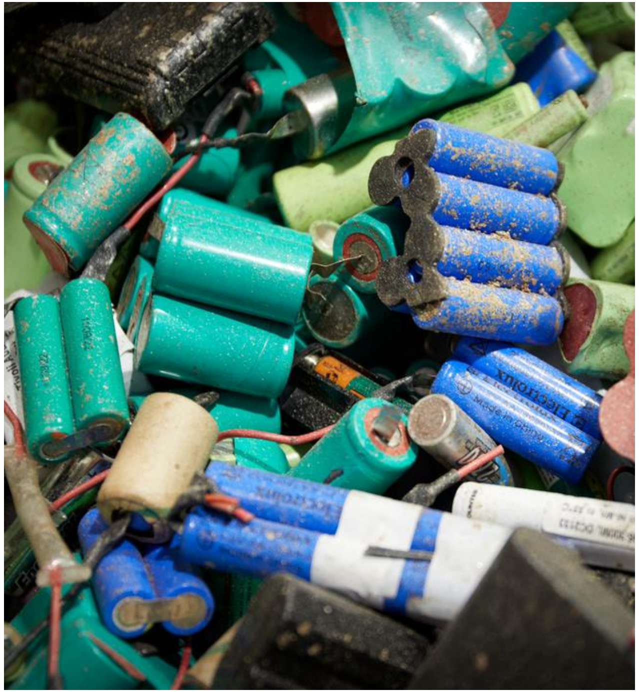
The scope of this study was limited to:

Existing industrialized processes. Emerging recycling processes, such as direct recycling and bio-metallurgical recycling, were excluded from the review.

Portable batteries. Defined as interoperable batteries having a standard format (e.g., AA, AAA, etc.) and batteries weighing <5kg, are linked or encapsulated in a product or casing, and are not designed for industrial use.

Li-Ion, alkaline, and NiMH battery types. Selected based on previous project results and data from El-Kretsen, indicating that these battery types make up the most significant volumes and potential value while containing significant amounts of CRMs. Alkaline and NiMH batteries were excluded from WP2 and WP3 after initial findings in WP1, indicating no viable options for closed-loop material recycling.

Critical raw materials. The project only aimed to study materials considered critical and of strategic importance to the EU, where the focus was put on lithium, cobalt, graphite, and manganese in LiBs, manganese in alkaline batteries, and rare earth elements in NiMH batteries. Nickel was also included in WP3, following the material recovery targets for Nickel in LiBs outlined in the new Battery Regulation.



SOURCE: EC, (2023)

ASSUMPTIONS

Assumptions for WP3 per graph

Currency:
- 1 SEK = 0.088 EUR
- 1 CNY = 0.13 EUR

Recycling cost for portable LiBs (LCO), page 29:
- Current main process cost based on LCO recycling cost for El-Kretsen and Enhanced Recycling cost based on potential LCO pre-treatment (excl. initial sorting cost) and recycling cost with processes capable of capturing CRM value

Projected recycling cost development for LiBs, page 29:
- Indexed representation of EC Impact Assessment Report of the Battery Directive, Pt. 3

Forecasted recycling cost development with a 6% share of LiBs (40% NMC, 60% LCO) and enhanced recycling of LCO batteries, page 30:
- Total battery volume of 3347 tonnes, where 187 tonnes are LiBs
- Current cost of 572 € per tonne (LCO not sent to enhanced process)
- Enhanced recycling cost of 625 € per tonne (LCO sent to enhanced process, all other batteries sent to same process as today)

Forecasted recycling cost development with 34% share of LiBs (40% NMC, 60% LCO) and enhanced recycling of LCO batteries, page 30:
- Total battery volume of 4748 tonnes, where 1485 tonnes are LiBs resulting in total collection rate of ~63%
- Current cost of 572 € per tonne (LCO not sent to enhanced process)
- Enhanced recycling cost of 1102 € per tonne (LCO sent to enhanced process, all other batteries sent to same as today)

Estimated enhanced recycling costs and revenue based on current costs and material prices, page 31:
- Enhanced Recycling cost based on potential LCO pre-treatment (excl. initial sorting cost) and recycling cost with processes capable of capturing CRM value
- Revenue from Li recovery based on virgin material value, to show maximum value (reflecting value of 100% of contained Li carbonate) based on current market value, and 50% value based on 50% Li carbonate recovery
- Cobalt could likely contribute towards material revenue in the future, however, since the additional value added from Enhanced recycling is uncertain compared to today, it was excluded, along with Nickel

COMPARISON OF THE ENVIRONMENTAL ASPECTS ASSOCIATED WITH PYROMETALLURGY AND HYDROMETALLURGY

Impact	Pyrometallurgy	Hydrometallurgy
GHG emissions	**Higher.** Pyrometallurgy is highly energy-intensive.[1,4]	**Lower.** However, the process produces GHG emissions through energy consumption in mechanical pre-treatment and other process steps.[4]
Air pollution	**Higher.** Thermal processes generate particulate matter, metal fumes, and acidic gases.[1]	**Lower.** Mechanical pre-treatment cause dust and volatile organic compounds.[1]
Water pollution	**Lower.** But the process can generate indirect groundwater pollution if slag is landfilled.[4]	**Higher.** High consumption of acids and reduction agents leads to the production of metal-laden acidic or alkaline wastewater.[1]
Water use	**Lower.** Water is mainly used for cooling.	**Higher.** Consumes large amounts of water throughout the process.
Solid waste generation	**Comparable or slightly lower.** Produces large amounts of slag.	**Comparable or slightly higher.** Produces large amounts of sludge and residual chemicals.[1]

! **Metallurgical processes vary in design and overall impact. For example, the environmental effects of hydrometallurgical recycling depend largely on the number of process steps and the solvents used - an LCA of cathode material recycling found that the most efficient process had a 50 % lower impact than the average.**

- **Both processes have a negative environmental impact but represent an overall reduction compared to primary extraction and processing of critical raw materials**
- **While pyrometallurgy has a greater climate impact, hydrometallurgy poses greater risks to marine ecotoxicity**
- **The main advantage of hydrometallurgical treatment is its higher metal extraction efficiency, reducing the need for primary materials**

Toro et al. (2023); Liu et al. (2023); Kallitsis et al. (2022); TemaNord 2024:502; Expert interviews

APPENDIX

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